Life-Cycle Assessment of Different Solar Cell

DISSERTATION

By

UPENTHIRAN A/L GANESON

14324

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(CHEMICAL)

SEPT 2014

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

LIFE CYCLE ASSESSMENT OF DIFFERENT SOLAR CELL

By

UPENTHIRAN A/L GANESON

14324

A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL)

APPROVED BY,

....
(DR. TASLIMA KHANAM)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPT 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

UPENTHIRAN A/L GANESON

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The life cycle of solar modules can have adverse effect on the environment in terms depletion of ozone layer, climate change, impact on land use, resource depletion and cause toxicological effect on human health and ecosystem. This can be solved using the life-cycle assessment (LCA) method where the severity of the environmental impact of a solar cell can be assessed which will assist the decision making process of a company or a government. The objective of this project is to use ReCiPe method to conduct the LCA and to come up with the solar module that has the least impact on the environment. ReCiPe method is specifically chosen because it has more advantage compared to other LCA methods. Besides that, other LCA methods have too many weak points which make the assessment less accurate. The scope of study for this project is focused on 4 types of solar cells which are mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe). For the methodology, the LCA of each solar cell was done using the SimaPro software where it addressed the environmental impact of the solar modules in graphical form. Before that, the inventory data for the manufacturing of the solar module was found and input into the database of the software. The analysis produced 3 types of results which are midpoint indicators, endpoint damage indicators and single score. From the results, it was decided that CdTe solar modules is the most environmental friendly module compared Mono-Si, Poly-Si and a-Si solar module. Further details of the project will be explained in the following chapters.

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to the Chemical Engineering Department of Universiti Teknologi PETRONAS (UTP) for providing me a platform to undertake this remarkable Final Year Project (FYP) course as a medium to enhance my skills and knowledge regarding my undergraduate studies in Chemical Engineering throughout these five years. By undertaking this project, I was able to understand the procedures and skill required to conduct a project which has made me a better engineering student.

Furthermore, a very special note of thanks to my kind supervisor, Dr. Taslima Khanam who is always willing to spend her time in assisting me and provided good support since the start of the project until it reaches completion. Through the weekly discussions with my supervisor, I have received numerous share of insight on the different aspects to be assessed for this project to become feasible. Her excellent support, patience and effective guidance have brought a great impact my project. Nevertheless, I would also like to thank the FYP committees for arranging various seminars as support and knowledge transfer to assist my work in the project. The seminars and lectures were indeed very helpful and provided useful tips to be implemented. I would like to thank all lecturers of Universiti Teknologi PETRONAS whom had given me guidance throughout the period of the project. Last but not least, my heartfelt gratitude goes to my family and friends for providing me continuous support throughout the easy and challenging times. Thank you all.

CHAPTER 1

INTRODUCTION

1.1 Background

Solar cell technologies are often considered as clean and 'carbon-free' energy as they do not generate any carbon dioxide during their operation. However, this is not so true when we consider the entire life-cycle of the solar cell where the extraction, processing and disposal of associated materials of a solar cell can have an adverse effect to the environment. The hazardous gas and waste produced during the life cycle of a solar cell can affect the environment in terms of depletion of ozone layer, climate change, impact on land use, resource depletion and cause toxicological effect on human health and ecosystem (Rebitzer et. al, 2004).

This problem can be solved using the life-cycle assessment (LCA) method. LCA is a method that is normally used to assess the environmental impact of a product and its manufacturing process (Sherwani et. al, 2010). This method is designed to reduce the potential impact of the product to the environment by guiding the decision making process of a company, organization or government on the process involved during the manufacturing process of the product. Besides that, LCA is the only tool that can measure a product's impact on the environment throughout its life cycle. There are various methods that are used to conduct LCA on products. Each method has its own type of impact indicators and procedure of assessing a product. The methods are normally selected according to the type of the product and the type of impact it has towards environment.

1.2 Problem Statement

In the past years, there have been various researches done on the life cycle assessment of solar cells using methods like CML 2001, Eco-indicator 99, IMPACT 2002+ and etc. However, to the best of our knowledge, there has never been a research done on the life cycle assessment of solar cells using ReCiPe method. One of the reasons is because it is a newly developed method which is a combination of

Eco-indicator 99 and CML. ReCiPe method is a method that transforms life cycle inventory results into a single value indicator score (Bengtsson & Howard, 2010). ReCiPe method is specifically chosen for this project because it has more advantage in assessing a product compared to other methods. One of it is that it has more impact indicators than any other method which covers a wider range of environmental impacts. The disadvantage of other methods is that it only covers a certain range of impact. They do not cover impacts like marine ecotoxicity, ionising radiation, particulate matter formation and water depletion which make the assessment less accurate.

Besides that, some LCA methods are too comprehensive which makes it difficult for organizations and government to assess the impacts of products on environment. ReCiPe method would give a single value indicator score which would make the assessment more clear when comparing one product from another. Furthermore, ReCiPe method assesses each impact category in 3 different perspectives which are individualist, hierarchist and egalitarian (Acero et. al, 2014). These perspectives represent a set of choices on issues time, expectations on management or the future technology development to reduce the environment impact. These perspectives would give a better analysis on the impacts compared to other methods which does not take time-frame or future technology into account.

1.3 Objectives

The objectives of this project are:-

- To use ReCiPe method to conduct life-cycle assessment on solar modules.

- To come up with a solar module that has the least impact on the environment.

1.4 Scope of Study

This project is focused on doing life-cycle assessment (LCA) on solar cells using only the ReCiPe method as it is the most suitable and the best method to assess solar cells. Besides that, the solar cells are assessed only using the Cradle-to Grave type. In other words, the solar cells will be assessed starting from its resource extraction till its disposal phase. Furthermore, only four types of solar cells are chosen for this project. The solar cells are mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe).

CHAPTER 2

LITERATURE REVIEW

2.1 Life Cycle Assessment

Life cycle assessment (LCA) or life cycle analysis is a technique that is normally used to assess various aspects related to the development of a product and its potential impact to the environment (Sherwani et. al, 2010). In other words, this method was designed for companies to determine the environmental impact of their products and its manufacturing processes. This method will be able to reduce the environmental impacts of products and services by guiding the decision-making process of the company.

It is important that all products undergo the LCA process as all the activities or processes involved throughout a product's life cycle can have an adverse effect on environment due to the emission of hazardous gas and waste throughout its life cycle (Rebitzer et. al, 2004). Some of the common impacts are climate change, ozone depletion, eutrophication which is excessive richness of nutrients in lake or other body of water, land use, ionising radiation which is a form of radiation consist of particles or gamma rays with sufficient energy to cause ionisation in a medium, resource depletion and toxicological stress on human health and ecosystems (Goedkoop et al, 2009).

LCA consist of several types that can be used to assess a product depending on the type and characteristic of the product. The types are as following.

2.2 Types of Life Cycle Assessment (LCA)

a) *Cradle to Grave*

- ❖ Assessment starts from the birth of the product or resource extraction (cradle) till its disposal phase (grave).

b) *Cradle to Gate*

- ❖ An assessment on a partial of the product's life cycle which is from the resource extraction to the factory gate which is before the product is sent to the consumer.

c) *Cradle to Cradle*

- ❖ It is also known as the closed loop production where the end of life of the product is a recycling process.

d) *Gate to Gate*

- ❖ This type is a partial LCA where it is only focused on a particular process alone.

There are 4 different phases in conducting LCA on product. These phases are independent from one another and the result of one phase will tell how the other phases are completed.

2.3 Phases in Life Cycle Assessment

2.3.1 Defining the Scope and Goal

- ➢ The initial step of LCA is defining the scope and goals of the study. In this first stage, the boundaries of the study should also be made explicit (Duda& Shaw, n.d). This is done by providing a description of the product system in terms of the system boundaries and a functional unit. The functional unit is an important basis as it enables alternative goods or services to be compared and analysed from one another (Rebtizer et.al, 2004). The assumptions and limitations of the product are also considered in this stage.

2.3.2 Life Cycle Inventory

- ➢ This step involves creating an inventory of flows and nature of the product. In this step, the energy, raw material requirements, environmental emissions of the product and process or activity are quantified (Duda& Shaw, n.d). The data must be related to the functional unit defined in the goal and scope. As a result, the life cycle inventory should provide all the information on the input and outputs in the form of elementary flow.

2.3.3 Life Cycle Impact Assessment

- According to Williams (2009), the impact assessment attempts to translate the inventory data into effects on human health, ecological health, and resource depletion. This is done by selection of impact categories, category indicators and characterization models. The impact will be categorized according to the severity of their effect.

2.3.4 Interpretation

- This phase shows the results of the analysis and all choices and assumptions made during the course of the analysis are evaluated. The main elements of the Interpretation phase are an evaluation of results in terms of consistency and completeness, an analysis of results and the formulation of the conclusions and recommendations of the study (Williams, 2009).

There are various methods used to assess the environment impact of a product throughout its life cycle. Each LCA method has its own set of impact categories (Acero et. al, 2014). The common methods used are as following.

2.4 Types of Life Cycle Assessment (LCA) Methods

2.4.1 Eco-indicator 99

Eco-indicator is one of the most widely used impact assessment methods in LCA. It was designed to replace its predecessor, Eco-indicator 95. The method was developed in order to simplify the interpretation and weighing process of the impacts. This method also allows the user to express the environmental impacts in a single score. The method covers 11 midpoint impact categories and then converge the midpoint categories into 3 types of damage categories (Budavari et. al, 2011).

The impact categories are normally assessed in 3 types of perspective which are individualist, hierarchist and egalitarian. These perspectives represent a set of choices on issues like time or expectations on proper management or future technology development that can avoid future damages. Individualist is based on "short-term interest, impact types that are undisputed, technological optimism as regards human adaptation". Hierarchist is the "most common policy principles with regards to time-frame and other issues". Lastly, Egalitarian is the "most precautionary perspective which takes into account the longest time-frame" (Goedkoop et al, 2009).

2.4.2 CML 2002

CML is impact assessment method that normally draws conclusion from the LCA study before the weighing is done. The weighing is done by using panel method which is by giving weighing factors based on different views of consultation panels (Budavari et. al, 2011). This method is divided in to 2 types of impact categories which are baseline and non-baseline. The baseline has 9 impact categories while the non-baseline has 7 impact categories (Acero et. al, 2014).

2.4.3 IMPACT 2002+

This method was specifically developed to improve the comparative assessment of eco-toxicity and human toxicity impact categories. It is an upgraded version of its previous version, IMPACT 2002. This method consist of 14 midpoint impact categories which is then converged to 4 damage categories which are human health, ecosystem quality, climate change and resource depletion (Budavari et. al, 2011).

2.4.4 BRE Eco-point

BRE stands for Building Research Establishment which was developed by the Environmental Profiles Methodology in 1999 in order to assess the environmental impacts of construction products. There are 3 types of LCA used in this method which are cradle-to-gate, cradle-to-site and cradle-to-grave. BRE Eco-point consists of 13 environmental impacts which would then be aggregated into a single Eco-point score after normalisation and weighing (Budavari et. al, 2011).

2.4.5 ReCiPe METHOD

ReCiPe is a method that transforms life cycle inventory results into a limited number of indicator scores (Bengtsson& Howard, 2010). This method will be specifically chosen for this project. One of the reasons is because it is a method that combines Eco-Indicator 99 and CML (Acero et. al, 2014). The ReCiPe method is also included in major life-cycle assessment (LCA) softwares and databases which make this method easy to be used. ReCiPe uses an environmental mechanism as the basis for the modelling which can be seen as a series of effects that can create a certain level of damage.

Besides that, ReCiPe method has more impact indicators compared to other methods. It has eighteen midpoint impact indicators and three endpoint damage indicators. The eighteen impact categories are addressed at the midpoint level and converged to endpoint level. Most of these midpoint impact categories are further converted and aggregated into 3 end point categories. As it can be seen from Figure 1, the 18 midpoint categories are combined to 3 damage categories which are human health, ecosystem and resources depletion (Bengtsson& Howard, 2010). Similar to Eco-indicator 99, each category is factored into 3 cultural perspectives which are individualist, hierarchist and egalitarian (Acero et. al, 2014).

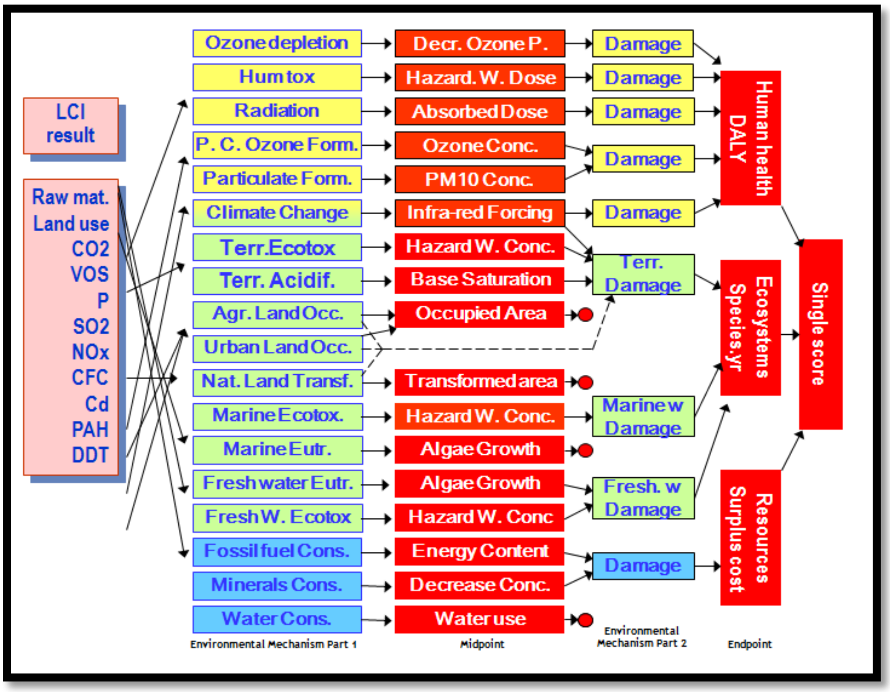

Figure 1: Relationship between LCI parameters (left), midpoint indicators (middle) and endpoint indicators (right) in ReCiPe 2008 (Goedkoop et al, 2009).

For ReCiPe method, after the data inventory is defined, the data will be converted into 18 midpoint impact indicators and then converted 3 endpoint categories. The following section will discuss on how the data is analysed and converted to the impact indicators which shows the severity of each environmental indicator. Each impact indicator would have its own impact potential to show the severity of the environmental impact and characterisation factor which will be used to multiply with the amount of substance to find out the severity of the damage it can cause towards human, ecosystem and resource. The impact indicators are as following.

2.5 ReCiPe Method Environmental Impact Indicators (Goedkoop et. al, 2009)

2.5.1 Climate Change

Climate change can cause a number of environmental mechanisms that affect both the human and ecosystem. For ReCiPe, it is only interested in assessing the marginal effect of CO_2 and other greenhouse gases (GHG). For the midpoint indicator, the global warming potential (GWP) will be calculated which is as shown in Eq. 1.0. The GWP of any substance expresses the integrated forcing of the substance relative to the integrated forcing of reference gas over the same time horizon. The GWP of different greenhouse gases can be used to determine which will cause the greatest radiative forcing over the time horizon.

$$GWP_{x,T} = \frac{\int_0^T a_x \times [x(t)]dt}{\int_0^T a_r \times [r(t)]dt} \qquad [Eq. 1.0]$$

Where,

$GWP_{x,T}$ *is the global warming potential of substance* x,

T *is the time horizon over which the calculation is considered*

a_x *and* a_r *is the radiative efficiency* $(Wm^{-2}kg^{-1})$

$[x(t)]$ *is the time dependent abundance of substance* x

$[r(t)]$ *is the time dependent abundance of reference gas*

Climate change can cause damage towards human and ecosystem. In order to calculate the damage, the temperature factor (TF) has to be calculated first as shown in Eq. 1.2.

$$TF = LT_{CO2} \times \frac{\Delta TEMP_t}{\sum_t E_{CO2}} \qquad [Eq. 1.1]$$

Where,

TF *is the temperature factor* $(°C.yr.kg^{-1})$

LT_{CO2} *is the lifetime of* $CO2$ (yr)

$\Delta TEMP_t$ *is the change in average temperature* $(°C)$

$\sum_t E_{CO2}$ *is the sum of annual mass od* $CO2$ $(kg.yr^{-1})$

For the damage on human health and ecosystem, the characterization factor will be the key. It will be used to multiply with the waste material emitted to find out the damage it can cause. For human health the damage will be represented in terms of disability-adjusted loss of life (DALY). For ecosystem damage, it will be in terms of loss of species in year form (yr). Eq. 1.3 and Eq. 1.4 shows the characterization factor of human health and ecosystem damage. This characterization factor will then be used to find the damage by multiplying them with the amount of CO2 or GHG released.

$$CF_{HH} = TF \times DF_{HH} \quad [Eq. 1.2]$$

Where,

CF_{HH} $is\ the\ characterization\ factor\ on\ human\ health$ $(DALY.kgCO2^{-1})$

TF $is\ the\ temperature\ factor$ $(°C.yr.kg^{-1})$

DF_{HH} $is\ the\ damage\ factor\ for\ human\ health$ $(DALY.yr^{-1}.°C^{-1})$

$$CF_{ES} = TF \times DF_{ES} \quad [Eq. 1.3]$$

Where,

CF_{ES} $is\ the\ characterization\ factor\ on\ ecosystem$ $(°C.yr.kgCO2^{-1})$

TF $is\ the\ temperature\ factor$ $(°C.yr.kg^{-1})$

DF_{ES} $is\ the\ damage\ factor\ for\ ecosystem$ $(°C^{-1})$

2.5.2 Ozone Depletion

Ozone layer is continuously formed and destroyed by the action of the sunlight and chemical reactions in the stratosphere. Ozone depletion occurs due to the increase in ozone depleting substance (ODS) in the atmosphere. The depletion is measured in terms of the decrease in stratospheric ozone concentration. The ozone depletion potential (ODP) is the characterisation factor that is used to calculate the ozone depletion capacity of an ODS. The equation is as shown in Eq. 2.0.

$$ODP_i(\infty) = \frac{\Delta OD_j}{\sum_{i \in j} \Delta m_i} \quad [Eq. 2.0]$$

Where

$ODP_i(\infty)$ $is\ the\ ozone\ depletion\ potential\ of\ substance\ i\ (ktn \times yr)$

$\Delta OD_j\ is\ the\ weighted\ sum\ of\ the\ avoided\ emission\ of\ ODS\ belonging\ to\ group\ j$

$\Delta m_i\ is\ the\ avoided\ amount\ of\ ODS\ i\ of\ group\ j$

In ReCiPe method, the ozone depletion only addresses its damage towards human health. The characterization factor for human health damage will be first determined which will be multiplied with the amount of ODS in the inventory to get the severity of the damage towards human health.

$$CF_j = \sum \frac{\int_{2007}^{2100} \Delta DALY_j\ dt}{\int_{2003}^{2040} \Delta OD_j\ dt} \quad [Eq.2.1]$$

Where,

$CF_j\ is\ the\ characterization\ factor\ of\ ODS\ towards\ human\ health\ (yr.kg\ ODS^{-1})$

$\Delta DALY_{j,S}\ is\ the\ avoided\ number\ of\ DALY\ (yr)$

$\Delta OD_j\ is\ the\ avoided\ emission\ of\ ODS\ of\ group\ j\ (kg\ ODS)$

2.5.3 Acidification

Acidification is actually the process of atmospheric deposition of inorganic substance that changes the acidity of soil. The change in soil acidity can affect specific kind of species in a harmful manner. For ReCiPe method, acidification represents the terrestrial acidification impact indicator. Base saturation (BS) is used as an indicator to express the acidity where it is the degree to which the adsorption complex of a soil. The equation of BS is shown in Eq. 3.0.

$$BS = \frac{BC}{CEC} \quad [Eq\ 3.0]$$

Where,

$BS\ is\ the\ base\ saturation$

$BC\ is\ the\ sum\ of\ basic\ cation\ (cation.kg\ soil^{-1})$

$CEC\ is\ the\ cation\ exchange\ capacity\ (cation.kg\ soil^{-1})$

For acidification, it only addresses the damage towards ecosystem. In order calculate the damage it has to the ecosystem, the characterization factor of acidification will be calculated using Eq. 3.1.

$$CF = SD_{terr} \times \sum A_j \times \frac{dPDF}{dM} \quad [Eq. 3.1]$$

Where,

$CF\ is\ the\ characterization\ factor\ for\ acidification\ (yr.kg^{-1})$

$SD_{terr}\ is\ the\ species\ density\ (species.m^{-2})$

$A_j\ is\ the\ area\ of\ forest\ (m^2)$

$PDF\ is\ the\ Potential\ Disappreared\ Fraction$

$M\ is\ the\ emission\ rate\ (kg.yr^{-1})$

2.5.4 Eutrophication

There are 2 impact indicators in ReCiPe method that addresses eutrophication which are freshwater eutrophication and marine water eutrophication. Aquatic eutrophication is the nutrient enrichment of the aquatic environment which can affect the ecosystem of aquatic lives. The eutrophication potential would represent the severity of the eutrophication of freshwater and marine water. In order to calculate the eutrophication potential, the fate factor needs to be calculated first using Eq. 4.0.

$$FF_x = \frac{dC_{x,j}}{dM_x} \qquad [Eq. 4.0]$$

Where,

$FF_x\ is\ the\ fate\ factor\ of\ nutrient\ x\ (yr.km^{-3})$

$dC_{x,j}\ is\ the\ marginal\ concentration\ increment\ (tn.km^{-3})$

$dM_x\ is\ the\ marginal\ increase\ of\ emission\ rate\ (tn.yr^{-1})$

Now the fate factor is known, the eutrophication factor can be calculated using Eq. 4.1.

$$EP = \frac{FF_x}{FF_{x\ at\ STP}} \quad [Eq. 4.1]$$

Where,

$EP\ is\ the\ eutrophication\ potential$

$FF_x\ is\ the\ fate\ factor\ of\ nutrient\ x\ (yr. km^{-3})$

$FF_{x\ at\ STP}\ is\ the\ fate\ factor\ of\ nutrient\ x\ at\ STP (yr. km^{-3})$

For eutrophication, it only addresses the damage towards ecosystem. In order calculate the damage it has to the ecosystem, the characterization factor of eutrophication will be calculated using Eq. 4.2.

$$CF = FF_x \times DF \quad [Eq. 4.2]$$

Where,

$CF\ is\ the\ characterization\ factor\ eutrophication\ (species. yr. kg^{-1})$

$FF_x\ is\ the\ fate\ factor\ of\ nutrient\ x\ (yr. km^{-3})$

$DF\ is\ the\ damage\ factor\ (km^3. kg^{-1})$

2.5.5 Particulate Matter and Petrochemical Oxidant Formation

Particulate matters (PM) are matters with diameter less than 10 um which represents a mixture of organic and inorganic substance. Meanwhile, petrochemical oxidant is a matter that is emitted during petrochemical reactions of Non Methane Volatile Organic Compound (NMVOC). Both these emission are considered as the same category as both can cause adverse effect towards human health.

The severity of these matter can be represented by finding out their formation potential (Eq. 5.1) but before that, the intake factor has to be calculated using Eq. 5.0. Then, the formation potential will be calculated using Eq. 5.1.

$$IF_{x,i} = \frac{dI_{x,i}}{dM_x} \quad [Eq. 5.0]$$

Where,

$IF_{x,i}$ $is\ the\ intake\ factor\ of\ pollutant\ x$

$dI_{k,i}$ $is\ the\ marginal\ increase\ in\ population\ intake\ rate\ of\ pollutant\ x(kg.yr^{-1})$

dM_x $is\ the\ marginal\ increase\ in\ emission\ of\ x\ (kg.yr^{-1})$

$$FP = \frac{IF_x}{IF_{PM10\ or\ Oxidant}} \qquad [Eq. 5.1]$$

Where,

$FP\ is\ the\ formation\ factor$

$IF_{x,i}$ $is\ the\ intake\ factor\ of\ pollutant\ x$

$IF_{PM10\ or\ Oxidant}$ $is\ the\ intake\ factor\ of\ PM10\ or\ Oxidant$

For particulate matter and petrochemical oxidant formation, ReCiPe only addresses the damage towards human health. In order calculate the damage it has to the ecosystem, the characterization factor of the formation will be calculated using Eq. 5.2.

$$CF_x = \sum_i \left(IF_{x,i} \times \sum_e \left(EF_{e,k,i} \times DF_{e,k} \right) \right) \qquad [Eq. 5.2]$$

Where,

CF_x $is\ the\ characterization\ factor\ of\ pollutant\ x\ (yr.kg^{-1})$

$IF_{x,i}$ $is\ the\ intake\ factor\ od\ pullutant\ x$

$EF_{e,k,i}$ $is\ the\ effect\ factor\ (kg^{-1})$

$DF_{e,k}$ $is\ the\ damage\ factor\ (yr)$

2.5.6 Land Use

Land use can cause damage because of the effect of occupation or transformation of land. These kinds of activities will affect the biodiversity of the land. For ReCiPe method, there are 3 types of land occupation that are addressed which are agriculture land occupation, urban land occupation and natural land occupation. The severity of the land occupation can be found out through the occupation potential which will be calculated using Eq. 6.0

$$OP = A_o \times t \quad [Eq. 6.0]$$

Where,

$OP\ is\ the\ occupation\ potential\ (m^2.yr^{-1})$

$A_o\ is\ the\ area\ occupied\ (m^2)$

$t\ is\ the\ time\ of\ occupation\ (yr)$

The damage land occupation has towards the ecosystem can be calculated using the characterization factor which can be found out through Eq. 6.1.

$$CF = \left(z_o - z_i + \frac{c_o - c_i {A_o}^{z_o - z_i}}{c_o}\right) \times t \times SD \quad [Eq. 6.1]$$

Where,

$CF\ is\ the\ characterization\ factor\ due\ to\ transformation\ (yr.m^{-2})$

$z\ is\ the\ species\ accumulation\ factor$

$c\ is\ the\ species\ richness\ factor$

$A\ is\ the\ area\ occupied\ (m^2)$

$t\ is\ the\ time\ of\ occupation\ (yr)$

$SD\ is\ the\ species\ density\ (species.m^{-2})$

2.5.7 Water Depletion

Water is an important resource. The extraction of water from dry areas can cause very significant damage to human and ecosystem. However, ReCiPe model does not express the damage at endpoint level. Severity of the water depletion can be determined using the water depletion potential which is shown in Eq. 7.0

$$WDP = \frac{w_{loss}}{w_o} \qquad [Eq. 7.0]$$

Where,

$WDP\ is\ the\ water\ depletion\ potential$

$w_{loss}\ is\ the\ water\ loss\ (m^3)$

$w_o\ is\ the\ initial\ amount\ of\ water\ (m^3)$

2.5.8 Mineral Resource Depletion

Minerals are actually naturally occurring substances. It is formed through geological process and has its own characteristics chemical composition. Minerals and metals are extracted from mining process to change them into commercial goods. However, the mining process can cause damage in terms of resource depletion. Resource depletion would cause the society to pay more for their goods.

The severity of the mineral depletion can be represented in terms of its damage ($). This can be done by calculating the characterization factor of the resource depletion using Eq. 8.0. The characterization factor then can be multiplied with the amount to mineral extracted to find out the severity of resource depletion.

$$CF = \frac{\Delta C}{\Delta Y} \times P \times NPV_T \qquad [Eq. 8.0]$$

Where,

$CF\ is\ the\ characterization\ factor\ of\ the\ resource\ depletion\ (\$.kg^{-1})$

$\Delta C\ is\ the\ cost\ increase\ (\$.kg^{-1})$

$\Delta Y\ is\ the\ extracted\ mass\ that\ caused\ price\ increase\ (kg)$

$P\ is\ the\ produced\ amount\ of\ resource\ over\ a\ certain\ period\ (kg.yr^{-1})$

$NPV_T\ is\ the\ net\ present\ value\ factor\ over\ a\ time\ T\ (yr)$

2.5.9 Fossil Fuel Depletion

Fossil fuel represents a group of resources that contain hydrocarbons which are normally turned into volatile materials like methane, petrol and non-volatile material like coal. As fossil fuel is continuously extracted from the core of the Earth, its production cost and energy requirement increases. When the production cost increase, the price of the product will increase as well. This causes society to pay more for fuel.

The severity of the fossil fuel depletion can be represented in terms of its damage ($). This can be done by calculating the characterization factor of the resource depletion using Eq. 9.0. The characterization factor then can be multiplied with the amount to resource extracted to find out the severity of fossil fuel depletion.

$$CF_{kg,fossil} = MCI_{kg} \times P \times \sum_{T} \frac{1}{(1.-d)^t} \qquad [Eq. 9.0]$$

Where,

$CF_{kg,fossil}$ *is the characterization factor fossil fuel depletion* $(\$.kg^{-1})$

P *is the annual production of fossil fuel* (kg)

MCI_{kg} *is the marginal cost increase* $(\$.kg^{-2})$

2.5.10 Toxicity

There are 2 types of toxicity addressed in this section which are human toxicity and ecotoxicity (freshwater and terrestrial). Toxicities happen when an area or person is exposed to a hazardous chemical which causes adverse effect towards them. In order to find out the damage severity towards ecosystem (ecotoxicity), the fate factor needs to be found out first using Eq. 10.0.

$$FF_{j,i,x} = \frac{\partial C_{j,x}}{\partial M_{i,x}} \qquad [Eq. 10.0]$$

Where,

$FF_{j,i,x}$ *is the fate factor for the transport efficiency of substance x* $(yr.m^{-3})$

$C_{j,x}$ *is the marginal concentration change of substance x* $(kg.m^{-3})$

$M_{i,x}$ *is the marginal emission change of substance x* $(kg.yr^{-1})$

The characterization factor is found first using Eq. 10.1. The characterization factor then can be multiplied with the amount of toxicants (kg) to find out the severity of the ecosystem damage (yr).

$$CF_{j,i,x} = SD_q \times FF_{j,i,x} \times E_{j,x} \times W \qquad [Eq. 10.1]$$

Where,

$CF_{j,i,x}$ $is\ the\ characterization\ factor\ of\ chemical\ x\ (yr.kg^{-1})$

SD_q $is\ the\ species\ density\ (m^{-3})$

$FF_{j,i,x}$ $is\ the\ fate\ factor\ for\ the\ transport\ efficiency\ of\ substance\ x\ (yr.m^{-3})$

$E_{j,x}$ $is\ the\ effect\ factor$ (yr. kg^{-1})

$W\ is\ the\ volume\ of\ the\ compartment\ (m^3)$

In order to find out the damage severity human health (toxicity), the human intake fraction needs to be found out first using Eq. 10.2. Then, the characterization factor is found using Eq. 10.3. The characterization factor then can be multiplied with the amount of toxicants (kg) to find out the severity of the human health damage.

$$iF_{r,i,x,g} = \frac{\partial I_{r,x,g}}{\partial M_{i,x}} \qquad [Eq. 10.2]$$

Where,

$iF_{r,i,x,g}$ $is\ the\ human\ intake\ fraction\ of\ substance\ x\ through\ route\ r$

$\partial I_{r,x,g}$ $is\ the\ marginal\ intake\ change\ of\ substance\ x\ through\ route\ r\ (kg.day^{-1})$

$\partial M_{i,x}$ $is\ the\ marginal\ change\ in\ emission\ of\ substance\ x\ (kg.day^{-1})$

$$CF_{r,i,x,g} = iF_{r,i,x,g} \times E_{r,x} \qquad [Eq. 10.3]$$

Where,

$CF_{r,i,x,g}$ $is\ the\ human\ characterization\ factor\ of\ substance\ x\ (yr.kg^{-1})$

$iF_{r,i,x,g}$ $is\ the\ human\ intake\ fraction\ of\ substance\ x\ through\ route\ r$

$E_{r,x}$ $is\ the\ effect\ factor\ of\ substance\ x\ (yr.kg^{-1})$

2.5.11 Ionising Radiation

Ionising radiation is the release of radioactive material to the environment. Prolonged exposure to ionising radiation can cause adverse effect towards human health like cancer. The damage towards human health is represented in terms of disability-adjusted loss of life year (DALY) as shown in Eq. 11.0. The DALY will show the damage severity of the radiation exposure in terms of absorbed dose on human body (man. Sv).

$$DALY = YLL + YLD \quad [Eq. 11.0]$$

Where,

$DALY\ is\ the\ disability - adjusted\ loss\ of\ year\ (yr. man\ Sv^{-1})$

$YLL\ is\ the\ sum\ of\ year\ of\ life\ loss\ (yr. man\ Sv^{-1})$

$YLD\ is\ the\ years\ of\ life\ disable\ (yr. man\ Sv^{-1})$

2.5.12 Normalization

The impacts indicators do not have the same unit which will make it hard to compare one impact from another. In order to find out the magnitude of each environmental impact, the SimaPro software would normalizes the data using European normalization. Normalization is the process of calculating the magnitude of the impact indicator by dividing the quantity of substance that contributed towards the impact category indicator with a reference value or normalization reference. The reference value is the average yearly environmental load in a country or a continent which in our case would be Europe. The calculation is shown in Eq 12.0. After normalization, the impact indicators will be dimensionless form which indicates the magnitude of each impact indicator. Through this, the impact indicators can be easily compared with one another.

$$Normalized\ Value = \frac{Amount\ of\ Substance}{Normalization\ Reference} \quad [Eq. 12.0]$$

Where,

$Amount\ of\ Substance\ is\ in\ kg\ or\ m^3 or\ m^2\ (depending\ on\ type\ of\ indicator)\ per\ year$

$Normalization\ Reference\ is\ in\ kg\ or\ m^3 or\ m^2\ per\ capita\ per\ year$

2.5.13 Weighing

After the impact indicators undergo normalization, they would undergo weighing process to convert the different impact indicators in to single score. Weighing would represent the magnitude of the solar modules in the form of single score with the unit of point (Pt). Eq 13.0 shows the weighing calculation. The single score is normally used to compare one module from another. The single score is assessed in 3 types of perspective which are individualist, hierarchist and egalitarian. These perspectives represent a set of choices on issues like time or expectations on proper management or future technology development that can avoid future damages.

$$Single\ Score\ (Pt) = Weighing\ factor\ \times Normalized\ Value \quad [Eq. 13.0]$$

2.6 Solar Cell

A solar cell or photovoltaic cell is a device that generates electricity directly from visible light. This is known as photovoltaic effect. Solar panels are now used all over the world as a replacement for non-renewable energy as it provides an attractive form of limitless alternative energy. The usage of solar cells can be a source of thermal energy and electrical energy (Bertolli, 2008). In order to generate useful power, it is necessary to connect a number of cells together to form a solar panel which is also known as a photovoltaic module (Stubbs, 2008). The electric energy generated from the solar cell is commonly referred to as solar power.

The basic mechanism of solar cell is related to the semiconductor physics of the photovoltaic cell. Solar cell is a large area of p-n junction which is where electricity is generated in the cell. More specifically, it is electron movement between p-type (positive) and n-type (negative) materials (Bertolli, 2008). When a solar cell is placed in the sun, the photons of light strike the electrons in the p-n junction and energize them which would knock them free of their atoms. A wire is set up to connect the p-type to the n-type which provides a path for the electrons to move away from each other. This flow of electrons is an electric current (How a Photovoltaic Cell Works, 2011).

Solar cells are normally set up to a grid-connected photovoltaic system. A grid-connected photovoltaic (PV) system is a type of power system that supplies electricity directly to households and businesses using photovoltaic panels or solar panels as power source. During the day, the PV panels produce direct current (DC). The current runs through an inverter that converts the DC into alternating current (AC). This is because AC is more suitable for electrical appliances and makes the export to the main electricity grid much easier (Typical PV System Components, 2014). Figure 2 shows the diagram of a grid-connected PV system.

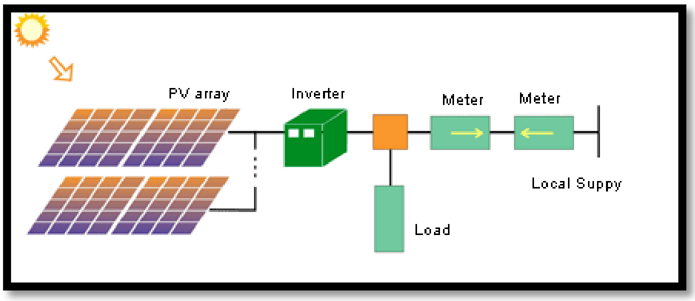

Figure 2: Diagram of Grid-connected PV System

There are several types of solar cells that are commonly used in industrial and residential areas. The types are as following.

2.7 Types of Solar Cells

There are two common types of photovoltaic cell which are wafer-based crystalline silicon cell and thin film cell. For wafer-based crystalline silicon cell, there are 2 types which are mono-crystalline silicon with a market share of 36% and the poly-crystalline silicon with a market share of 45% (Glunz et. al, n.d). Mono-crystalline silicon cells are solar cells manufactured from a single crystal while poly-crystalline silicon are made by melting different silicon crystals together (Bertolli, 2008). In terms of product life, mono- crystalline silicon and poly-crystalline silicon has a product life of more than 25 years (Cherrak & Kirci, 2012).

On the other hand, thin film system has cadmium telluride (CdTe) film with a market share of 6%, amorphous silicon (a-Si) film with a market share of 5% and copper indium gallium selenide (CIGS) film with a market share of 2% (Glunz et. al, n.d). CdTe is a cell that uses a cadmium telluride semiconductor layer to convert sunlight in to electricity. Amorphous-silicon is a cell which deposited with thin silicon film layer on glass or other substrate material and CIGS is a cell made up from semiconductor metal composed of copper, indium, gallium and selenium. In terms of product life, CdTe has a life of 20 years, amorphous silicon has a product life of 10 to 20 years and finally, CIGS has a life of more than 25 years (Cherrak & Kirci, 2012).

The manufacturing process of each solar cell differs from one another. It is important that the processes are studied as the type of process involved during the manufacturing phase of the solar cell determines the severity of its impact to the environment. The manufacturing processes of the solar cells are as following.

2.8 Manufacturing Process of Solar Cells

2.8.1 Manufacturing Silicon Solar Cell (Stoppato, 2008)

i. **Silica Extraction and Refining**
   - The process of manufacturing silicon solar cell begins with the extraction of silica. Silica is normally extracted from quartz sand.

ii. **Silica to mg-Silicon Transformation**
   - The pulverised quartz and a mixture of coal are fused in a crucible using an electric arc. Then, the reduction process takes place where metallurgic silicon (mg-Si) is produced.

$$SiO2 + 2C \longrightarrow Si + 2CO$$

iii. **mg-Si to Solar Silicon Transformation**
   - The silicon will undergo various types of process before it becomes solar-grade silicon (sog-Si). First, the silicon would undergo hydrogenation which is a process where the silicon would be treated with hydrogen. This process is done in a fluid bed reactor at 500°C and 3.5MPa with a copper-based catalyst.
   - Then, a series of fractional distillations is done which eliminates impurities. The fractional distillation is a process that would separate the impurities and the silicon according to their different boiling points. Lastly, a pyrolysis process which is a decomposition process at high temperature takes place. This will form sog-Si.

iv. **Transformation into Wafer**

- The silicon would then be transformed to wafer using casting method where the silicon is poured into a mold and is solidified. Columnar silicon will be formed, where the crystals will be vertically aligned. Then, the columnar silicon would be cut into wafers in the form of cells.

v. **Chemical Treatment**

- A chemical treatment is done using $KOH–NH_3$ solution to remove the damages on the wafer surface and to give better solar radiation absorption.

vi. **n-film Formation (Doping)**

- The film is created by diffusing phosphorus on the surface of the wafer. The process takes place at high temperature which is between 850 to 900°C. Then, saturated nitrogen is passed over the wafer in the presence of oxygen. Finally, a film diffusing phosphorus is created.

vii. **Passivation and Anti-reflection Coating (ARC)**

- The cells are passivated and coated by an anti-reflection film. Passivation is the process of coating the cell with protective material. They are normally passivated in aluminium oxide to improve the efficiency of the cell. Both passivation and anti-reflection coating will be done using the Plasma Chemical Vapour Deposition (PCVD) process.

viii. **Panel Assembly**

- Finally, the cells are tested and assembled depending on the configuration chosen.

2.8.2 Manufacturing Amorphous Silicon from Silica (Chamsilpa & Tanongkiat, 2010)

i. The amorphous silicon is made by depositing silicon onto glass or another substrate material like transparent plastic. Then, silane gas (SiH4) is reacted with the silicon using the Plasma Chemical Vapour Deposition device.

ii. During the silane gas reaction, dopants like phosphine and diborane are included in the reaction. Dopants are substances that are used to create desired electrical characteristics in a semiconductor. In the case of amorphous silicon, it is to create the p-type, n-type region and p-n junction in the cell.

iii. The plasma gets excited and decomposes the gas which generates radicals and ions. Finally, a thin hydrogenated silicon film is formed on the heated substrates.

2.8.3 Manufacturing Cadmium Telluride (CdTe) Solar Cell (Fthenakis, 2004)

i. Cadmium (Cd) Extraction

- Cadmium is normally obtained from sphalerite (ZnS) which is a major-cadmium bearing mineral. It is present in both zinc and lead ores. Cadmium is generated as a by-product of smelting zinc ores and lead ores. After the ores are mined, they are processed by undergoing crushing, screening and milling process. Then, they will undergo the smelting process which is a process of extracting zinc and other metals from the ores by heating and melting then ores.

ii. Tellurium (Te) Extraction

- Tellurium is a rare metal that is extracted from the by-product of slimes of processed copper, lead, gold, and bismuth ores. After the ores are mined, they undergo several purification processes in order to obtain the metals and remove impurities. Then, tellurium is extracted from the slimes of the processes.

iii. Purification of Cadmium and Tellurium

- The residues of both materials would undergo the leeching process where the residues would be filtered out from other impurities. Then, the residues would undergo additional leaching with sulphuric acid and then filtered through three stages to remove zinc, copper, and thallium. Finally, they will undergo vacuum-distillation.

iv. Production of CdTe

- The high purity Cd and Te produced from the purification process are used in synthesizing high purity CdTe for solar cells. Cadmium telluride (CdTe) is produced from cadmium and tellurium powder through proprietary method.

v. Manufacturing CdTe Photovoltaic

- The manufacturing of CdTe photovoltaic is done using electro-deposition method. In electro-deposition, CdTe thin film is deposited on a substrate attached to the cathode of an electrolytic system using an aqueous solution of cadmium sulphate ($CdSO_4$) or cadmium chloride ($CdCl_2$) and tellurium dioxide (TeO_2). Electro-deposition of CdTe usually is accompanied by chemical-bath deposition of CdS. This process would produce thin film cadmium telluride cells.

2.9 Difference between Current Project from Previous Researches

This project is different from the previous LCA researches done on solar cells because there has never been an analysis done on different solar cells using ReCiPe method where the solar cells are compared against one another to select the cell that has the least impact on environment. ReCiPe method has been used to analyse only one type of solar cell without comparison with other cells. Besides that, my research conducts the analysis up till single score value where it is analysed in 3 different perspectives which are hierarchist, individual and egalitarian. These perspectives represent a set of choices or assumptions on issues like time or expectations on proper management or future technology development that can avoid future damages. In previous researches, the LCA on solar cell is only done up till damage indicator which makes the analysis incomplete.

The common types of method used in previous researches for LCA of different solar cell are Eco-indicator 99 and CML. The solar cells are analysed using this method and compared against one another. However, the results generated from Eco-indicator 99 and CML method are not as accurate as ReCiPe method. ReCiPe method is the latest LCA method which covers a higher number of impact indicators and analyses in different perspectives which will give a more accurate and reliable result. Furthermore, my research is different from previous research as the functional unit for the inventories is per kW power produced. In most of the previous research, the inventories are in per m^2 area of the module. The reason the inventories were in kW basis was to create common basis for different solar cells and to know the amount or area of module required to produce sufficient amount of electricity for industrial and domestic uses.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

1. The scope and goal of the study were indentified.
2. The scope of study was focused on 4 types of solar cells which are mono-crystalline silicon (Mono-Si), poly-crystalline silicon (Poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe) solar cells.
3. The goal of the study is to come up with the solar cell with the least impact on the environment and use ReCiPe method to conduct LCA on different solar cells.
4. An initial research on solar module and the methods used for life-cycle assessment was conducted to get a better understanding of the project.
5. The inventories for the energy, raw material requirement and the environmental emission of the solar module were found from literatures. Besides that, the inventories for the balance of system (BOS) of the module were also found which contained all the information regarding the roof mounting, inverter and electrical installation.
6. The inventories found were converted kW basis. This is to come up with a standardized inventory where it contains all the energy, raw material requirement and the environmental emission for a solar module that can produce 1kW power.
7. The conversion was done first by finding the amount of power the inventory's module can generate. The inventory found was the amount to produce $1m^2$ of module. The inventories were converted by finding out the area required to produce 1 kW power. This was done using the ratio method.

8. An initial study on SimaPro software was done to get a better understanding on the software.

9. The life-cycle assessment on all 4 types of solar cells was done using SimaPro software.

10. The goal and the scope were specified in the software. Then, the preferred library intended to be used in the project was selected.

11. Then, all the inventories of the solar module were entered in the software. The inventories were entered according the process flow of the solar cell production. The output of the process was entered first by entering its amount and selecting the unit. Then, the data for the input of the process was entered.

12. The emission and other waste outputs of the process were then specified in the software. The inventory for the electricity, transport and the emission from the electricity and transport was also added to the system.

13. The same procedure was repeated for all 4 types of solar module and the data was saved in the software.

14. The data inventory for all 4 types of solar module was analysed using the ReCiPe method by doing a midpoint impact assessment on them. The impact assessment was then translated into damage on human health, ecosystem and resource depletion. The life cycle of the solar module will then be compared with one another. This was done using the software as it would produce a weighted total score for all of the life cycles. The solar module with the least impact on the environment was selected.

15. Finally, a report containing all the findings, analysis of data and future recommendations was written.

3.2 Key Milestone

- ***FYP 1***

Week 1-2

- Understanding the project.
- Identify the objectives and scope of study.

Week 3-4

- Conduct preliminary studies on existing researches to understand the concept of life-cycle assessment of solar cells.
- Find inventories data for the energy, raw material and environment emssion of solar cells and convert them to 1kW basis.

Week 5-6

- Conduct studies on SimaPro and familiarizing with the software.
- Preparation and submission of extended proposal.

Week 7-9

- Start to conduct life cycle assessment on solar cells using SimaPro software.
- Proposal defence.

Week 9-12

- Continuation of project work using SimaPro software.
- Preparation of Interim Report.

Week 13-14

- Submission of Interim Report

- ***FYP 2***

Week 1-4

- Continue to conduct life-cycle assessment (LCA) on 4 types of solar modules.
- Obtain midpoint indicator, endpoint damage indicator and single score results.

Week 5-7

- Summary of results.
- Comparison of results and interpretation.
- Select the most environmental friendly solar module according to the interpretation.

Week 8

- Conclude the results and provide reccommendations.
- Submission of Progress Report.

Week 9 -12

- Preparation of Dissertation and Technical Paper.
- Pre-SEDEX.

Week 13-14

- Submission of Dissertation and Technical Paper.
- Project Viva.

3.3 Gantt Chart

- **FYP 1**

No.	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Title Selection and Supervisor Allocation														
2	Understanding the Project														
3	Identifying the Objectives and Scope of Study														
4	Conducting Preliminary Studies on the Project														
5	Developing Inventories Data														
6	Conducting Studies on SimaPro Software														
7	Preparation of Extended Proposal														
8	Submission of Extended Proposal														
9	Start Project Work Using SimaPro Software														
10	Proposal Defence														
11	Continuation of Project Work														
12	Preparation of Interim Report														
13	Submission of Interim Report														

- **FYP 2**

No.	Detail	Week													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Conduct LCA On 4 Types Of Solar Module														
2	Comparison of Results														
3	Analysis and Interpretation of Results														
4	Conclude the Results with Recommendations														
5	Preparation & Submission of Progress Report														
6	Preparation of Dissertation														
7	Preparation of Technical Paper														
8	Pre-SEDEX														
9	Submission of Dissertation														
10	Submission of Technical Paper														
11	Project Viva														

CHAPTER 4

RESULTS AND DISCUSSION

The life cycle assessment (LCA) on the 4 types of solar cells was conducted using SimaPro software where the inventories of the solar module were entered into the software and analysed. The inventories were analysed using ReCiPe method. Since the inventories were taken from European literatures, European normalization value was used for the impact indicator and damage assessment.

For this project, obtaining the inventory data for the raw materials, energy requirement, emissions and disposals that were involved throughout the life cycle of a solar module is the key element to the analysis. Besides that, the inventory for the installation system or also known as balance of system (BOS) of the photovoltaic system was also included. For the BOS, 4 types of criteria were identified. The criteria are the area of module required to generate 1 kW power, the area and type of mounting required, the electrical installation for 1 kW module and inverter for 1 kW module. For the type of mounting, it was fixed to slanted-roof mounting for all 4 types of module as it is the most common one used. The slanted roof mounting area will be different from one module to another. This causes the inventories of the mounting to be different. The change in mounting area causes the amount of materials used to be different from one another.

Each solar module will produce 3 types of results. The first one is the midpoint indicator graph where all the 18 impact indicators were addressed and the severity of each impact indicator is shown for the whole module and its sub-assemblies. The next graph would be the damage graph where the damage towards human health, ecosystem and resource was addressed. Finally, would be the single score graph where the 3 types of damages caused throughout the life cycle of a solar cell was converted to a single score value. The single score was analysed in 3 types of perspective which are individualist, hierarchist and egalitarian.

Figure 3 shows the diagram of a solar module with all the BOS components that we have included in this analysis. As it can be seen from the figure, the solar panel is connected to the slanted-roof mounting and then it is connected to the inverter to convert DC current to AC current. The wiring is then connected to the switch box or also known as the electrical installation in the inventory. The current will then be sent to the grid and electrical loads.

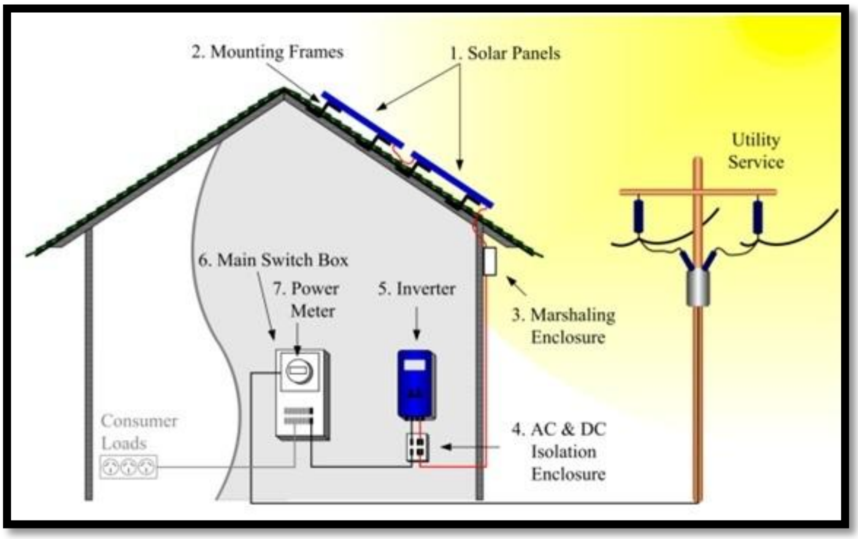

Figure 3: Diagram of Solar Module and BOS Components

4.1 Life Cycle Assessment (LCA) for Cadmium Telluride (CdTe) Solar Module

i. Inventories

For CdTe solar module, the data obtained from the literature is the inventory to produce 1m^2 of CdTe module. The model of CdTe solar module used in the literature generates 84 W for 0.72 m^2 area. Using the conversion factor, the inventory data was converted to 1 kW basis which requires a module area of 8.57 m^2. The inventory for the CdTe module is shown in Table 1. The BOS for CdTe module installation was included in Table 2 and the inventory for the mounting system is in Table 3. The inventory for the electrical system and inverter for 1 kW module was also included in Table 4 and Table 5.

Table 1: Inventory Table to Produce 1 kW CdTe Module (Bekkelund, 2013)

Cadmium Telluride (CdTe) Module for 1kW Power		
	Amount	**Unit (per kW)**
PRODUCT:		
CdTe PV Module	8.57E+00	m2
MATERIALS		
solar glass, low iron	6.46E+01	kg
flat glass, uncoated	6.44E+01	kg
tempering, flat glass	6.44E+01	kg
ethyvinylacetate foil	8.33E+00	kg
cadmium telluride, semi-conductor grade	1.89E-01	kg
cadmium sulphide, semiconductor grade	1.71E-02	kg
cadmium chloride, semiconductor grade	1.05E-03	kg
copper	9.68E-02	kg
solder, bar	3.21E-03	kg
indium	3.35E-03	kg
chromium	3.09E-03	kg
aluminium, production mix	2.31E-02	kg
silicone product	2.63E-02	kg
nitric acid, 50% in H2O	4.91E-01	kg
sulphuric acid	3.37E-01	kg
sodium hydroxide, 50% in H2O	4.23E-01	kg
isopropanol	1.78E-02	kg
silica sand	4.01E-01	kg
sodium chloride powder	3.88E-01	kg
hydrogen peroxide, 50% in H2O	1.43E-01	kg
chemicals, inorganic	3.22E-01	kg
chemicals, organic	8.36E-02	kg
nitrogen, liquid	6.28E-01	kg
helium	3.12E-01	kg
corrugated board, mixed fibre single wall	4.48E+00	kg
glass fibre, reinforced plastic, polyamide, injection moulding	9.26E-01	kg
tap water	1.54E+03	kg
ENERGY		
electricity, medium voltage	2.49E+02	kWh
natural gas, burned in modulating > 100kW	2.27E+01	MJ
TRANSPORT		
transport, lorry >16t, fleet average	2.82E+01	tkm
transport, fleet, rail	6.55E+01	tkm
transport, transoceanic freight	3.15E+03	tkm
DISPOSAL		
disposal, waster, Si waferprod., inorganic, residual material	4.29E-02	kg

disposal, municipal, solid waste	2.57E-02	kg
disposal plastic mixture	6.08E+00	kg
treatment, sewage	1.30E-01	m3
EMISSION TO AIR		
heat, waste	1.79E+03	MJ
cadmium	1.13E-07	kg
EMISSION TO WATER		
cadmium, ion	3.80E-06	kg

Table 2: Inventory Table for the CdTe Module with its BOS (Bekkelund, 2013)

CdTe Module with its Balance of System (BOS) for 1 kW Power		
MATERIAL	**Amount**	**Unit (per kW)**
CdTe PV Module	8.570E+00	m2
slanted-roof construction, mounted, on roof	8.310E+00	m2
electrical installation (for 1kW)	1.00E+00	unit
inverter, 1000 W	1.00E+00	unit
ENERGY		
electricity, low voltage	1.33E-02	kWh
TRANSPORT		
transport, van <3.5t	2.03E+01	tkm
transport, lorry > 16t, fleet average	8.86E+01	tkm
EMISSION TO AIR		
heat, waste	4.67E-02	MJ

Table 3: Inventory Table for the Slanted-Roof Mounting for 1kW CdTe Module (Bekkelund, 2013)

Slanted-Roof Construction, Mounted, On Roof for 1kW CdTe Module		
	Amount	**Unit (per kW)**
PRODUCT		
slanted- roof construction, mounted, on roof	8.310E+00	m2
MATERIAL		
aluminium, production mix, wrought alloy	2.360E+01	kg
corrugated board, mixed fibre, single wall	1.105E+00	kg
polyethylene, HPDE, granulate	1.163E-02	kg
polystyrene, high impact	5.834E-02	kg
section bar extrusion, aluminium	2.360E+01	kg
sheet rolling, steel	1.247E+01	kg
steel, low-alloyed	1.247E+01	kg
TRANSPORT		
transport, lorry > 16t, fleet average	1.870E+00	tkm

transport, freight, rail	1.247E+01	tkm
transport, van <3.5t	3.607E+00	tkm
DISPOSAL		
disposal, packaging cardboard, 19.6% water	1.105E+00	kg
disposal, building, polyethylene/ polypropylene products	1.163E-02	kg
disposal, building, polystyrene isolation, flame retardent	5.834E-02	kg

Table 4: Inventory Table for 1 kW Electrical Installation (Jungbluth, 2012)

Electrical Installation for 1kW Module		
PRODUCT	**Amount**	**Unit (per kW)**
Electrical Installation	1.00E+00	unit
MATERIAL		
copper	4.90E+00	kg
brass	6.67E-03	kg
zinc, primary	1.33E-02	kg
steel, low-alloyed	2.87E-01	kg
nylon 6	7.67E-02	kg
polyethylene, HDPE, granulate	5.87E+00	kg
polyvinylchloride, bulk polymerised	7.10E-01	kg
polycarbonate	6.67E-02	kg
epoxy resin, liquid	6.67E-04	kg
wire drawing, copper	4.90E+00	kg
TRANSPORT		
transport, lorry, fleet average	7.17E-01	tkm
transport, freight, rail	4.47E+00	tkm
DISPOSAL		
disposal, plastic, industry electronics, 15.3% water	6.73E+00	kg
disposal, building, electric wiring	2.00E-02	kg

Table 5: Inventory Table for 1 kW Inverter (Jungbluth, 2012)

Inverter, 1000 W		
	Amount	**Unit (per kW)**
PRODUCT		
Inverter, 1000 W	1.00E+00	unit
MATERIALS		
aluminium, production mix, cast alloy	1.26E+00	kg
copper	4.00E-03	kg
steel, low-alloyed	1.56E-01	kg
acrylonotrile-butadiene-styrene copolymer, ABS	2.96E-01	kg

polycarbonate	1.36E-01	kg
polyethylene, HDPE, granulate	2.80E-02	kg
styrene-acrylonitrile copolymer, SAN	4.00E-03	kg
polyvinylchloride	4.00E-03	kg
printed wiring board, through hole	1.19E-01	kg
transformer, high voltage use	6.20E-01	kg
connector, slump connection	1.00E-01	kg
inductor, ring core choke type	1.48E-01	kg
integrated circuit, IC, logic type	1.20E-02	kg
transistor, wired, small size, through-hole mounting	1.60E-02	kg
diode, glass	2.00E-02	kg
capacitor, film	1.44E-01	kg
capacitor, electrolyte type, >2cm height	1.08E-01	kg
capacity, tantalum	9.60E-03	kg
resistor, metal film type	2.00E-03	kg
sheet rolling, steel	1.56E-01	kg
wire drawing, copper	4.00E-03	kg
section bar extrusion, aluminium	1.36E+00	kg
ENERGY		
electricity, medium voltage	8.48E+00	kWh
PACKAGING		
corrugated board, mixed fibre, single wall	2.24E+00	kg
polystyrene foam slab	2.60E-01	kg
fleece, polyethylene	6.00E-02	kg
TRANSPORT		
transport lorry >16t, fleet average	7.32E-01	tkm
transport, freight, rail	3.78E+00	tkm
transport, transoceanic, freight ship	1.62E+01	tkm
EMISSION TO AIR		
heat, waste	3.06E+01	MJ
DISPOSAL		
disposal, packaging cardboard, 19.6% water	2.24E+00	kg
disposal, polystyrene, 0.2% water	2.64E-01	kg
disposal polyethylene, 0.4% water	6.00E-02	kg
disposal, plastic, industrial electronics, 15.3% water	4.60E-01	kg
disposal, treatment of printed wiring boards	1.38E+00	kg

ii. Network

Figure 4 below shows the network or the tree of cadmium telluride (CdTe) solar module where it shows the materials and process combined to produce the CdTe solar cell. Since there are a lot of materials and process involved in the production of CdTe solar module, only the materials and process that had the highest contribution towards the production of the module were shown in the network.

In order to produce a complete module that generates 1 kW power, the module requires 8.57m^2 of CdTe module, 8.31m^2 of slanted-roof mounting, 1 unit of electrical installation (1 kW) and 1 unit of inverter (1 kW) which was not included in the network. Even though, the inverter was included in the impact indicator and damage assessment, it is not shown in the network because its percentage of contribution towards the production of module is very low.

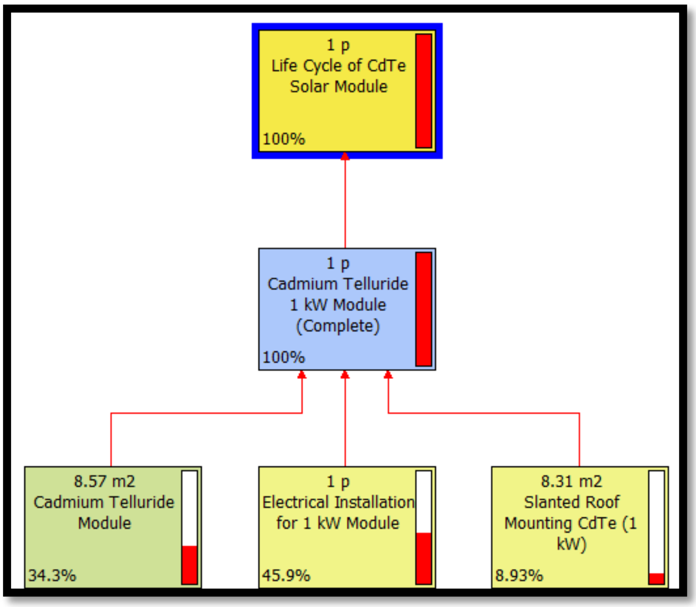

Figure 4: CdTe Solar Module Network

iii. Midpoint Indicator

The midpoint indicator for ReCiPe method contains 18 impact indicators or in other words, it addresses 18 types of environmental impact. The environmental impacts do not have the same unit so it is hard for us to compare one impact from another. In order to find out the magnitude of each environmental impact, the SimaPro software normalizes the data using European normalization.

During normalization, the quantity of substance that contributed towards the impact category indicator is divided with a reference value or normalization reference. The reference value is the average yearly environmental load in a country or a continent. In other words, it is the quantity of specific substance emitted yearly that causes the potential impact divided with the number of capita in a country or continent. After normalization, the impact indicators will be dimensionless form which indicates the magnitude of each impact indicator. Through this, the impact indicators can be easily compared with one another.

Figure 5 shows the graph of normalized midpoint impact indicator for the complete CdTe module with its balance of system (BOS). As it can be seen from Figure 3, the life cycle of CdTe solar module contributes highest towards the metal depletion which has a value 0.153 and fossil depletion which has a value of 0.15 compared to other impact indicators. The lowest severity of impact indicators is the contribution towards petrochemical oxidant formation which is around 0.00001. There was no value for water depletion because the production of CdTe module does not contribute towards water depletion.

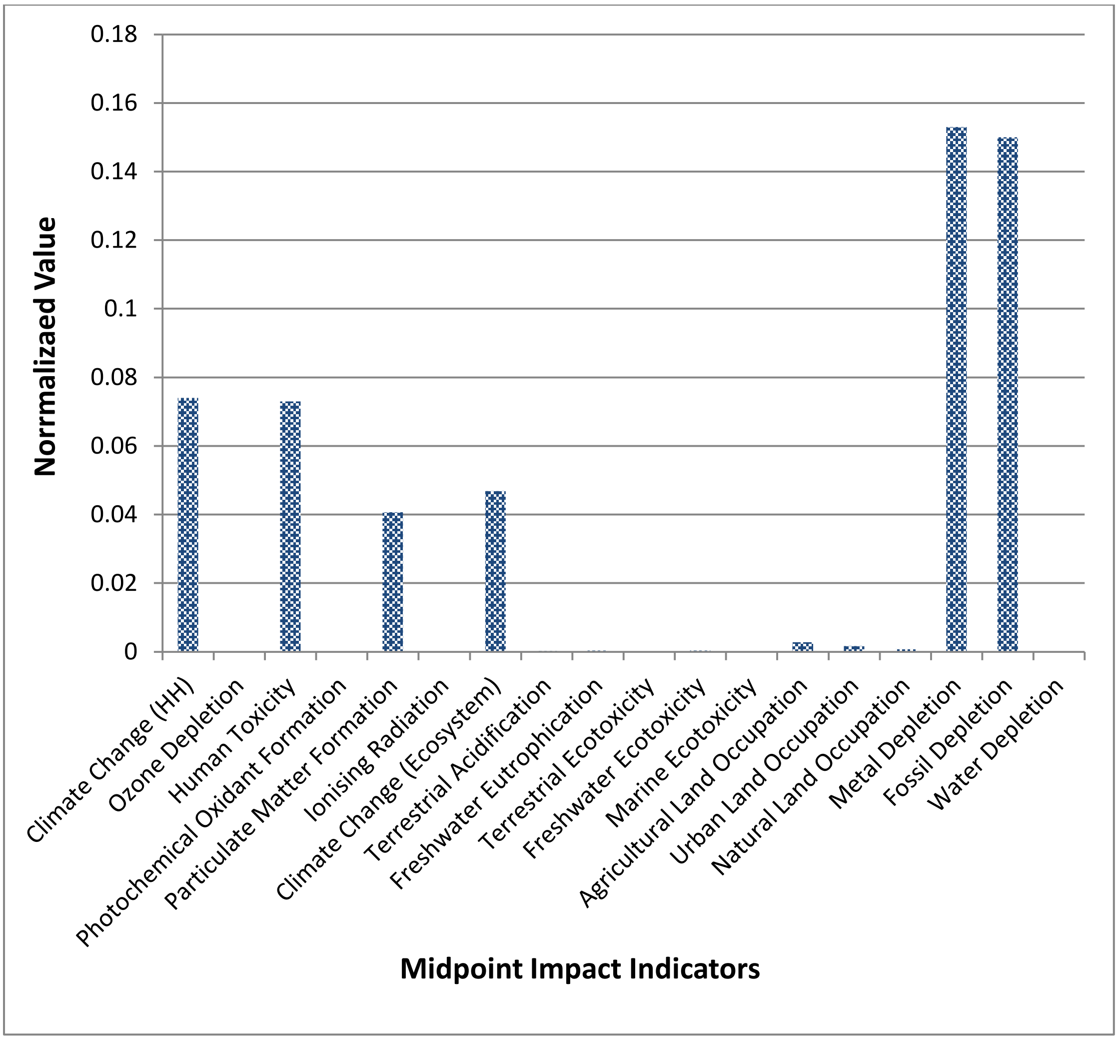

Figure 5: Normalized Midpoint Impact Indicators of CdTe Solar Module

The impact indicators of major sub-assemblies were also assessed to find out the impact of each sub-assembly. Figure 6 shows the graph of midpoint impact indicators for the sub-assemblies. For slanted-roof mounting sub-assembly, it has the highest impact on fossil depletion with a value of 0.054 and then lowest impact on ozone depletion with a value of 0.000003. For inverter sub-assembly, it has the highest impact on metal depletion with a value of 0.02 and lowest impact on photochemical oxidant formation with a value of 0.00000083. For electrical installation, it has the highest impact on metal depletion with a value of 0.12 and lowest impact on ozone depletion with a value of 0.00000026. Finally for the CdTe module sub-assembly, it has the highest impact on fossil depletion with a value of 0.065 and lowest impact on ozone depletion with a value of 0.0000032.

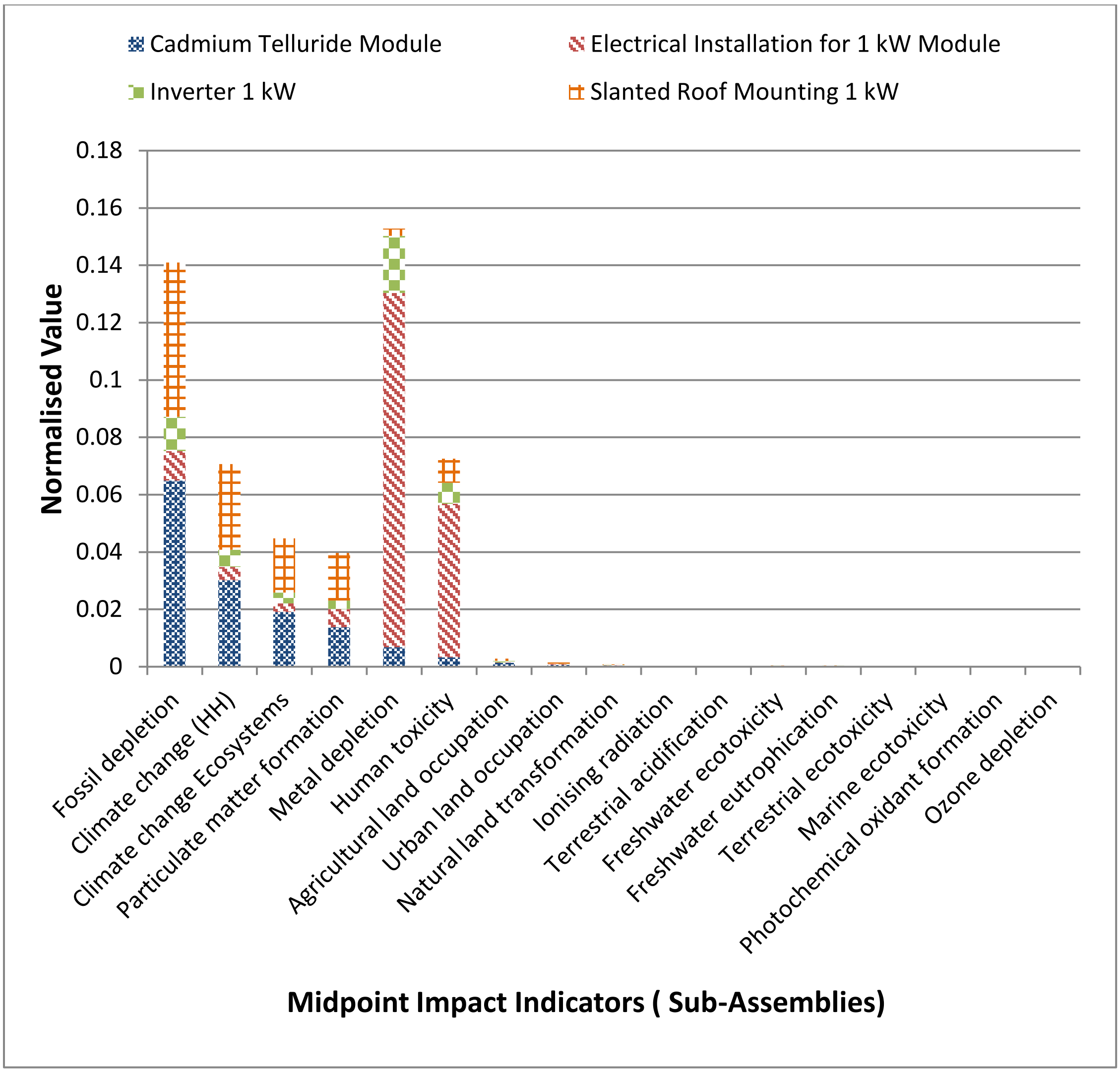

Figure 6: Normalized Midpoint Impact Indicators for Sub-Assemblies of CdTe Solar Module

iv. Endpoint Damage Indicator

After the midpoint indicator analysis is done, the data will be converged towards the damages each impact indicator can cause towards human health, ecosystem and resources. Similar to midpoint impact indicators, the damage indicator would undergo normalization because each damage indicator has its own unit and cannot be compared to one another without normalization. Figure 7 shows the graph of damage indicators of the complete CdTe solar module. It can be seen from Figure 7, the life cycle of CdTe solar module has the highest damage towards resource with a value of 0.303, followed by human health with a value of 0.188 and the lowest damage is towards the ecosystem with a value of 0.0529.

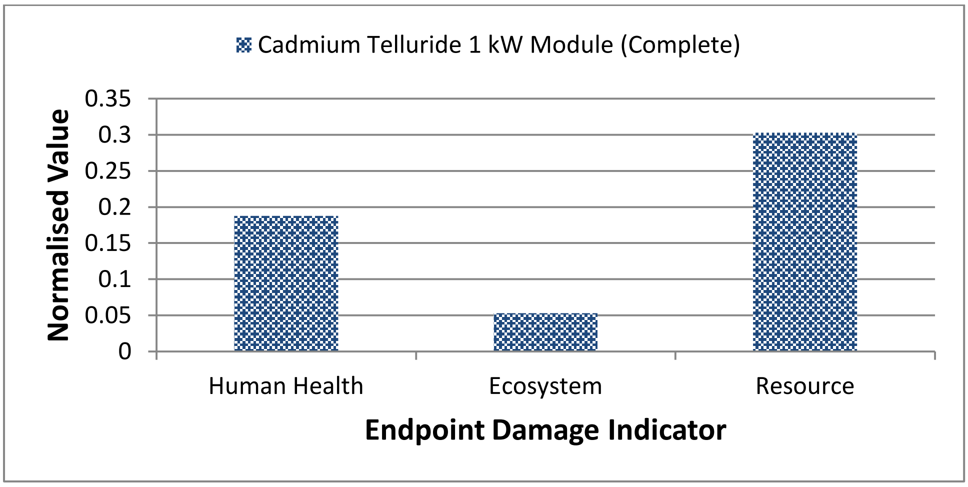

Figure 7: Normalized Damage Indicators of CdTe Solar Module

The damage assessment for the major sub-assemblies was also done to find out the damage the sub-assemblies cause towards human health, ecosystem and resource. Each sub-assembly damage values were normalized so that they can be compared to one another. Figure 8 shows the graph of damage assessment for the sub-assemblies. For the damage towards resource, the electrical installation sub-assembly has the highest contribution with value of 0.133 and inverter has the lowest contribution with a value of 0.032. For the damage towards human health, the electrical installation sub-assembly has the highest contribution with value of 0.065 and inverter has the lowest contribution with a value of 0.016. Finally, for the damage towards ecosystem, the cadmium telluride module sub-assembly has the highest contribution with value of 0.025 and electrical installation has the lowest contribution with a value of 0.0039.

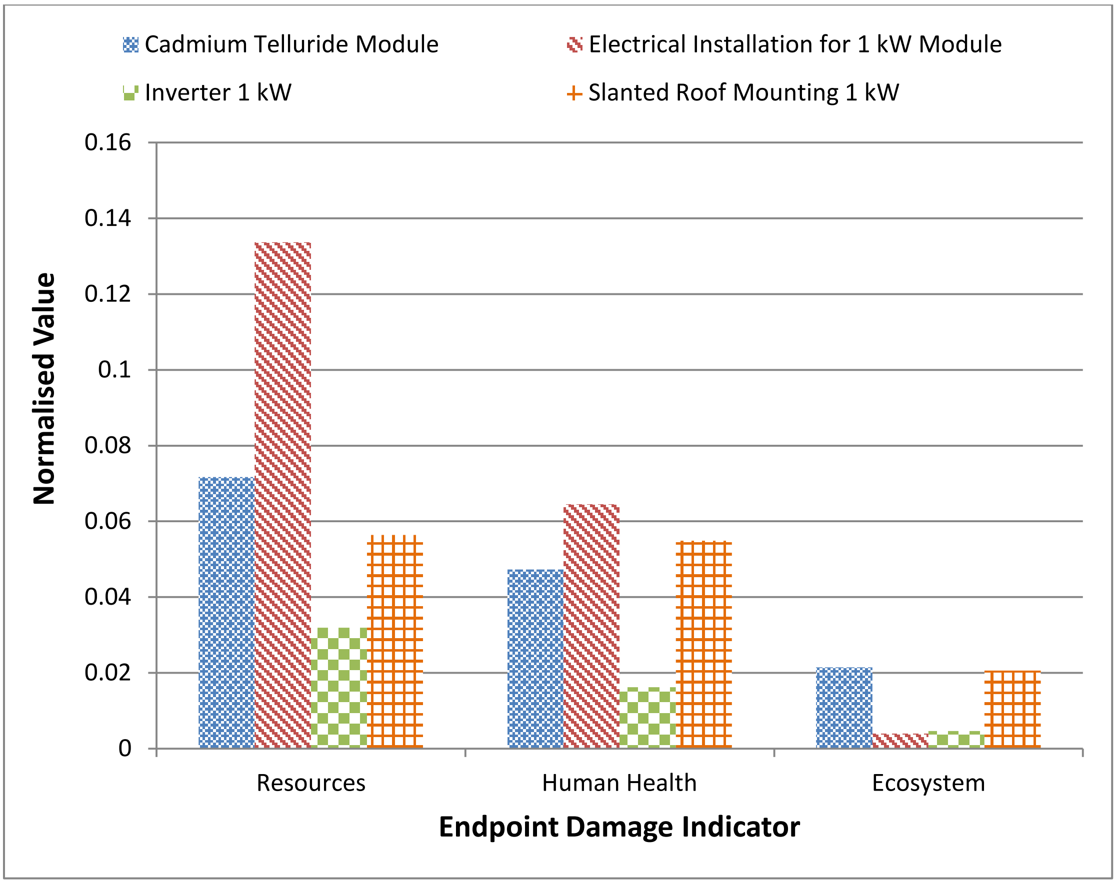

Figure 8: Normalized Damage Indicators for Sub-Assemblies of CdTe Solar Module

v. *Single Score*

The damage indicators would then undergo weighing process where each of the damage indicators is multiplied with the weighing factor to form a single score for the module. The data is represented in the unit of point (Pt). The single score is normally used to compare one product from another. The single score was assessed in 3 types of perspective which are individualist, hierarchist and egalitarian. These perspectives represent a set of choices on issues like time or expectations on proper management or future technology development that can avoid future damages.

Figure 9 shows the graph of single score for the 3 perspectives. The first one is hierarchist perspective which is the most common policy principles with regards to time-frame and other issues. It has a total score of 157 Pt. The single score is a the summation of the damage scores where the damage towards human health has an indicator score of 75.2 Pt, damage towards ecosystem has the score of 21.2 Pt and the damage towards resource has a score of 60.6 Pt.

The next one is individualist perspective. Individualist is based on short-term interest, impact types that are undisputed, technological optimism as regards human adaptation. The graph shows that individualist perspective has a score of 159.2 Pt. The single score is a the summation of the damage scores where the damage towards human health has an indicator score of 43.7 Pt, damage towards ecosystem has the score of 21.5 Pt and the damage towards resource has a score of 94 Pt.

The last one is egalitarian perspective. Egalitarian is the most precautionary perspective which takes into account the longest time-frame. For egalitarian perspective which has a total score of 794 Pt, has the score for damage towards human health is 675 Pt, damage towards ecosystem has the score of 58.4 Pt and the damage towards resource has a score of 60.6 Pt. This shows that as the time frame increases, the production of CdTe solar module would cause a higher damage towards human health.

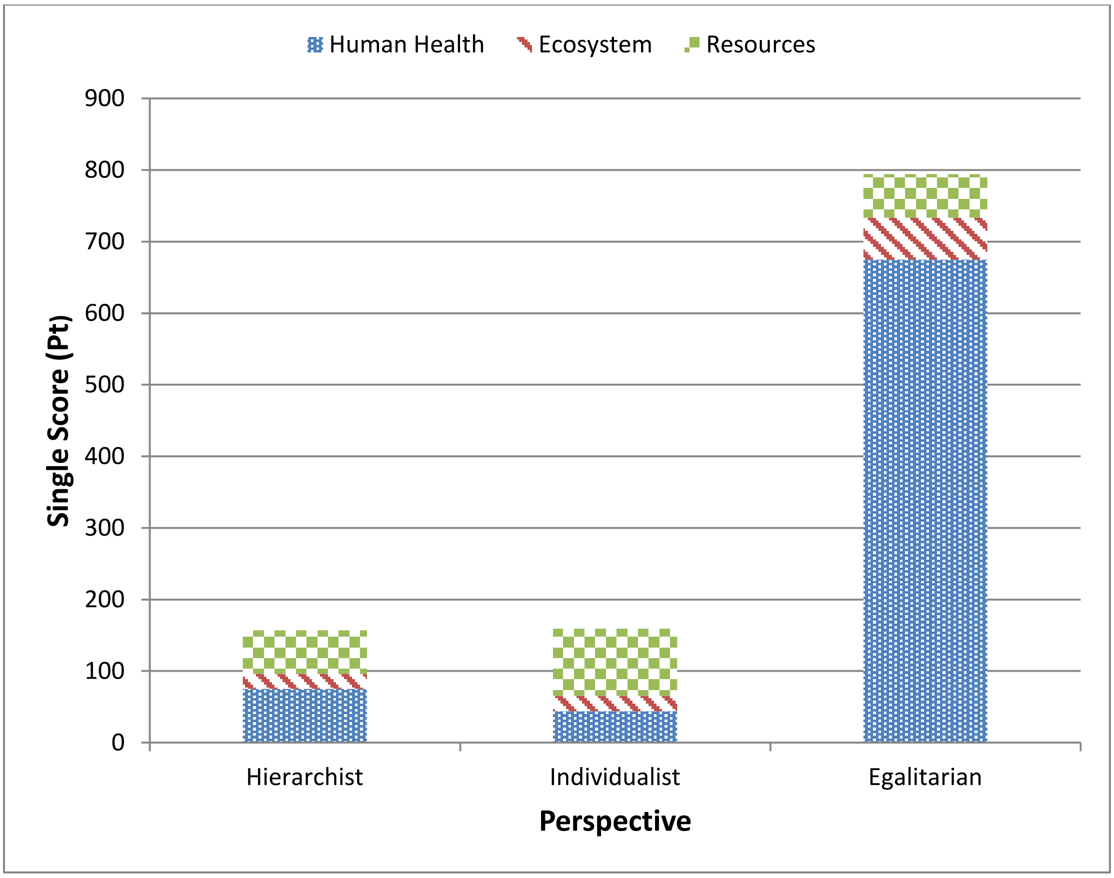

Figure 9: Single Score based on Perspective for CdTe Solar Module

The single score assessment for the major sub-assemblies were also conducted. Figure 10 shows the graph of single score for the sub-assemblies. The assessment was only done based on hierarchist perspective. CdTe solar module sub-assembly has a score of 41.8 Pt with a human health score of 18.9 Pt, ecosystem score of 8.59 Pt and resource score of 14.3 Pt. Electrical installation sub-assembly has a score of 54.09 Pt with a human health score of 25.8 Pt, ecosystem score of 1.59 Pt and resource score of 26.7 Pt. Inverter sub-assembly has a score of 14.7 Pt with a human health score of 6.48 Pt, ecosystem score of 1.85 Pt and resource score of 6.39 Pt. Finally, slanted-roof mounting sub-assembly has a score of 41.54 Pt with a human health score of 22 Pt, ecosystem score of 8.24 Pt and resource score of 11.3 Pt. The figure shows that electrical installation sub-assembly has the highest damage score and inverter sub-assembly has the lowest damage score.

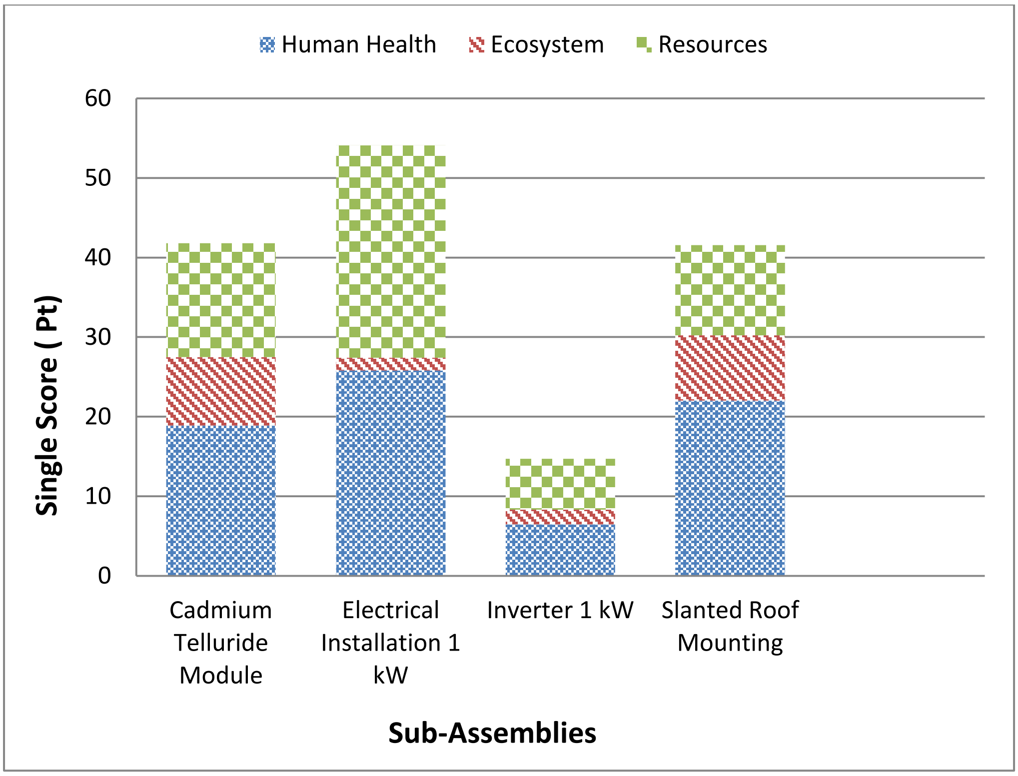

Figure 10: Single Score for Sub-Assemblies of CdTe Solar Module

4.2 Life Cycle Assessment (LCA) for Amorphous Silicon (a-Si) Solar Module

i. Inventories

For amorphous silicon (a-Si) solar module, the data obtained from the literature is the inventory to produce 1m^2 of a-Si module. The model of a-Si solar module used in the literature generates 128W for 2.3 m^2 area. Using the conversion factor, the inventory data was converted to 1 kW basis which requires a module area of 17.96m^2. In order to make the module, it requires equal amount of a-Si laminate. The inventory for the a-Si module is in Table 6 and the inventory for the a-Si laminate is in Table 7. The BOS for a-Si module installation was included in Table 8. The inventory for the mounting is in Table 9. The inventory for the electrical system and inverter is similar to CdTe as both modules produce 1 kW power module (Table 4 & Table 5).

Table 6: Inventory Table to Produce 1 kW a-Si Module (Jungbluth, 2012)

Amorphous Silicon (a-Si) Module for 1kW Power		
	Amount	**Unit (per kW)**
PRODUCT:		
a-Si PV Module	1.796E+01	m2
MATERIAL		
photovoltaic laminate, a-Si	1.796E+01	m2
sheet rolling steel	3.92E+01	kg
aluminium alloy, AlMg3	6.00E+01	kg
steel, low-alloyed	3.92E+01	kg
TRANSPORT		
transport, transoceanic freight ship	1.25E+02	tkm
transport, freight, rail	7.47E+01	tkm

Table 7: Inventory Table to Produce a-Si Laminate for 1kW of a-Si Module (Jungbluth, 2012)

Amorphous Silicon (a-Si) Laminate for 1kW Module		
	Amount	**Unit (per kW)**
PRODUCT:		
a-Si PV Laminate	1.796E+01	m2
MATERIALS		
aluminium alloy, AlMg3	2.57E-01	kg
copper	1.20E+00	kg

steel, low-alloyed	1.73E+01	kg
brazing solder, cadmium free	4.71E-02	kg
soft solder	1.74E-01	kg
polyethylene, HDPE, granulate	1.98E+01	kg
packaging film, LDPE	5.57E+00	kg
polyvinylfluoride film	2.21E+00	kg
glass fibre reinforced plastic, polyamide, injection moulding	6.43E-01	kg
synthetic rubber	1.21E+00	kg
COATING		
silicon tetrahydride	6.43E-02	kg
indium	1.61E-02	kg
cadmium telluride, semiconductor grade	1.61E-02	kg
phosphoric acid, fertiliser grade, 70% in H2O	1.35E-03	kg
oxygen, liquid	8.71E-03	kg
hydrogen, liquid	3.92E-01	kg
PACKAGING		
polyethylene, LPDE, granulate	3.30E-01	kg
TRANSPORT		
transport, lorry >16t, fleet average	1.52E-01	tkm
transport, transoceanic freight ship	1.63E+02	tkm
transport, freight, rail	2.69E+01	tkm
DISPOSAL		
disposal, municipal solid waste, 22.9% water	5.39E-01	kg
disposal, rubber, unspecified	1.21E+00	kg
disposal polyvinylfluoride	2.21E+00	kg
disposal, plastics, mixture, 15.3% water	6.21E+00	kg
treatment, glass production effluent	7.13E-02	m3
EMISSION TO AIR		
heat, waste	3.13E+03	MJ

Table 8: Inventory Table for the a-Si Module with its BOS (Jungbluth, 2012)

Amorphous Silicon (a-Si) Module with its Balance of System (BOS)		
MATERIAL	**Amount**	**Unit (per kW)**
a-Si PV Module	1.796E+01	m2
slanted-roof construction, mounted, on roof	1.744E+01	m2
electrical installation (for 1kW)	1.00E+00	unit
inverter, 1000 W	1.00E+00	unit
ENERGY		
electricity, low voltage	1.33E-02	kWh
TRANSPORT		
transport, van <3.5t	1.78E+01	tkm
transport, lorry > 16t, fleet average	7.39E+01	tkm

transport transoceanic freight ship	2.95E+02	tkm
EMISSION TO AIR		
heat, waste	4.80E-02	MJ

Table 9: Inventory Table for the Slanted-Roof Mounting for 1kW a-Si Module (Jungbluth, 2012)

Slanted-Roof Construction, Mounted, On Roof for 1kW a-Si Module		
	Amount	**Unit (per kW)**
PRODUCT		
slanted- roof construction, mounted, on roof	1.744E+01	m2
MATERIAL		
aluminium, production mix, wrought alloy	4.95E+01	kg
corrugated board, mixed fibre, single wall	2.32E+00	kg
polyethylene, HPDE, granulate	2.44E-02	kg
polystyrene, high impact	1.22E-01	kg
section bar extrusion, aluminium	4.95E+01	kg
sheet rolling, steel	2.62E+01	kg
steel, low-alloyed	2.62E+01	kg
TRANSPORT		
transport, lorry > 16t, fleet average	3.92E+00	tkm
transport, freight, rail	2.62E+01	tkm
transport, van <3.5t	7.57E+00	tkm
DISPOSAL		
disposal, packaging cardboard, 19.6% water	2.32E+00	kg
disposal, building, polyethylene/ polypropylene products	2.44E-02	kg
disposal, building, polystyrene isolation, flame retardant	1.22E-01	kg

ii. Network

Figure 11 below shows the network or the tree of amorphous silicon (a-Si) solar module where it shows the materials and process used to produce the a-Si solar cell. The materials and process that had the highest contribution towards the production of the module were the only one shown in the network. In order to produce a complete module that generates 1 kW power, the module requires 17.96 m^2 of a-Si module, 17.44 m^2 of slanted-roof mounting, 1 unit of electrical installation (1 kW) and 1 unit of inverter (1 kW) which was not included in the network. The inverter is not shown in the network because its percentage of contribution towards the production of module is very low.

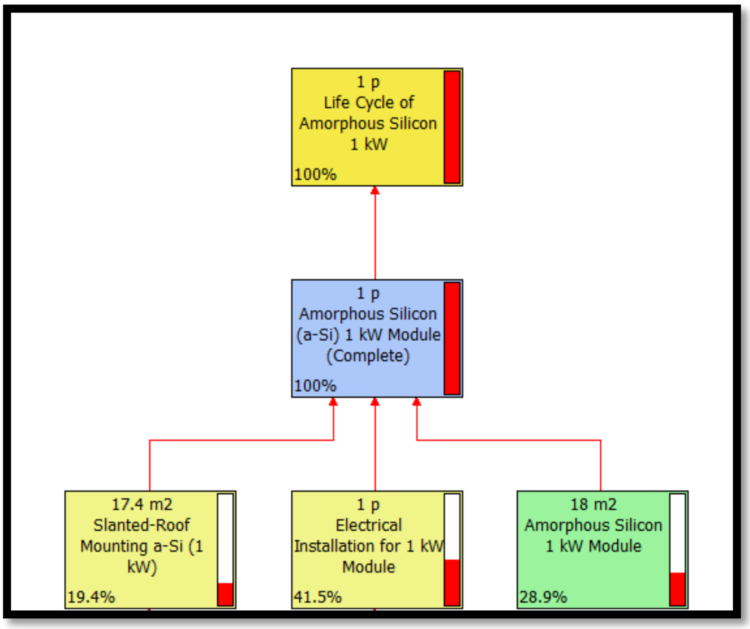

Figure 11: a-Si Solar Module Network

iii. Midpoint Indicator

The ReCiPe method addresses 18 types of midpoint impact indicators. Similar to CdTe solar module, each impact indicator had different unit so they were normalized using European normalization so that they can be compared to one another. After normalization, the impact indicators will be dimensionless which would indicate the severity of each impact indicator. Figure 12 shows the graph of normalized midpoint impact indicator for the complete a-Si module with its balance of system (BOS). As it can be seen from Figure 12, the life cycle of a-Si solar module contributes highest towards the metal depletion which has a value 0.32. The lowest severity of impact indicators is the contribution towards petrochemical oxidant formation which is around 0.000014.

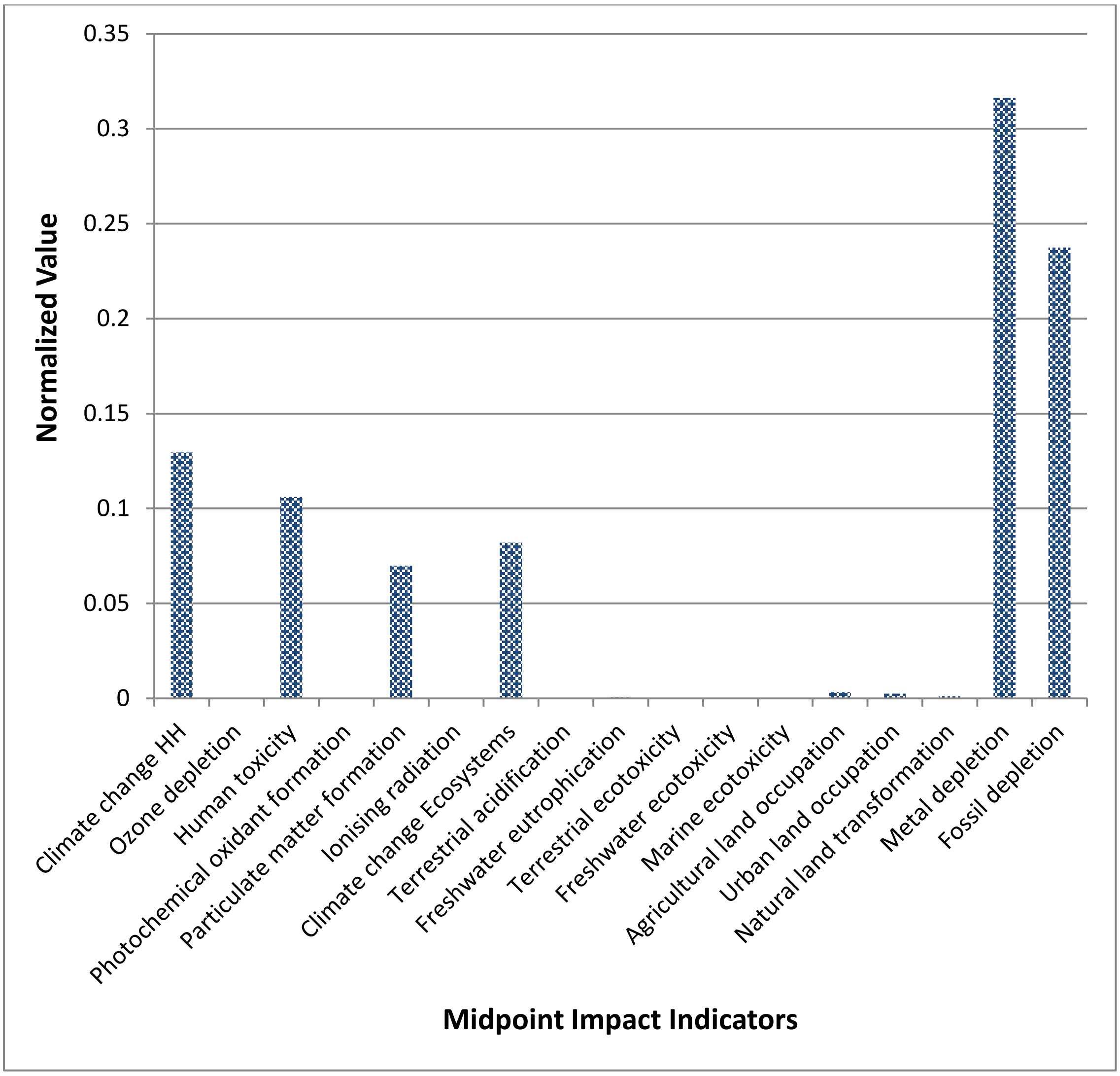

Figure 12: Normalized Midpoint Indicator of a-Si Solar Module

The impact indicators of major sub-assemblies were also assessed to find out the impact of each sub-assembly. Figure 13 shows the graph of midpoint impact indicators for the sub-assemblies. For the a-Si module sub-assembly, it has the highest impact on metal depletion with a value of 0.15 and lowest impact on ozone depletion with a value of 0.000012. For electrical installation, it has the highest impact on metal depletion with a value of 0.12 and lowest impact on ozone depletion with a value of 0.00000026. For inverter sub-assembly, it has the highest impact on metal depletion with a value of 0.02 and lowest impact on photochemical oxidant formation with a value of 0.00000083. Finally, for slanted-roof mounting sub-assembly, it has the highest impact on fossil depletion with a value of 0.11 and then lowest impact on ozone depletion with a value of 0.0000065.

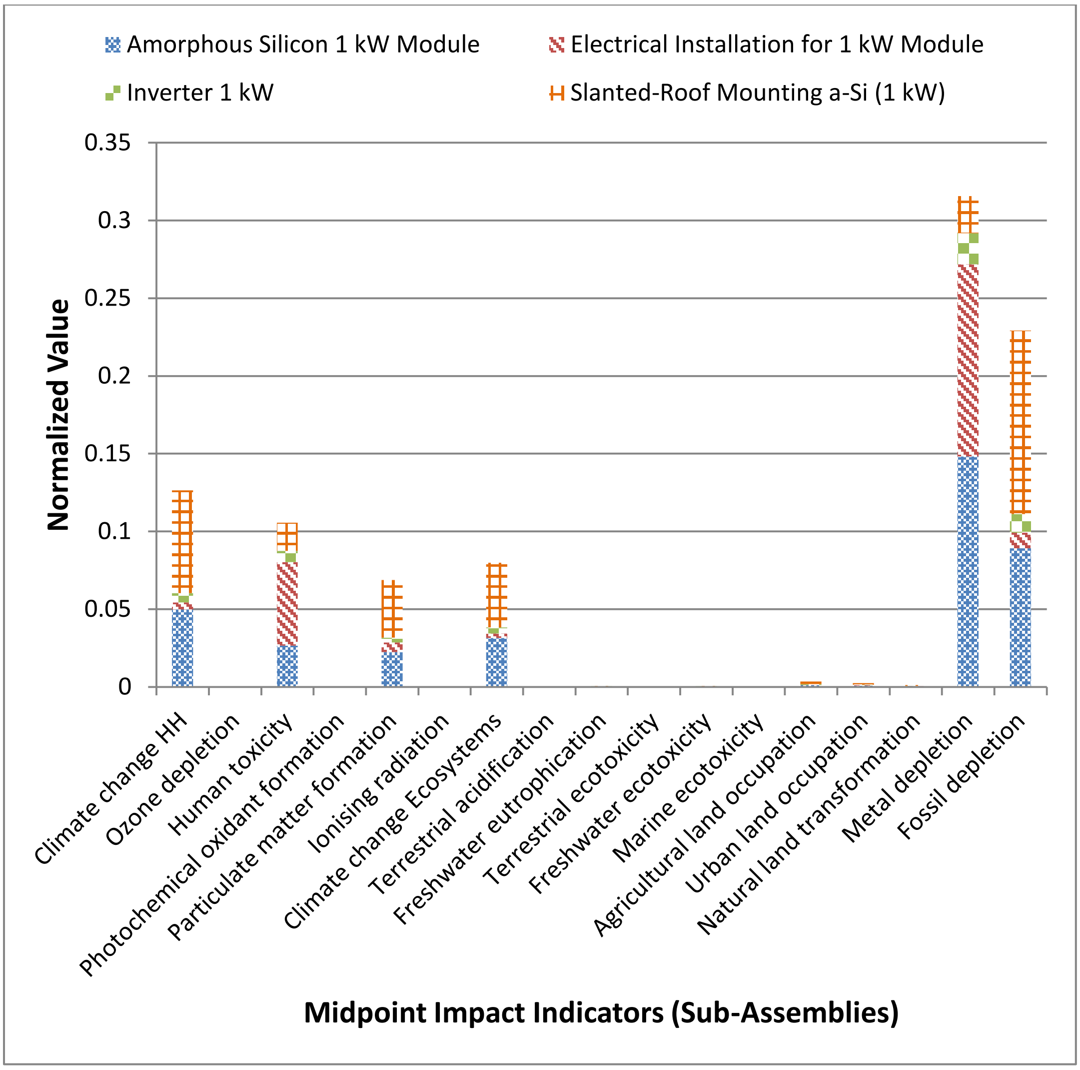

Figure 13: Normalized Midpoint Indicator for Sub-Assemblies of a-Si Solar Module

iv. Endpoint Damage Indicator

For endpoint damage indicator, the data will be converged towards the damages each impact indicator can cause towards human health, ecosystem and resources. Similar to midpoint impact indicators, the damage indicator would undergo normalization because each damage indicator has its own unit and cannot be compared to one another without normalization. Figure 14 shows the graph of damage indicators of the complete a-Si solar module. The life cycle of a-Si solar module has the highest damage towards resource with a value of 0.55, followed by human health with a value of 0.31 and the lowest damage is towards the ecosystem with a value of 0.09.

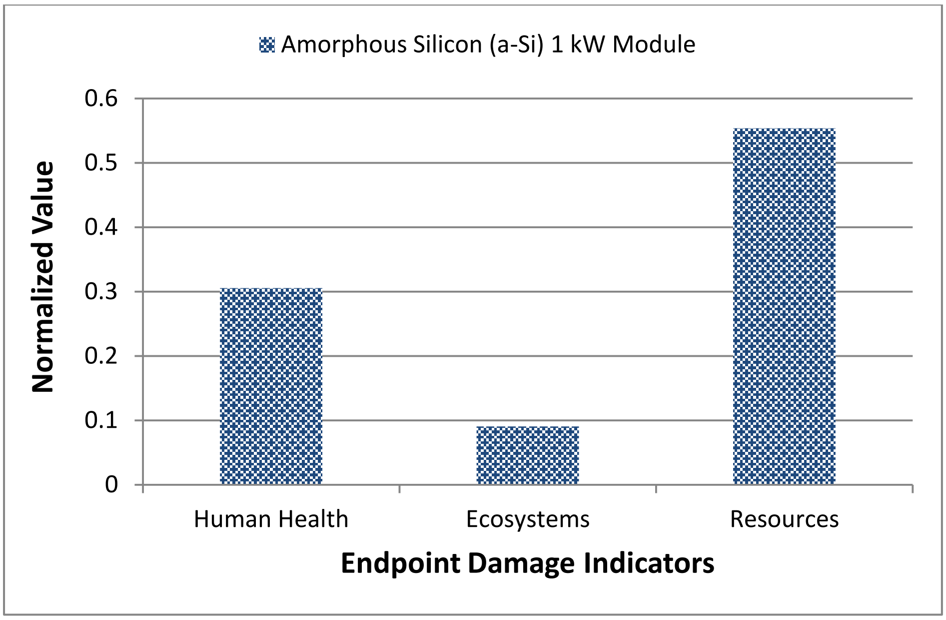

Figure 14: Normalized Damage Indicators of a-Si Solar Module

The damage assessment for the major sub-assemblies was also done to find out the damage the sub-assemblies cause towards human health, ecosystem and resource. Each sub-assembly damage values were normalized so that they can be compared to one another. Figure 15 shows the graph of damage assessment for the sub-assemblies. For damage towards human health, slanted-roof mounting has the highest contribution with a value of 0.12 and inverter has the lowest contribution with a value of 0.016. For damage towards ecosystem, slanted-roof mounting has the highest contribution with a value of 0.045 and electrical installation has the lowest contribution with a value of 0.004. Finally, for the damage towards resources, the amorphous silicon module sub-assembly has the highest contribution with value of 0.23 and inverter has the lowest contribution with a value of 0.032.

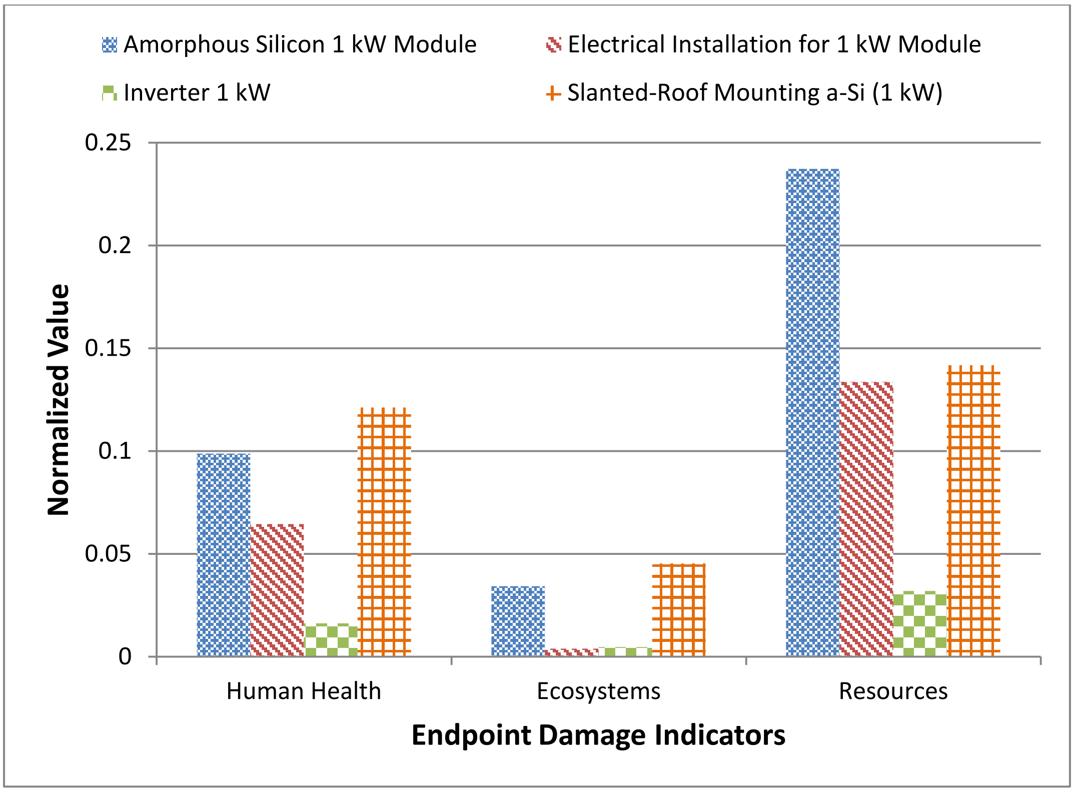

Figure 15: Normalized Damage Indicators for Sub-Assemblies of a-Si Solar Module

v. *Single Score*

The damage indicators would undergo weighing process where each of the damage indicators is multiplied with the weighing factor to form a single score for the module. The data is represented in the unit of point (Pt). The single score is normally used to compare one product from another. Similar to CdTe solar module, the single score was assessed in 3 types of perspective which are individualist, hierarchist and egalitarian.

Figure 16 shows the graph of single score for the 3 perspectives. For hierarchist perspective, the graph shows that the life cycle of amorphous silicon (a-Si) solar module has a score of 269 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 122.2 Pt, damage towards ecosystem has the score of 36.1 Pt and the damage towards resource has a score of 110.7 Pt. For individualist perspective, it has a total score of 295.3 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 75.4 Pt, damage towards ecosystem has the score of 36.5 Pt and the damage towards resource has a score of 183.4 Pt. Finally, for egalitarian perspective, graph shows that it has a score of 1184.3 Pt. The score for damage towards human health is 974.5 Pt, damage towards ecosystem has the score of 99.1 Pt and the damage towards resource has a score of 110.7 Pt. It can be seen that as the time frame increases, the production of a-Si solar module would cause a higher damage towards human health.

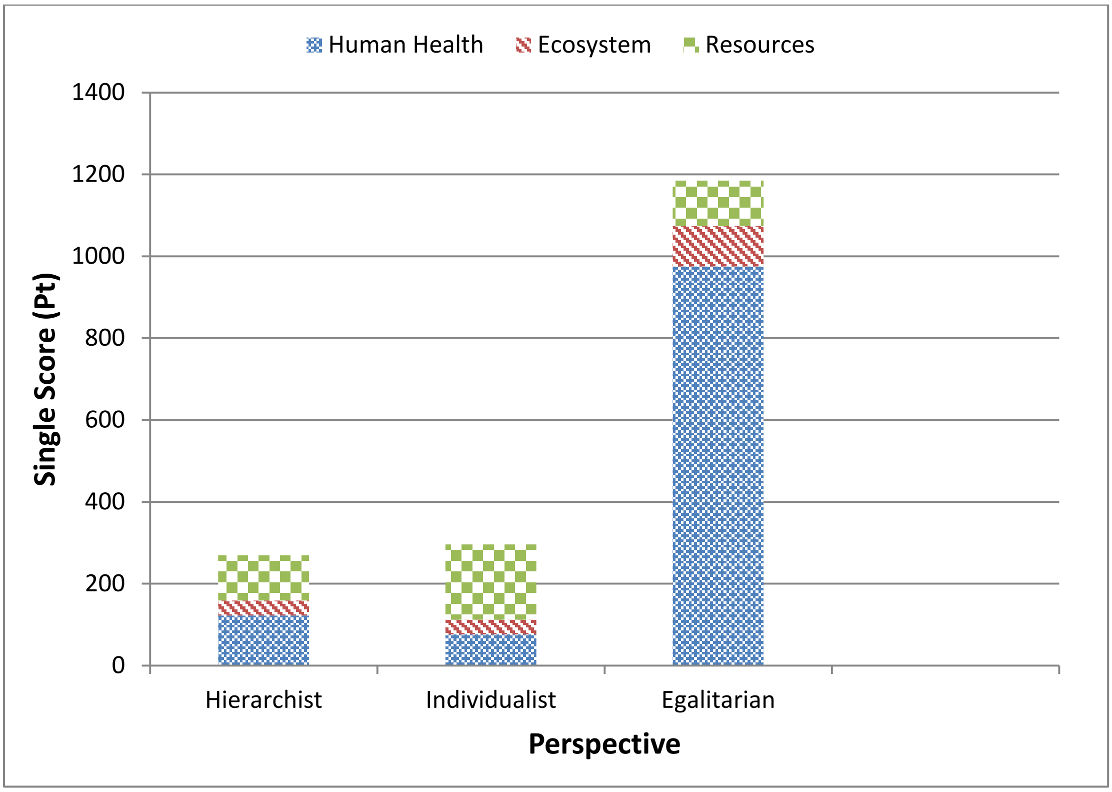

Figure 16: Single Score based on Perspectives for a-Si Solar Module

The single score assessment for the major sub-assemblies were also done. Figure 17 shows the graph of single score for the sub-assemblies. Amorphous silicon (a-Si) solar module sub-assembly has a total score of 100.7 Pt with a human health score of 39.5 Pt, ecosystem score of 13.7 Pt and resource score of 47.5 Pt. Electrical installation sub-assembly has a total score of 54.1 Pt with a human health score of 25.8 Pt, ecosystem score of 1.59 Pt and resource score of 26.7 Pt. Inverter sub-assembly has a total score of 14.7 Pt with a human health score of 6.48 Pt, ecosystem score of 1.85 Pt and resource score of 6.39 Pt. Finally, slanted-roof mounting sub-assembly has a total score of 95.1 Pt with a human health score of 48.5 Pt, ecosystem score of 18.2 Pt and resource score of 28.4 Pt. The figure shows that amorphous silicon (a-Si) module sub-assembly has the highest damage score and inverter sub-assembly has the lowest damage score.

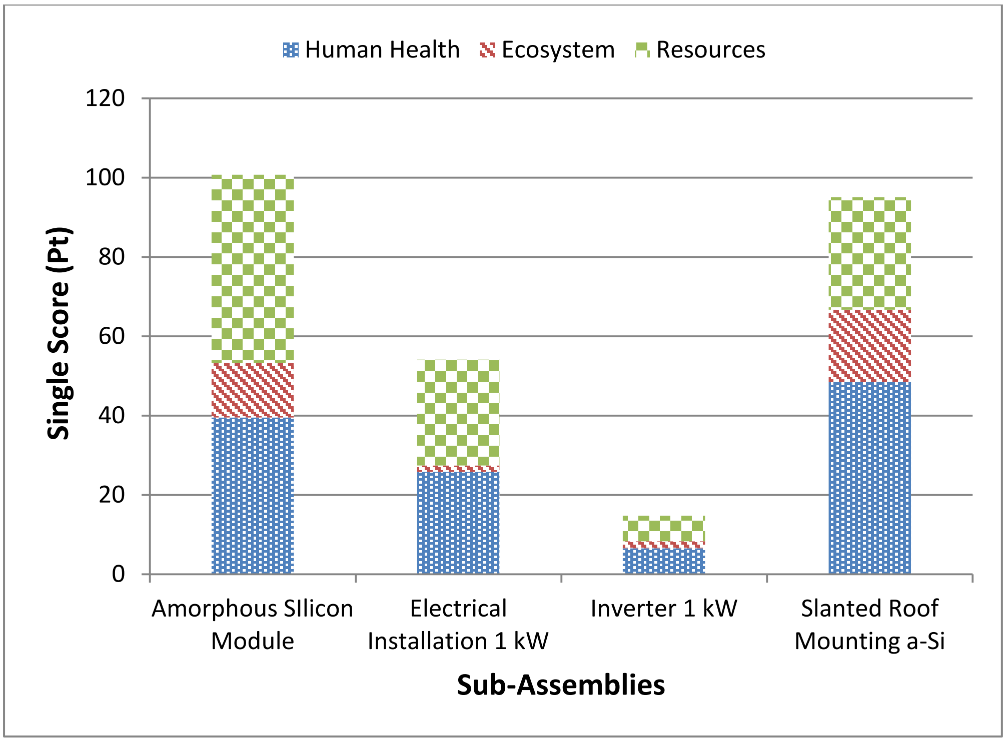

Figure 17: Single Score for Sub-Assemblies of a-Si Solar Module

4.3 Life Cycle Assessment (LCA) for Poly-Crystalline Silicon (Poly-Si) Solar Module

i. Inventories

The data obtained from the literature is the inventory to produce $1m^2$ of Poly-Si module. The model of Poly-Si solar module used in the literature generates 220W for $1.68m^2$ area. Using the conversion factor, the inventory data was converted to 1 kW basis which requires a module area of $7.63m^2$. Since the process of producing Poly-Si module involves multiple processes, the inventory table was divided in to several sections.

The manufacturing process of Poly-Si module begins with the process of manufacturing solar grade silicon which is in Table 10. After that, the solar grade silicon will be used to manufacture the Poly-Si wafer (Table 11) which will then be used to produce the silicon cell (Table 12). Finally, the cell will be used to produce the Poly-Si module that generates 1 kW power (Table 13). The BOS for poly-Si module installation was included in Table 14. The inventory for the slanted-roof mounting is in Table 15. The inventory for the electrical system and inverter is similar to CdTe as both modules produce 1 kW power (Table 4 & Table 5).

Table 10: Inventory Table to Produce Solar Grade Silicon for 1 kW Poly-Si Module (Bekkelund, 2013)

Solar Grade Silicon (sg-Si) for 1kW Poly-Si Module		
	Amount	**Unit (per kW)**
PRODUCT		
sg-Si	9.33E+00	kg
MATERIAL		
silica sand	3.78E+01	kg
limestone, crushed	1.40E-01	kg
anode, aluminium electrolysis	1.12E+00	kg
sodium hydroxide, 50% in H2O, production mix	3.25E+00	kg
ENERGY		
electricity, medium voltage, production UCTE	5.15E+02	kWh
light fuel oil, burned in industrial furnace 1MW	8.74E+00	MJ
liquefied petroleum gas	2.59E-01	kg
chips, Scandinavian softwood	1.56E-01	m3
hard coal coke	9.89E+01	MJ
hard coal	2.93E+01	kg
diesel	9.10E-02	kg
TRANSPORT		
transport, transoceanic tanker	3.33E+02	tkm
transport, lorry EURO5	3.33E+01	tkm
WASTE		
disposal, slag from MG silicon production, 0% water	1.85E+01	kg
iron scrap	4.97E-01	kg
disposal, hazardous waste, 25% water	2.65E+00	kg
disposal, refinery sludge, 89.5% water	1.32E+00	kg
RESOURCES		
water, unspecified	1.71E+00	m3
EMMISSION TO AIR		
carbon dioxide, fossil, unspecified	3.03E+01	kg
sulphur dioxide, unspecified	2.97E-01	kg
nitrogen oxides, unspecified	5.46E-01	kg
carbon dioxide, biogenic, unspecified	9.61E+01	kg
carbon monoxide, fossil, unspecified	8.86E-02	kg
particulates, >2.5 and <10um, unspecified	1.54E-02	kg
dinitrogen monoxide, unspecified	9.33E-04	kg
methane, fossil, unspecified	3.50E-03	kg
NMVOC, non methane volatile organic compound	2.57E-03	kg
PAH, polycyclic aromatic hydrocarbons, unspecified	3.73E-05	kg
dioxins, 2,3,7,8-tetrachlorodibenzo-p-dioxin	4.67E-11	kg
mercury	1.15E-06	kg

arsenic	8.40E-06	kg
cadmium	7.00E-08	kg
zinc	9.98E-06	kg
lead	3.85E-06	kg
copper	5.55E-06	kg
chromium	1.17E-07	kg
molybdenum	1.75E-06	kg
nickel	3.03E-06	kg
aluminium	2.17E-05	kg
antimony	1.10E-07	kg
boron	3.91E-06	kg
tin	1.10E-07	kg
calcium	1.08E-05	kg
cyanide	9.61E-05	kg
fluorine	5.43E-07	kg
hydrogen fluoride	7.00E-03	kg
hydrogen sulphide	7.00E-03	kg
iron	5.43E-05	kg
potassium, low population density	8.68E-04	kg
silicone plant	1.05E-01	kg
sodium	1.08E-05	kg
EMMISSION TO WATER		
aluminium, unspecified	5.63E-05	kg
arsenic, ion, unspecified	1.29E-05	kg
iron, ion, unspecified	1.42E-04	kg
copper, ion, unspecified	1.89E-05	kg
chromium, ion, unspecified	1.77E-05	kg
nickel, ion, unspecified	4.11E-05	kg
zinc, ion, unspecified	6.30E-06	kg
sulphur, unspecified	1.96E-04	kg

Table 11: Inventory Table to Produce Poly-Si Wafer for 1 kW Poly-Si Module (Bekkelund, 2013)

Poly-crystalline Silicon Wafer for 1kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
poly-Si wafer	7.18E+00	m2
MATERIALS		
sg-Si	9.33E+00	kg
glass wool	7.18E-02	kg
wire drawing	1.07E+01	kg
silicon carbide	3.52E+00	kg

silicon carbide, recycling	1.54E+01	kg
nitrogen, liquid	3.83E-01	kg
argon, liquid	2.18E+00	kg
helium	9.76E-04	kg
triethylene glycol	7.90E-01	kg
triethylene glycol, recycling	1.87E+01	kg
dipropylene glycol monomethyl ether	2.18E+00	kg
acrylic binder, 34% in H2O	1.44E-02	kg
alkylbenzene sulfonate, linear, petrochemical	1.70E+00	kg
sodium hydroxide, 30% in H2O, production mix	1.07E-01	kg
hydrochloric acid, 30% in H2O	1.95E-02	kg
acetic acid, 98% in H20	2.80E-01	kg
tap water	4.60E-02	kg
water, deionised	4.66E+02	kg
paper, wood free, coated,	1.36E+00	kg
polystyrene, high impact, HIPS	1.44E+00	kg
packaging film, LDPE	7.18E-01	kg
brass	5.35E-02	kg
steel, low-alloyed	1.06E+01	kg
ENERGY		
electricity, medium voltage production UCTE	2.15E+02	kWh
natural gas, burned in industrial furnace	2.84E+01	MJ
WASTE		
disposal, waste, silicon wafer production, 0% water	1.22E+00	kg
EMMISSION TO AIR		
heat, waste, unspecified	2.07E+02	MJ
EMMISSION TO WATER		
AOX, Adsorbable Organic Halogen as Cl	3.60E-03	kg
cadmium, ion	4.34E-05	kg
chromium, ion	2.18E-04	kg
COD, Chemical Oxygen Demand	2.13E-01	kg
copper, ion	4.34E-04	kg
lead	2.18E-04	kg
mercury	4.34E-05	kg
nickel, ion	4.34E-04	kg
nitrogen	7.14E-02	kg
phosphate	3.60E-03	kg
BOD5, Biological Oxygen Demand	2.13E-01	kg
DOC, Dissolved Organic Carbon	7.97E-02	kg
TOC, Total Organic Carbon	7.97E-02	kg

Table 12: Inventory Table to Produce Poly-Si Cell for 1 kW Poly-Si Module (Bekkelund, 2013)

Poly-crystalline Silicon Cell for 1kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
Poly-Si Cell	6.78E+00	m2
MATERIALS		
Poly-Si wafer	7.18E+00	m2
phosphoric acid, fertilizer grade, 70% in H20	9.82E-03	kg
metallization paste	1.32E-01	kg
polystyrene, expandable	2.76E-03	kg
nitrogen, liquid	1.25E+01	kg
oxygen, liquid	6.91E-01	kg
argon, liquid	1.74E-01	kg
tetrafluoroethylene	2.14E-02	kg
ammonia, liquid	4.56E-02	kg
silicon tetrahydride	8.20E-03	kg
sodium hydroxide, 50% in H2O, production mix	1.06E+00	kg
acetic acid, 98% in H2O	1.92E-02	kg
hydrochloric acid, 30% in H2O	3.08E-01	kg
hydrogen fluoride	2.55E-01	kg
nitric acid, 50% in H2O	1.81E-01	kg
phosphoryl chloride	1.47E-03	kg
phosphoric acid, industrial grade, 85% in H2O	5.16E-02	kg
sodium silicate, spray powder 80%	5.06E-01	kg
calcium chloride	1.46E-01	kg
titanium dioxide, production mix	9.62E-06	kg
isopropanol	5.33E-01	kg
ethanol from ethylene	4.33E-03	kg
solvents, organic, unspecified	9.69E-03	kg
water, deionised	9.28E+02	kg
ENERGY		
electricity, medium voltage	2.05E+02	kWh
natural gas, burned in industrial furnace	3.22E+01	MJ
light fuel oil, burned in industrial furnace	7.93E+00	MJ
WASTE		
disposal, waste, Si wafer, inorganic, residual material	1.87E+00	kg
treatment, PV cell production effluent	1.47E+00	m3
RESOURCES		
water, unspecified natural origin, cooling	6.78E+00	m3
EMMISION TO AIR		
aluminium, unspecified	5.24E-03	kg
hydrogen chloride	1.80E-03	kg

hydrogen fluoride	3.28E-05	kg
lead	5.24E-03	kg
particulates, < 2.5 um	1.80E-02	kg
silicon tetrahydride	4.92E-04	kg
silver high population	5.24E-03	kg
sodium hydroxide, high population	3.28E-04	kg
tin	5.24E-03	kg
NMVOC, non-methane volatile organic compound	1.31E+00	kg
carbon dioxide, fossil	1.91E+01	kg
nitrogen oxides	3.39E-04	kg
heat, waste	7.38E+02	MJ

Table 13: Inventory Table to Produce 1 kW Poly-Si Module (Bekkelund, 2013)

Poly-crystalline Silicon Module for 1kW Power		
	Amount	**Unit (per kW)**
PRODUCT:		
Poly-Si PV Module	7.63E+00	m2
MATERIALS		
Poly-Si cell	6.78E+00	m2
aluminium, production mix at plant	1.89E+01	kg
polyphenylene sulfide, at plant	1.16E+01	kg
solar glass, low-iron, at regional storage	7.33E+01	kg
ethylvinylacetate, foil, at plant	7.39E+00	kg
polyvinylfluoride film, at plant	8.01E-01	kg
polyethylene, terephthalate, granulate, amorphous	2.71E+00	kg
copper, at regional storage	8.01E-01	kg
tin, at regional storage	4.04E-02	kg
lead, at regional storage	2.24E-02	kg
nickel 99.5%, at plant	1.19E+00	kg
1-Propanol, at plant	5.91E-02	kg
acetone, liquid, at plant	9.46E-02	kg
silicone product, at plant	8.85E-01	kg
packaging, corrugated board, mixed fibre, single wall	8.01E+00	kg
tap water, at plant	1.57E+02	kg
ENERGY:		
electricity, medium voltage, production UCTE, at grid	4.85E+01	kWh
WASTE:		
disposal, plastics, mixture, 15.3% water	2.95E-01	kg
disposal polyvinylflouride, 0.2% water	2.66E-01	kg
EMISSSION TO AIR:		
heat, waste, unspecified	1.30E+02	MJ

Table 14: Inventory Table for the Poly-Si Module with its BOS (Bekkelund, 2013)

Poly-crystalline Silicon (Poly-Si) Module with its Balance of System (BOS)		
MATERIAL	**Amount**	**Unit (per kW)**
poly-Si PV Module	7.630E+00	m2
slanted-roof construction, mounted, on roof	7.430E+00	m2
electrical installation (for 1kW)	1.00E+00	unit
inverter, 1000 W	1.00E+00	unit
ENERGY		
electricity, low voltage	7.70E-02	kWh
TRANSPORT		
transport, van <3.5t	1.42E+01	tkm
transport, lorry > 16t, fleet average	5.75E+01	tkm
transport, transoceanic, freight ship	2.30E+02	
EMISSION TO AIR		
heat, waste	2.78E-01	MJ

Table 15: Inventory Table for Poly-Si Module Slanted Roof Mounting (Bekkelund, 2013)

Slanted-Roof Construction, Mounted, On Roof for 1kW Poly-Si Module		
	Amount	**Unit (per kW)**
PRODUCT		
slanted- roof construction, mounted, on roof	7.430E+00	m2
MATERIAL		
aluminium, production mix, wrought alloy	2.110E+01	kg
corrugated board, mixed fibre, single wall	9.882E-01	kg
polyethylene, HPDE, granulate	1.040E-02	kg
polystyrene, high impact	5.216E-02	kg
section bar extrusion, aluminium	2.110E+01	kg
sheet rolling, steel	1.115E+01	kg
steel, low-alloyed	1.115E+01	kg
TRANSPORT		
transport, lorry > 16t, fleet average	1.672E+00	tkm
transport, freight, rail	1.115E+01	tkm
transport, van <3.5t	3.225E+00	tkm
DISPOSAL		
disposal, packaging cardboard, 19.6% water	9.882E-01	kg
disposal, building, polyethylene/ polypropylene products	1.040E-02	kg
disposal, building, polystyrene isolation, flame retardant	5.216E-02	kg

ii. Network

Figure 18 shows the network of poly-crystalline silicon (Poly-Si) solar module where it shows the materials and process assembled to produce the Poly-Si solar module which produces 1 kW power. Since there is a lot of materials and process involved in the production of Poly-Si solar module, only the materials and process that had the highest contribution towards the production of the module were shown in the network.

In order to produce a complete module that generates 1 kW power, the module requires 7.63m^2 of Poly-Si module, 7.43m^2 of slanted-roof mounting, 1 unit of electrical installation (1 kW) and 1 unit of inverter (1 kW). As it can be seen from the network, the slanted-roof mounting and inverter sub-assembly is not shown in the network. This is because even though, the mounting and inverter were included in the impact indicator and damage assessment, they are not shown in the network because their percentage of contribution towards the production of module is very low.

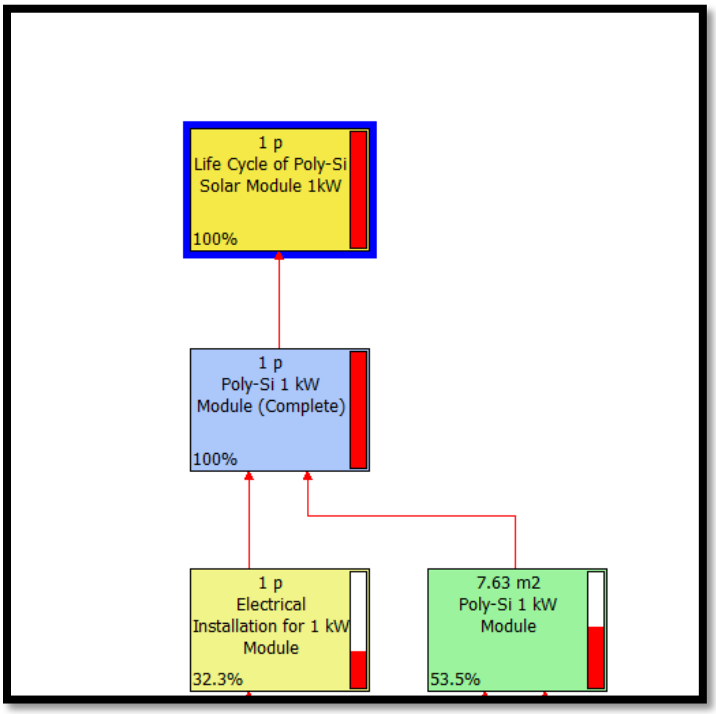

Figure 18: Poly-Si Solar Module Network

iii. Midpoint Indicator

The ReCiPe method addresses 18 types of midpoint impact indicators. Each impact indicator had different unit so they were normalized using European normalization so that they can be compared to one another. After normalization, the impact indicators will be dimensionless which would indicate the magnitude of each impact indicator. Figure 19 shows the graph of normalized midpoint impact indicator for the complete Poly-Si module (1 kW) with its balance of system (BOS). As it can be seen from Figure 19, the life cycle of Poly-Si solar module contributes highest towards the fossil depletion which has a value 0.28. The lowest severity of impact indicators is the contribution towards petrochemical oxidant formation which is around 0.00002.

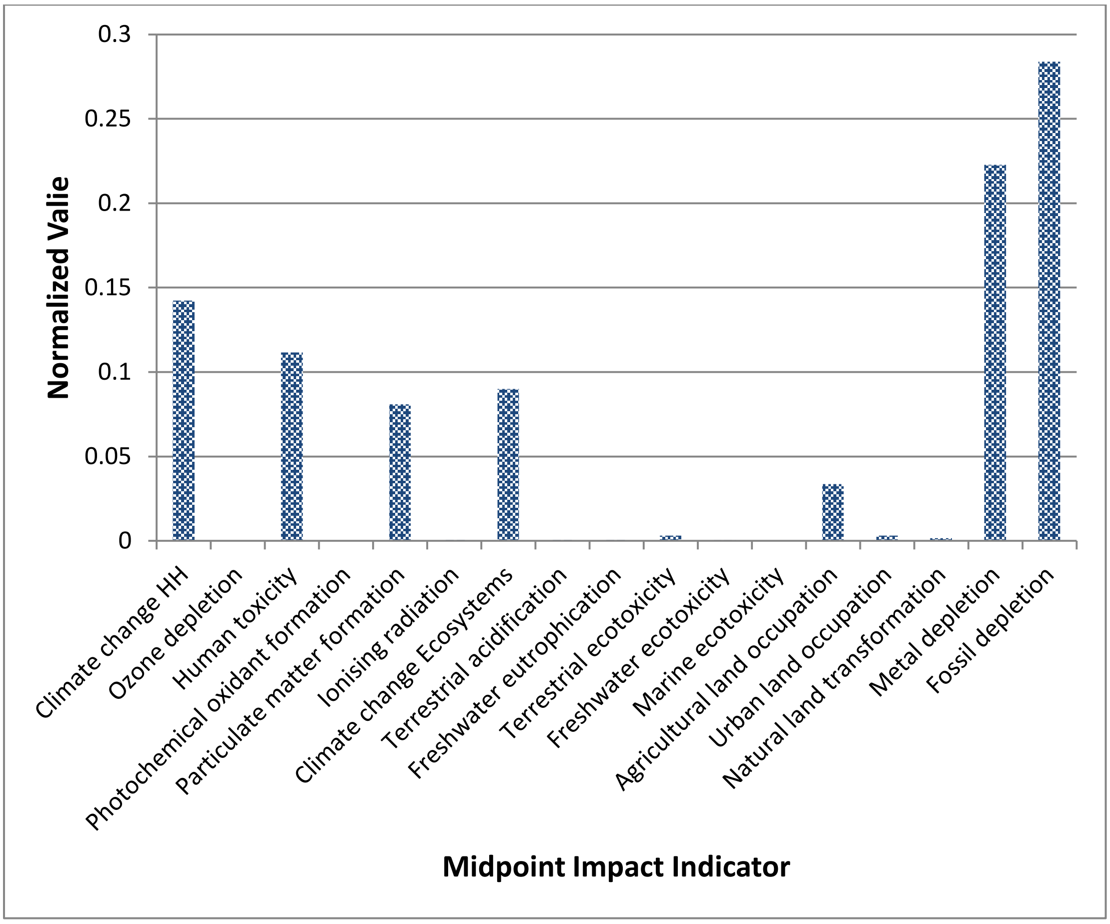

Figure 19: Normalized Midpoint Indicator for Poly-Si Solar Module

The impact indicators of major sub-assemblies used to produce Poly-Si solar module were also assessed to find out the impact of each sub-assembly. Figure 20 shows the graph of midpoint impact indicators for the sub-assemblies. For Poly-Si module sub-assembly, it has the highest impact on fossil depletion with a value of 0.2 and lowest impact on petrochemical oxidant formation with a value of 0.000015. For electrical installation, it has the highest impact on metal depletion with a value of 0.12 and lowest impact on ozone depletion with a value of 0.00000026. For inverter sub-assembly, it has the highest impact on metal depletion with a value of 0.02 and lowest impact on photochemical oxidant formation with a value of 0.00000083. Finally, for slanted-roof mounting sub-assembly, it has the highest impact on fossil depletion with a value of 0.05 and then lowest impact on ozone depletion with a value of 0.0000027.

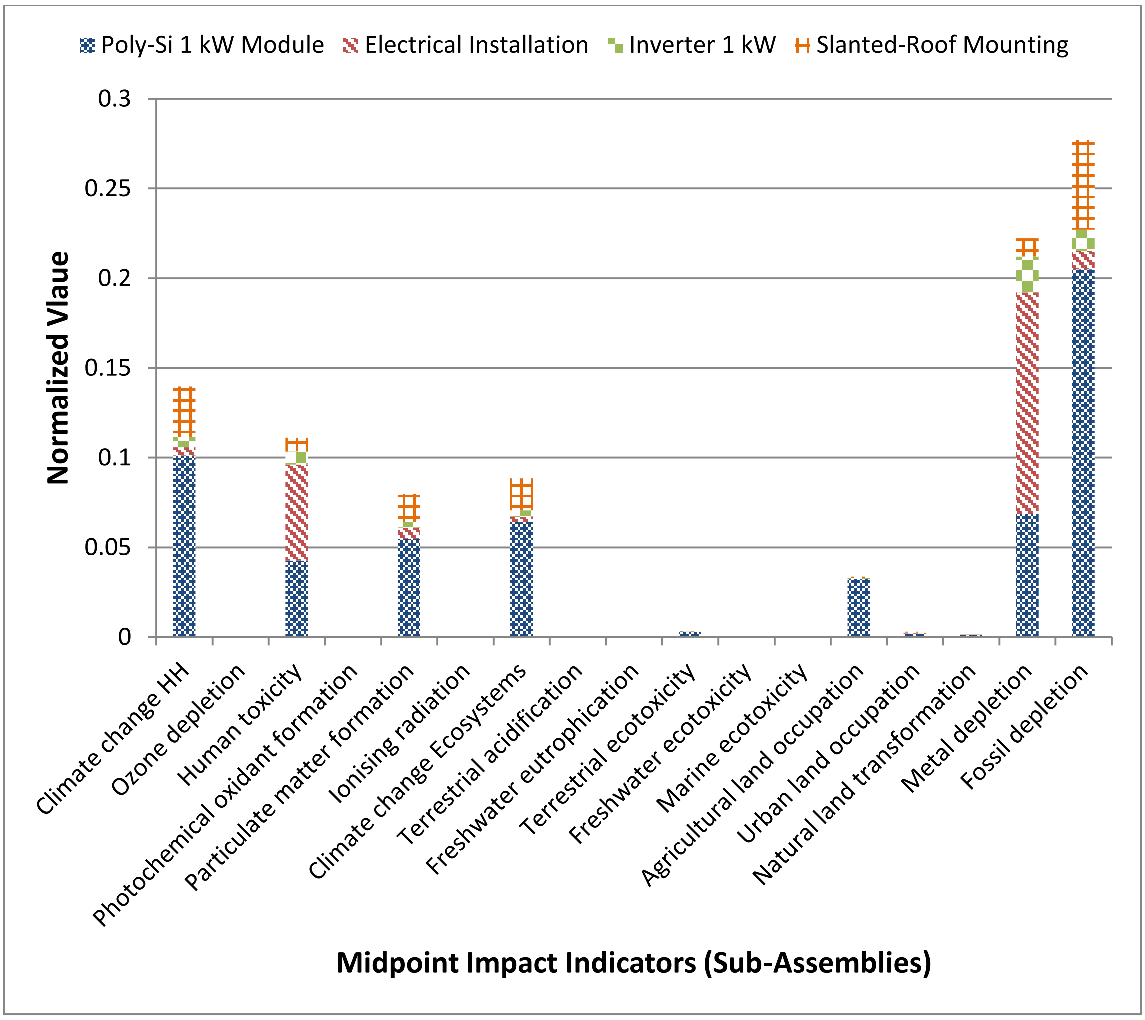

Figure 20: Normalized Midpoint Indicator for Sub-Assemblies of Poly-Si Solar Module

iv. Endpoint Damage Indicator

In order to find out endpoint damage indicator, the data will be converged towards the damages each impact indicator can cause towards human health, ecosystem and resources. The damage indicator would undergo normalization because each damage indicator has its own unit and cannot be compared to one another without normalization. Figure 21 shows the graph of damage indicators of the complete Poly-Si solar module. The life cycle of Poly-Si solar module has the highest damage towards resource with a value of 0.51, followed by human health with a value of 0.34 and the lowest damage is towards the ecosystem with a value of 0.13.

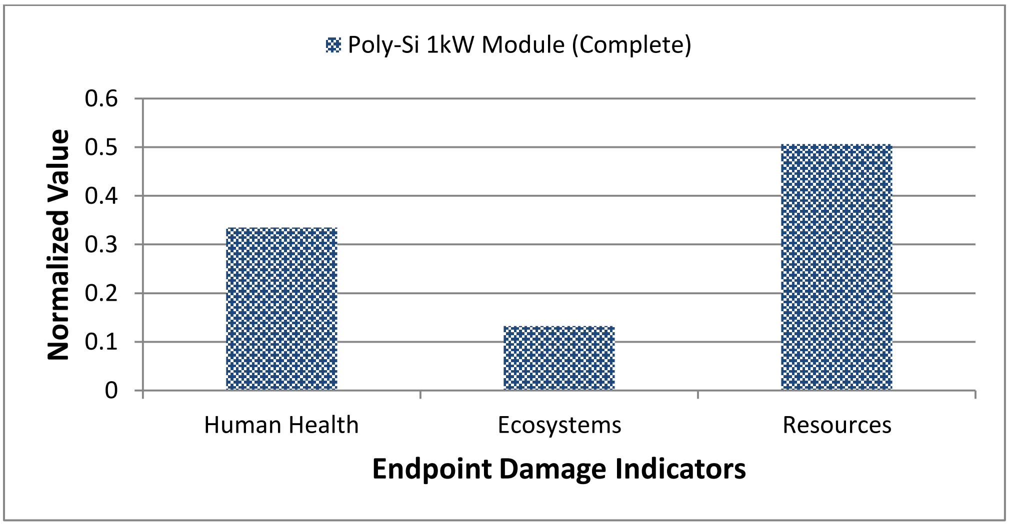

Figure 21: Normalized Damage Indicators for Poly-Si Solar Module

The damage assessment for the major sub-assemblies was also done to find out the damage the sub-assemblies cause towards human health, ecosystem and resource. Each sub-assembly damage values were normalized so that they can be compared to one another. Figure 22 shows the graph of damage assessment for the sub-assemblies. For damage towards human health, Poly-Si module sub-assembly has the highest contribution with a value of 0.20 and inverter has the lowest contribution with a value of 0.016. For damage towards ecosystem, Poly-Si module has the highest contribution with a value of 0.1 and electrical installation has the lowest contribution with a value of 0.004. Finally, for the damage towards resources, Poly-Si module sub-assembly has the highest contribution with value of 0.27 and inverter has the lowest contribution with a value of 0.032.

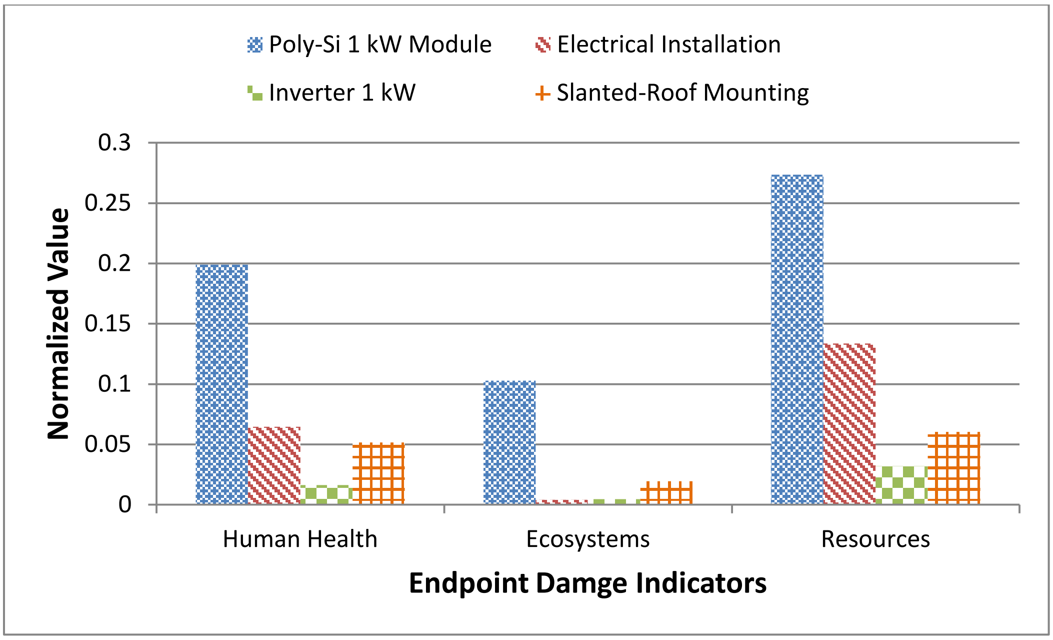

Figure 22: Normalized Damage Indicators of Sub-Assemblies for Poly-Si Solar Module

v. *Single Score*

Similar to midpoint indicator, the damage indicators would undergo weighing process where each of the damage indicators is multiplied with the weighing factor to form a single score for the module which is represented in the unit of point (Pt). The single score is normally used to compare one product from another. The single score of Poly-Si solar module was assessed in 3 types of perspective which are individualist, hierarchist and egalitarian.

Figure 23 shows the graph of single score for the 3 perspectives. For hierarchist perspective, the graph shows that Poly-Si solar module has a score of 288 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 134 Pt, damage towards ecosystem has the score of 53 Pt and the damage towards resource has a score of 101 Pt. For individualist perspective, it has a total score of 281.2 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 87.1 Pt, damage towards ecosystem has the score of 48.1 Pt and the damage towards resource has a score of 146 Pt. Finally, for egalitarian perspective, graph shows that it has a score of 1166 Pt. The score for damage towards human health is 950 Pt, damage towards ecosystem has the score of 115 Pt and the damage towards resource has a score of 101 Pt.

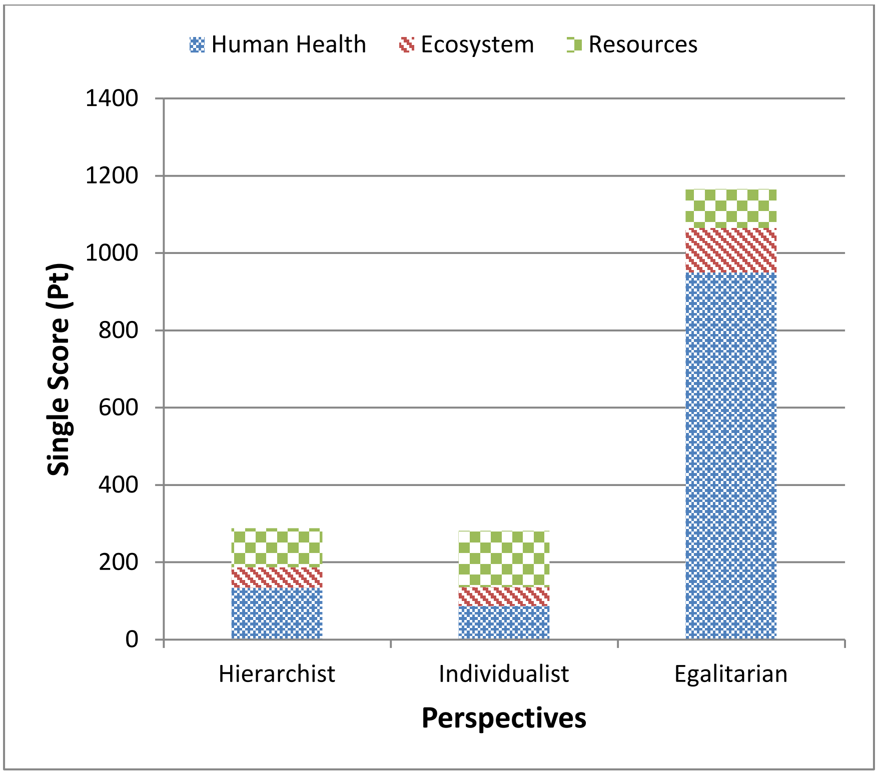

Figure 23: Single Score based on Perspective for Poly-Si Solar Module

The single score assessment for the major sub-assemblies were also done. Figure 24 shows the graph of single score for the sub-assemblies. Poly-crystalline silicon (Poly-Si) solar module sub-assembly has a total score of 175.4 Pt with a human health score of 79.6 Pt, ecosystem score of 41.2 Pt and resource score of 54.7 Pt. For slanted-roof mounting sub-assembly has a total score of 40.4 Pt with a human health score of 20.6 Pt, ecosystem score of 7.74 Pt and resource score of 12.1 Pt. Inverter sub-assembly has a total score of 14.7 Pt with a human health score of 6.48 Pt, ecosystem score of 1.85 Pt and resource score of 6.39 Pt. Finally, the electrical installation sub-assembly has a total score of 54.1 Pt with a human health score of 25.8 Pt, ecosystem score of 1.59 Pt and resource score of 26.7 Pt. The figure shows that Poly-Si module sub-assembly has the highest damage score and inverter sub-assembly has the lowest damage score.

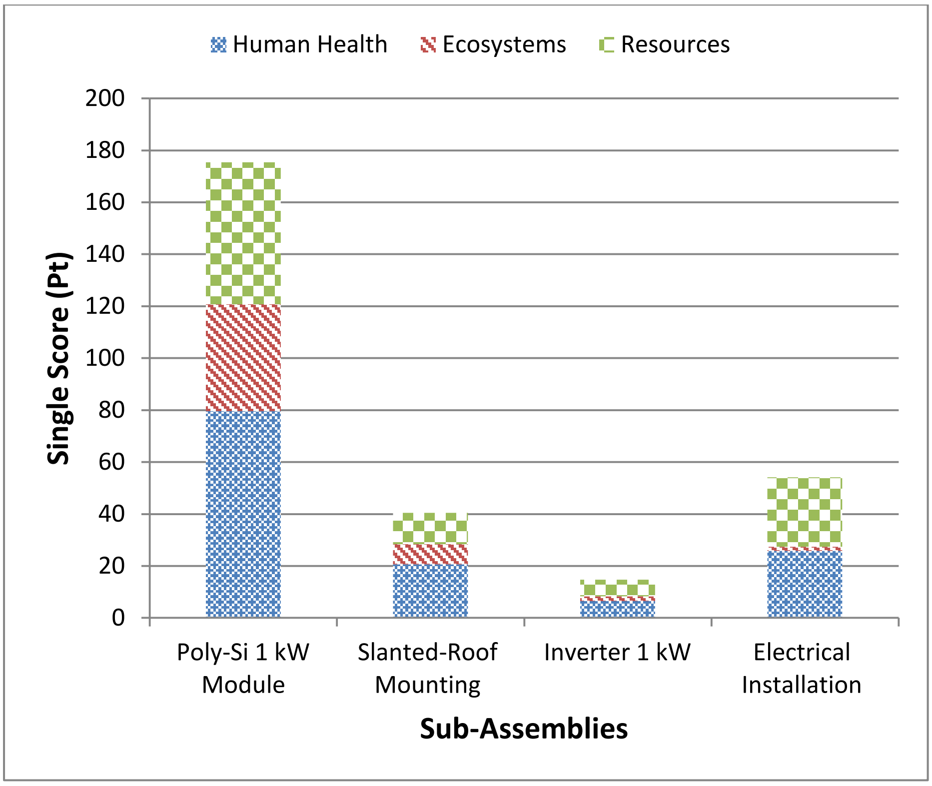

Figure 24: Single Score for Sub-Assemblies of Poly-Si Solar Module

4.4 Life Cycle Assessment (LCA) for Mono-Crystalline (Mono-Si) Solar Module

i. Inventories

The data obtained from the literature is the inventory to produce $1m^2$ of Mono-Si module. The model of Mono-Si solar module used in the literature generates 210W for $1.60m^2$ area. Using the conversion factor, the inventory data was converted to 1 kW basis which requires a module area of $7.60m^2$. Since the process of production of Mono-Si module involves multiple processes, the inventory table was divided into several sections.

The manufacturing process of Mono-Si module begins with the process of processing metallurgic silicon which is in Table 16. Then, the metallurgic silicon will be used to manufacture solar grade silicon (Table 17). After that, the solar grade silicon will be used to manufacture the Mono-Si wafer (Table 18) which will then be used to produce the Mono-Si cell (Table 19). Finally, the cell will be used to produce the Mono-Si module that generates 1 kW power (Table 20).

After the module is made, it needs to be installed with its balance of system (BOS) to become a complete PV system which can supply electricity for domestic or commercial uses. The inventory for the balance of system (BOS) is in Table 21. The inventory for the slanted roof mounting required for a 1 kW mono-Si module is in Table 22. The inventory for the electrical system and inverter is similar to CdTe as both modules produce 1 kW power (Table 4 & Table 5).

Table 16: Inventory Table to Produce Metallurgic Silicon for 1 kW Mono-Si Module (Jungbluth, 2012)

Metallurgic Silicon (MG-Si) for 1 kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
MG-Si	7.44E+00	kg
MATERIALS		
wood chips, mixed, u=120%	2.42E-02	m3
hard coal coke	1.72E+02	MJ
graphite	7.44E-01	kg
charcoal	1.26E+00	kg
petroleum coke	3.72E+00	kg
silica sand	2.01E+01	kg
oxygen, liquid	1.49E-01	kg
DISPOSAL		
disposal, slag from MG-Si production, 0% H2O	1.86E-01	kg
TRANSPORT		
transport, transoceanic freight ship	1.90E+01	tkm
transport, lorry >16t, fleet average	1.16E+00	tkm
transport, freight, rail	5.13E-01	tkm
EMISSIONS TO AIR		
heat, waste	5.30E+02	MJ
arsenic	7.01E-08	kg
aluminium	1.15E-05	kg
antimony	5.84E-08	kg
boron	2.08E-06	kg
cadmium	2.34E-09	kg
calcium	5.77E-06	kg
carbon monoxide, biogenic	4.61E-03	kg
carbon monoxide, fossil	1.03E-02	kg
carbon dioxide, biogenic	1.20E+01	kg
carbon dioxide, fossil	2.66E+01	kg
chromium	5.84E-08	kg
chlorine	5.84E-07	kg
cyanide	5.11E-05	kg

fluorine	2.89E-07	kg
hydrogen sulphide	3.72E-03	kg
hydrogen fluoride	3.72E-03	kg
iron	2.89E-05	kg
lead	2.56E-06	kg
mercury	5.84E-08	kg
NMVOC, non-methane volatile organic compounds	7.14E-04	kg
nitrogen oxides	7.25E-02	kg
particulates, >10um	5.77E-02	kg
potassium	4.61E-04	kg
silicon	5.59E-02	kg
sodium	5.77E-06	kg
sulphur dioxide	9.08E-02	kg
tin	5.84E-08	kg
ENERGY		
electricity, medium voltage	8.18E+01	kWh

Table 17: Inventory Table to Produce Solar Grade Silicon for 1 kW Mono-Si Module (Jungbluth, 2012)

Solar Grade Silicon (sg-Si) for 1 kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
sg-Si	6.58E+00	kg
MATERIALS		
MG-Si	7.44E+00	kg
hydrochloric acid, 30% in H2O	1.05E+01	kg
hydrogen, liquid	3.30E-01	kg
sodium hydroxide, 50% in H2O,production mix	2.29E+00	kg
TRANSPORT	1.75E+01	kg
transport, lorry >16t, fleet average	1.58E+01	kg
ENERGY		
electricity, medium voltage	7.24E+02	kWh
heat, at cogent 1MWe lean burn, allocation energy	1.22E+03	MJ
EMISSION TO AIR		
heat, waste	2.31E+03	MJ
EMISSIONS TO WATER		
AOX, Absorbable Organic Halogen	8.29E-05	kg
BOD5, Biological Oxygen Demand	1.35E-03	kg
DOC, Dissolved Organic Carbon	5.99E-03	kg
TOC, Total Organic Carbon	5.99E-03	kg
COD, Chemical Oxygen Demand	1.33E-02	kg
chloride	2.37E-01	kg

copper, ion	6.71E-07	kg
nitrogen	1.37E-03	kg
phosphate	1.84E-05	kg
sodium, ion	2.22E-01	kg
zinc, ion	1.29E-05	kg
iron, ion	3.69E-05	kg

Table 18: Inventory Table to Produce Mono-Si Wafer for 1 kW Mono-Si Module (Jungbluth, 2012)

Mono-crystalline Silicon Wafer for 1kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
Mono-Si wafer	7.43E+00	m2
MATERIALS		
sg-Si	6.58E+00	kg
silicon carbide	3.64E+00	kg
silicon carbide, recycling	1.59E+01	kg
sodium hydroxide, 50% in H2O, production mix	1.11E-01	kg
hydrochloric acid, 30% in H2O	2.01E-02	kg
acetic acid, 98% in H2O	2.90E-01	kg
triethylene glycol	8.17E-01	kg
triethylene glycol, recycling	1.93E+01	kg
dipropylene glycol monomethyl ether	2.23E+00	kg
alkylbenzene sulfonate, linear, petrochemical	1.78E+00	kg
arcylic binder, 34% in H2O	1.49E-02	kg
glass wool mat	7.43E-02	kg
paper, wood free, coated	1.41E+00	kg
polystyrene, high impact, HIPS	1.49E+00	kg
packaging film, LDPE	7.43E-01	kg
brass	5.54E-02	kg
steel, low-alloyed	1.10E+01	kg
wire drawing, steel	1.11E+01	kg
tap water	4.46E-02	
DISPOSAL		
disposal, waste, silicon wafer production, 0% water	8.17E-01	kg
TRANSPORT		
transport lorry >16t, fleet average	7.58E+00	tkm
transport, freight, rail	3.07E+01	tkm
EMISSIONS TO AIR		
heat, waste	2.14E+02	MJ
EMISSIONS TO WATER		
AOX, Absorbable Organic Halogen	3.72E-03	kg
cadmium, ion	4.50E-04	kg

chromium, ion	2.25E-04	kg
COD, Chemical Oxygen Demand	2.20E-01	kg
copper, ion	4.50E-04	kg
lead	2.25E-04	kg
mercury	4.50E-05	kg
nickel, ion	4.50E-04	kg
nitrogen	7.39E-02	kg
phosphate	3.72E-03	kg
BOD5, Biological Oxygen Demand	2.20E-01	kg
DOC, Dissolved Organic Carbon	8.25E-02	kg
TOC, Total Organic Carbon	8.25E-02	kg
ENERGY		
electricity, medium voltage, production UCTE	5.94E+01	kWh
natural gas, burned in industrial furnace	2.97E+01	MJ

Table 19: Inventory Table to Produce Mono-Si Cell for 1 kW Mono-Si Module (Jungbluth, 2012)

Mono-crystalline Silicon Cell for 1kW Module		
	Amount	**Unit (per kW)**
PRODUCT		
Mono-Si Cell	7.01E+00	m2
INPUT FROM FOREGROUND		
Mono-Si wafer	7.43E+00	m2
MATERIALS		
metallization paste, front side	5.19E-02	kg
metallization paste, back side	3.46E-02	kg
metallization paste, back side, aluminium	5.04E-01	kg
ammonia, liquid	4.72E-02	kg
phosphoric acid, fertiliser grade. 70% in H2O	5.38E-02	kg
phosphoryl chloride	1.11E-02	kg
titanium dioxide, production mix	9.95E-06	kg
ethanol from ethylene	4.49E-02	kg
isopropanol	5.53E-01	kg
solvents, organic, unspecified	1.00E-02	kg
silicone product	8.48E-03	kg
sodium silicate, spray powder 80%	5.24E-01	kg
calcium chloride	1.51E-01	kg
acetic acid, 98% in H2O	1.98E-02	kg
hydrochloric acid, 30% in H2O	3.20E-01	kg
hydrogen fluoride	2.64E-01	kg
nitric acid, 50% in H2O	1.87E-01	kg
sodium hydroxide, 50%in H2O, production mix	1.10E+00	kg
argon, liquid	1.80E-02	kg

oxygen, liquid	7.15E-01	kg
nitrogen, liquid	1.30E+01	kg
tetrafluoroethylene	2.22E-02	kg
polystyrene, expandable	2.85E-03	kg
TRANSPORT		
transport, transoceanic freight ship	6.20E+00	tkm
transport, lorry >16t, fleet average	3.42E+00	tkm
transport, freight, rail	1.07E+01	tkm
DISPOSAL		
water, completely softened	9.60E+02	kg
treatment, PV cell production effluent, to wastewater treatment	1.52E+00	m3
disposal, waste, Si waferprod., inorganic, 94% H2O	1.93E+00	kg
EMISSION TO AIR		
heat, waste	7.64E+02	MJ
aluminium	5.42E-03	kg
ethane, hexafluoro-,HFC-116	8.34E-04	kg
hydrogen chloride	1.86E-03	kg
hydrogen fluoride	3.40E-05	kg
lead	5.42E-03	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.36E+00	kg
nitrogen oxides	3.51E-04	kg
methane, tetrafluoro-, R-14	1.74E-03	kg
particulates, < 2.5 um	1.86E-02	kg
silicon	5.10E-04	kg
silver	5.42E-03	kg
sodium	3.40E-04	kg
tin	5.42E-03	kg
ENERGY		
electricity, medium voltage, production UCTE	2.12E+02	kWh
natural gas, burned in industrial furnace	3.34E+01	MJ
light fuel oil, burned in industrial furnace	7.99E+00	MJ

Table 20: Inventory Table to Produce 1 kW Mono-Si Module (Jungbluth, 2012)

Mono-crystalline Silicon Module for 1 kW Power		
	Amount	**Unit (per kW)**
PRODUCT		
Mono-Si Module	7.60E+00	m2
INPUT FROM FOREGROUND		
Mono-Si Cell	7.01E+00	m2
MATERIALS		
aluminium alloy, AlMg3	2.00E+01	kg

nickel, 99.5%	1.24E-03	kg
brazing solder, cadmium free	6.66E-02	kg
solar glass,	7.68E+01	kg
copper	8.59E-01	kg
glass fibre reinforced plastic, polyamide, injection moulding	1.43E+00	kg
ethylvinylacetate foil	7.60E+00	kg
polyvinylfluoride film	8.36E-01	kg
polyethylene terephthalate, granulate , amorphous	2.83E+00	kg
silicone product	9.27E-01	kg
acetone, liquid	9.88E-02	kg
methanol	1.64E-02	kg
vinyl acetate	1.25E-02	kg
lubricating oil	1.22E-02	kg
corrugated board, mixed fibre, single wall	8.36E+00	kg
1-propanol	6.19E-02	kg
TRANSPORT		
transport, lorry >16 t, fleet average	1.38E+01	tkm
transport, freight, rail	7.18E+01	tkm
DISPOSAL		
disposal, municipal solid waste, 22.9% water	2.28E-01	kg
disposal, polyvinylfluoride, 0.2% H2O	8.36E-01	kg
disposal, plastics, mixture, 15.3% H2O	1.28E+01	kg
disposal, used mineral oil, 10% H2O	1.22E-02	kg
treatment, sewage, from residence	1.62E-01	m3
tap water	1.62E+02	kg
tempering, flat glass	7.68E+01	kg
wire drawing, copper	8.59E-01	kg
EMISSION TO AIR		
Heat, waste	1.29E+02	MJ
ENERGY		
electricity, medium voltage, production UCTE	3.58E+01	kWh
natural gas, burned in industrial furnace	4.11E+01	MJ

Table 21: Inventory Table for the Mono-Si Module with its BOS (Jungbluth, 2012)

Mono-crystalline Silicon (Mono-Si) Module with its Balance of System (BOS)		
MATERIAL	**Amount**	**Unit (per kW)**
mono-Si PV Module	7.600E+00	m2
slanted-roof construction, mounted, on roof	7.360E+00	m2
electrical installation (for 1kW)	1.00E+00	unit
inverter, 1000 W	1.00E+00	unit
ENERGY		
electricity, low voltage	7.70E-02	kWh

TRANSPORT		
transport, van <3.5t	1.41E+01	tkm
transport, lorry > 16t, fleet average	5.71E+01	tkm
EMISSION TO AIR		
heat, waste	2.85E-01	MJ

Table 22: Inventory Table for Mono-Si Module Slanted Roof Mounting (Jungbluth, 2012)

Slanted-Roof Construction, Mounted, On Roof for 1kW Mono-Si Module		
	Amount	**Unit (per kW)**
PRODUCT		
slanted- roof construction, mounted, on roof	7.360E+00	m2
MATERIAL		
aluminium, production mix, wrought alloy	2.090E+01	kg
corrugated board, mixed fibre, single wall	9.789E-01	kg
polyethylene, HPDE, granulate	1.030E-02	kg
polystyrene, high impact	5.167E-02	kg
section bar extrusion, aluminium	2.090E+01	kg
sheet rolling, steel	1.104E+01	kg
steel, low-alloyed	1.104E+01	kg
TRANSPORT		
transport, lorry > 16t, fleet average	1.656E+00	tkm
transport, freight, rail	1.104E+01	tkm
transport, van <3.5t	3.194E+00	tkm
DISPOSAL		
disposal, packaging cardboard, 19.6% water	9.789E-01	kg
disposal, building, polyethylene/ polypropylene products	1.030E-02	kg
disposal, building, polystyrene isolation, flame retardant	5.167E-02	kg

ii. Network

Figure 25 shows the network of mono-crystalline silicon (Mono-Si) solar module. Since there is a lot of materials and process involved in the production of Poly-Si solar module, only the materials and process that had the highest contribution towards the production of the module were shown in the network. In order to produce a complete module that generates 1 kW power, the module requires 7.6m^2 of Mono-Si module, 7.36m^2 of slanted-roof mounting, 1 unit of electrical installation (1 kW) and 1 unit of inverter (1 kW).

As it can be seen from the network, the slanted-roof mounting and inverter sub-assembly is not shown in the network. Similar to Poly-Si network, this is because even though, the mounting and inverter were included in the impact indicator and damage assessment, they are not shown in the network because their percentage of contribution towards the production of module is very low.

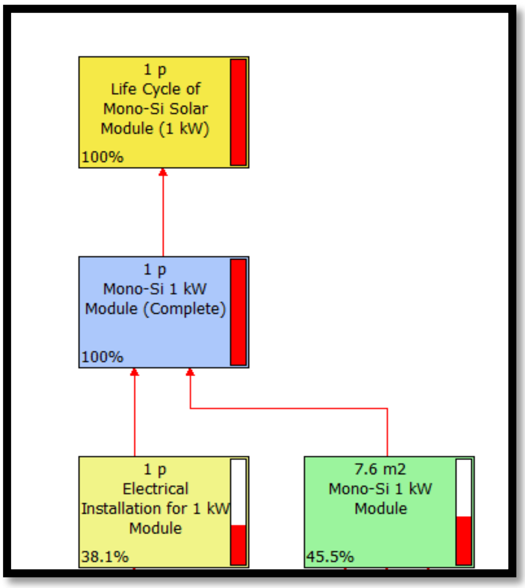

Figure 25: Mono-Si Solar Module Network

iii. Midpoint Indicator

There are 18 types of midpoint impact indicators addressed in the ReCiPe method. European normalization was used to normalize the value so that so that they can be compared to one another. Figure 26 shows the graph of normalized midpoint impact indicator for the complete Mono-Si module (1 kW) with its balance of system (BOS). As it can be seen from Figure 24, the life cycle of Mono-Si solar module contributes highest towards the fossil depletion which has a value 0.24. The lowest severity of impact indicators is the contribution towards petrochemical oxidant formation which is around 0.000018.

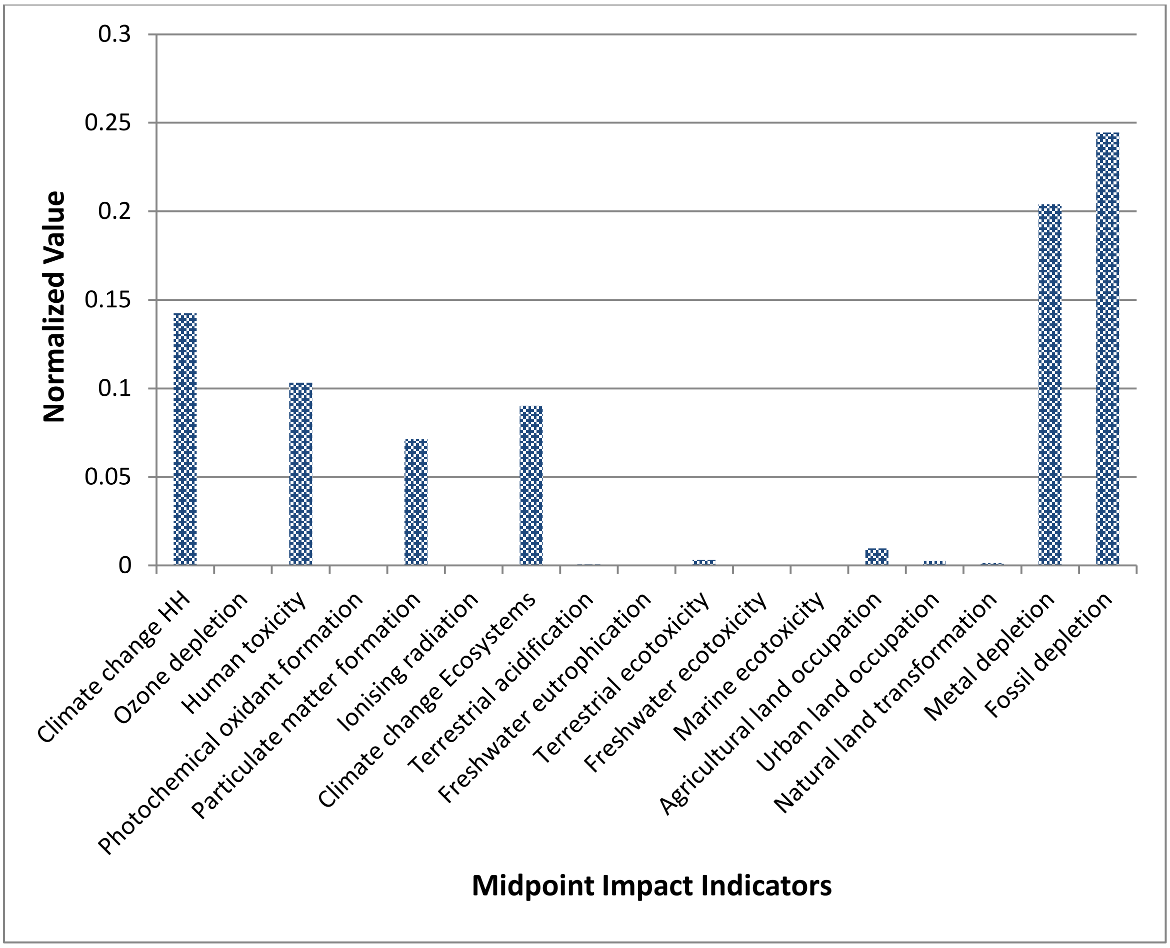

Figure 26: Normalized Midpoint Indicator for Mono-Si Solar Module

The impact indicators of major sub-assemblies used to produce Mono-Si solar module were also assessed to find out the impact of each sub-assembly. Figure 27 shows the graph of midpoint impact indicators for the sub-assemblies. For Poly-Si module sub-assembly, it has the highest impact on fossil depletion with a value of 0.16 and lowest impact on petrochemical oxidant formation with a value of 0.000013. For electrical installation, it has the highest impact on metal depletion with a value of 0.12 and lowest impact on ozone depletion with a value of 0.00000026. For inverter sub-assembly, it has the highest impact on metal depletion with a value of 0.02 and lowest impact on photochemical oxidant formation with a value of 0.00000083. Finally, for slanted-roof mounting sub-assembly, it has the highest impact on fossil depletion with a value of 0.05 and then lowest impact on ozone depletion with a value of 0.00000273.

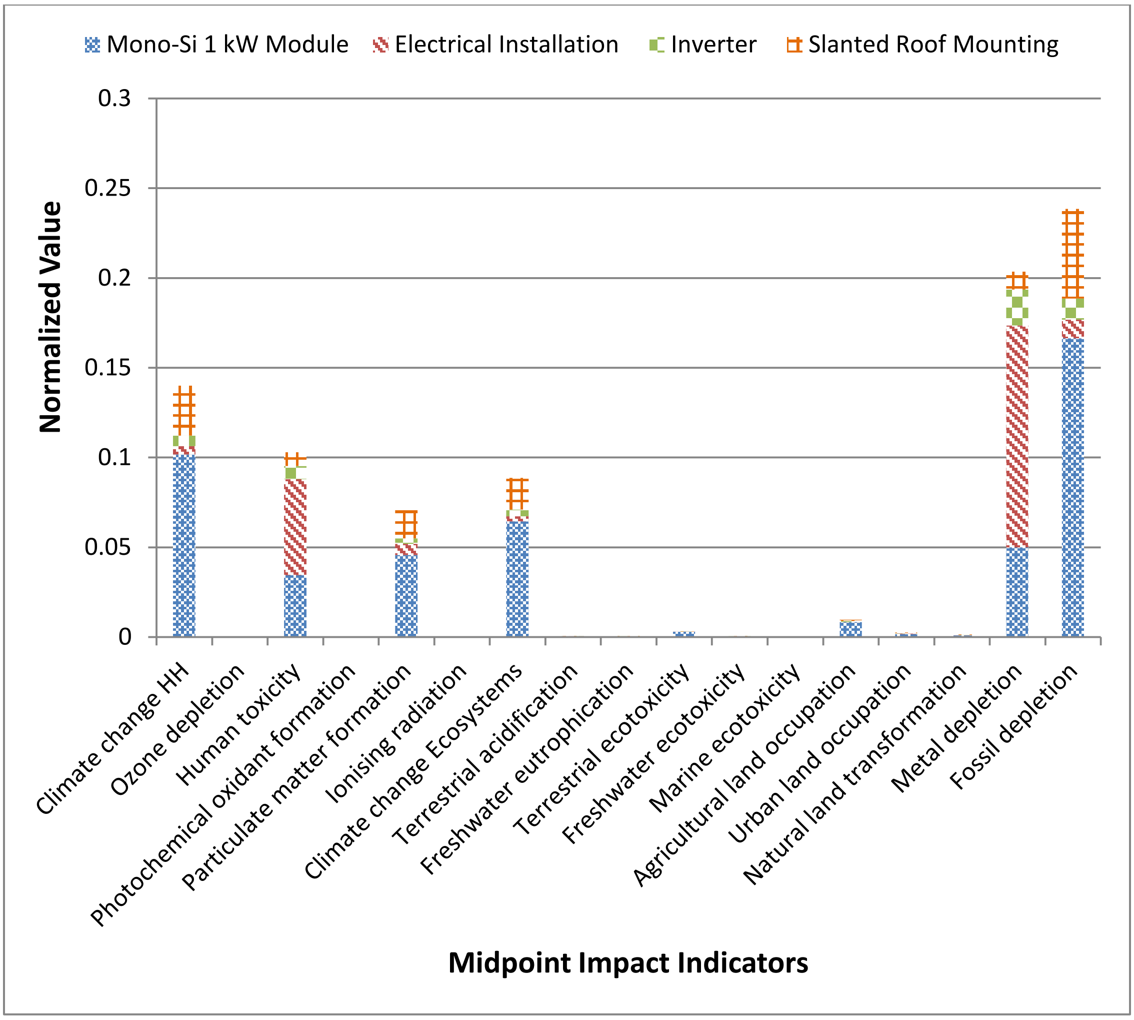

Figure 27: Normalized Midpoint Indicator for Sub-Assemblies of Mono-Si Solar Module

iv. Endpoint Damage Indicator

The data was then converged towards the damage each impact indicator can cause towards human health, ecosystem and resources. The damage indicator would undergo normalization because each damage indicator has its own unit and cannot be compared to one another without normalization. Figure 28 shows the graph of damage indicators of the complete Mono-Si solar module. The life cycle of Mono-Si solar module has the highest damage towards resource with a value of 0.44, followed by human health with a value of 0.32 and the lowest damage is towards the ecosystem with a value of 0.11.

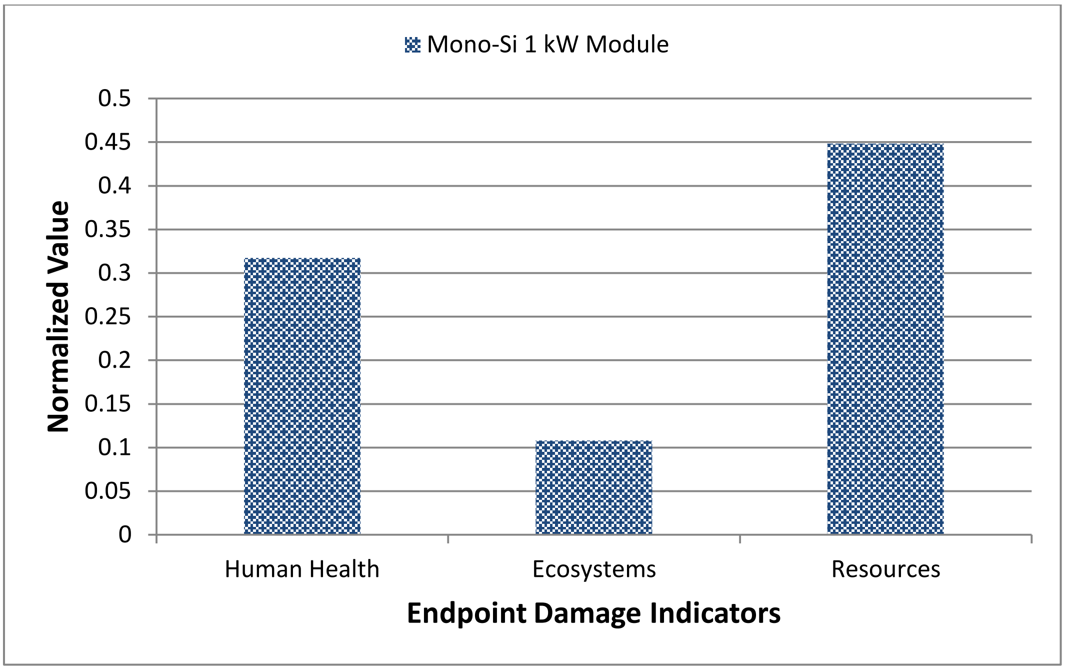

Figure 28: Normalized Damage Indicators for Mono-Si Solar Module

The damage assessment for the major sub-assemblies was also done to find out the damage the sub-assemblies cause towards human health, ecosystem and resource. Each sub-assembly damage values were normalized so that they can be compared to one another. Figure 29 shows the graph of damage assessment for the sub-assemblies. For damage towards human health, Mono-Si module sub-assembly has the highest contribution with a value of 0.18 and inverter has the lowest contribution with a value of 0.016. For damage towards ecosystem, Mono-Si module has the highest contribution with a value of 0.078 and electrical installation has the lowest contribution with a value of 0.004. Finally, for the damage towards resources, Mono-Si module sub-assembly has the highest contribution with value of 0.22 and inverter has the lowest contribution with a value of 0.032.

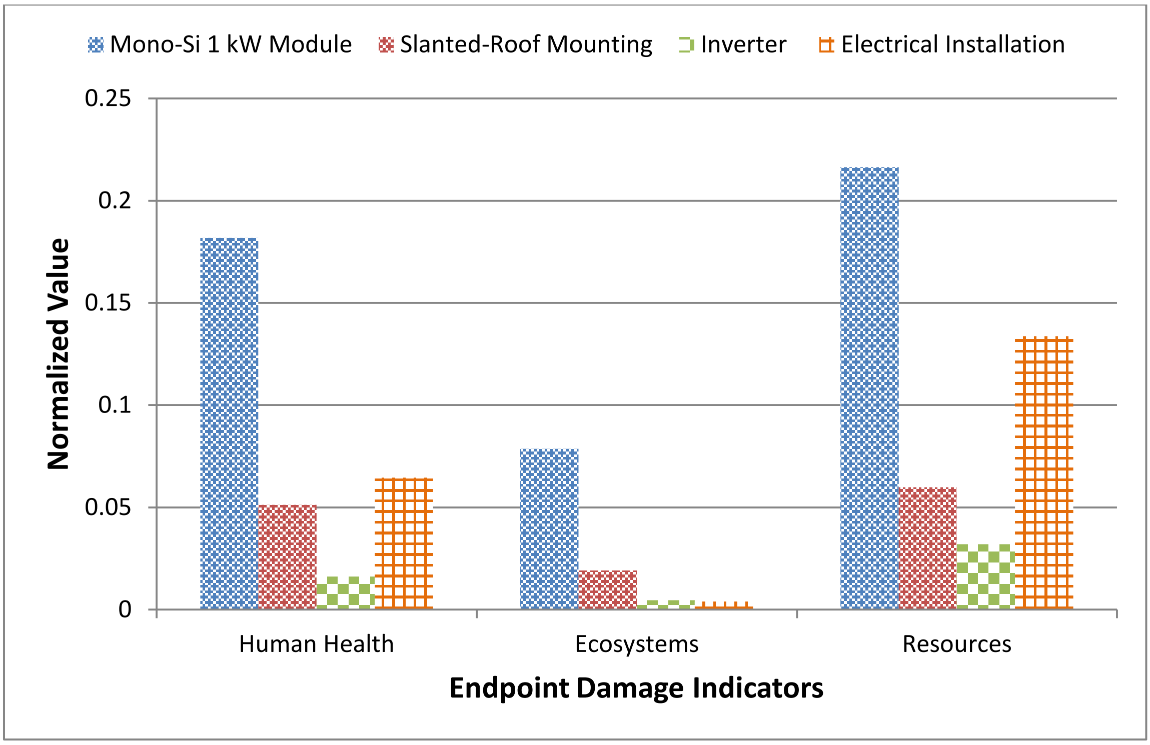

Figure 29: Normalized Damage Indicators of Sub-Assemblies for Mono-Si Solar Module

v. Single Score

The damage indicators were then converted to single score. They would undergo weighing process where each of the damage indicators is multiplied with the weighing factor to form a single score for the module which is represented in the unit of point (Pt). The single score is normally used to compare one product from another. The single score of Mono-Si solar module was assessed in 3 types of perspective which are individualist, hierarchist and egalitarian.

Figure 30 shows the graph of single score for the 3 perspectives. For hierarchist perspective, the graph shows that Mono-Si solar module has a score of 260 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 127 Pt, damage towards ecosystem has the score of 43.2 Pt and the damage towards resource has a score of 89.8 Pt. For individualist perspective, it has a total score of 262 Pt where the damage towards human health has an indicator score of 85.4 Pt, damage towards ecosystem has the score of 45.4 Pt and the damage towards resource has a score of 132 Pt. Finally, for egalitarian perspective, graph shows that it has a score of 1068 Pt. The score for damage towards human health is 872 Pt, damage towards ecosystem has the score of 106 Pt and the damage towards resource has a score of 89.7 Pt.

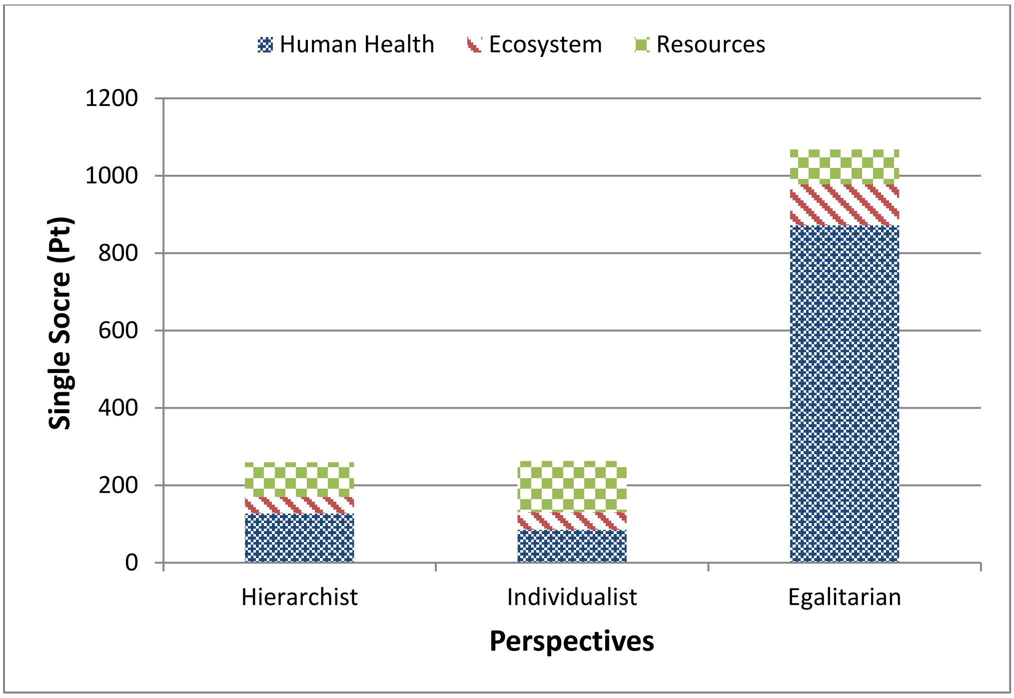

Figure 30: Single Score based on Perspective for Mono-Si Solar Module

The single score assessment for the major sub-assemblies were also done. Figure 31 shows the graph of single score for the sub-assemblies. Mono-crystalline silicon (Mono-Si) solar module sub-assembly has a total score of 147.5 Pt with a human health score of 72.7Pt, ecosystem score of 31.5Pt and resource score of 43.2 Pt. For slanted-roof mounting sub-assembly has a total score of 40.1Pt with a human health score of 20.4 Pt, ecosystem score of 7.67 Pt and resource score of 11.9 Pt. Inverter sub-assembly has a total score of 14.7 Pt with a human health score of 6.48 Pt, ecosystem score of 1.85 Pt and resource score of 6.39 Pt. Finally, the electrical installation sub-assembly has a total score of 54.1 Pt with a human health score of 25.8 Pt, ecosystem score of 1.59 Pt and resource score of 26.7 Pt. The figure shows that Poly-Si module sub-assembly has the highest damage score and inverter sub-assembly has the lowest damage score.

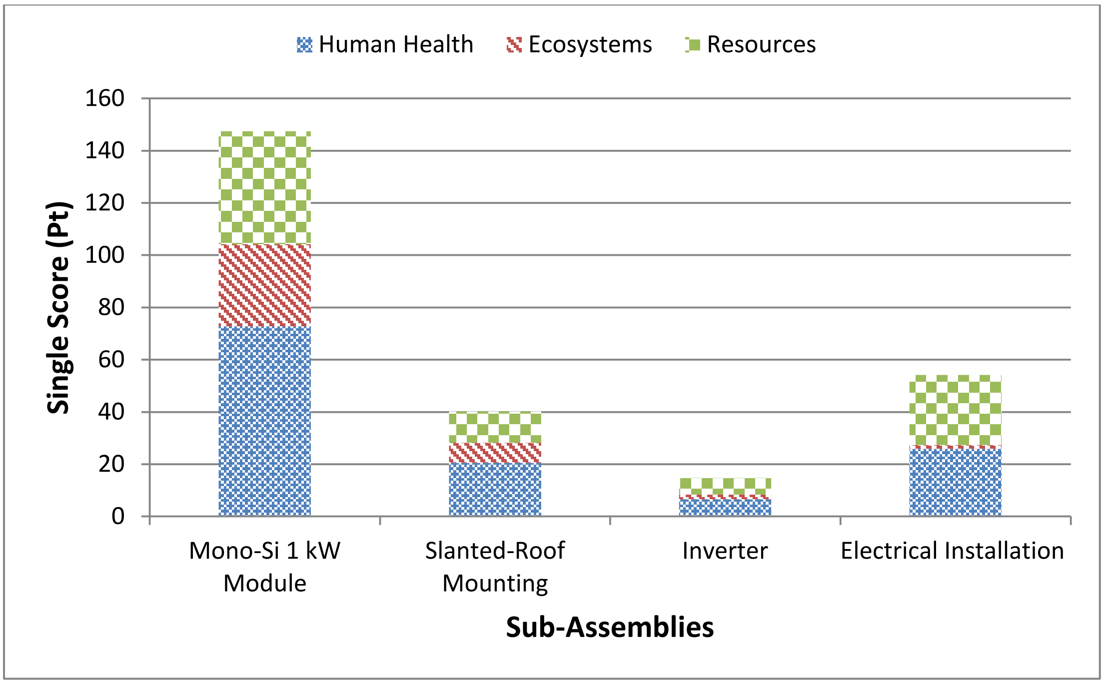

Figure 31: Single Score for Sub-Assemblies of Mono-Si Solar Module

4.5 Results Summary

The life cycle assessment (LCA) on the 4 types of solar module using ReCiPe method produced 3 types of results which are midpoint indicators result, endpoint indicators result and single score result. The midpoint indicator results addressed all 18 impact indicators and showed the severity of each indicator for each type of solar module. The results were normalized using European normalization so that they can be compared to one another.

For CdTe solar module, it contributed highest towards the metal depletion which had a value of 0.153 and contributed lowest towards petrochemical oxidant formation which was around 0.00001. For a-Si solar module, it contributed highest towards the metal depletion which had a value of 0.32 and lowest towards petrochemical oxidant formation which was around 0.000014. The life cycle of Poly-Si solar module contributed highest towards fossil depletion which had a value of 0.28 and lowest towards petrochemical oxidant formation which was around 0.00002. Lastly, for Mono-Si solar module, it contributed highest towards fossil depletion with a value of 0.24 and lowest contribution towards petrochemical oxidant formation which was around 0.000018.

The endpoint damage indicator results addressed the damages the module can cause towards human health, ecosystem and resource. Since each damage indicator had different unit, the results were normalized using European normalization. Table 23 shows the summary of normalized damage indicators for each solar module. CdTe solar module has the highest damage towards resource with a value of 0.303, followed by human health with a value of 0.188 and the lowest damage is towards the ecosystem with a value of 0.053.

For a-Si solar module, it has the highest damage towards resource with a value of 0.55 followed by human health with a value of 0.31 and the lowest damage is towards the ecosystem with a value of 0.09. For Poly-Si solar module, it has the highest damage towards resource with a value of 0.51, followed by human health with a value of 0.34 and the lowest damage is towards the ecosystem with a value of 0.13. The life cycle of Mono-Si solar module has the highest damage towards resource with a value of 0.44, followed by human health with a value of 0.32 and the lowest damage is towards the ecosystem with a value of 0.11.

Table 23: Summary of Normalized Damage Indicators:

Damage Indicators	**CdTe**	**a-Si**	**Poly-Si**	**Mono-Si**
Human Health	0.188	0.31	0.34	0.32
Ecosystem	0.053	0.09	0.13	0.11
Resource	0.303	0.55	0.51	0.44

The single score results was formed by converting the 3 types of damages caused throughout the life cycle of a solar cell to a single score value. The single score was analysed in 3 types of perspective which are individualist, hierarchist and egalitarian. Table 24 show the single score results based on perspective. For CdTe solar module, it had a score of 157 Pt for hierarchist perspective, score of 159.2 Pt for individualist perspective and 794 Pt for egalitarian perspective. For a-Si solar module, it had a score of 269.1 Pt for hierarchist perspective, score of 296.3 Pt for individualist perspective and 1184.3 Pt for egalitarian perspective. Poly-Si had a score of 288 Pt for hierarchist perspective, score of 281.2 Pt for individualist perspective and 1166 Pt for egalitarian perspective. Finally, Mono-Si had a score of

260 Pt for hierarchist perspective, score of 262 Pt for individualist perspective and 1068 Pt for egalitarian perspective.

Table 24: Summary of Single Scores based on Perspectives

SINGLE SCORE (Pt)			
Solar Module	***Hierarchist***	***Individualist***	***Egalitarian***
CdTe	157	159.2	794
a-Si	269.1	296.3	1184.3
Poly-Si	288	281.2	1166
Mono-Si	260	262	1068

4.6 Comparison of Results and Interpretation

Now that the assessment for the 4 types of solar modules using ReCiPe method is done, the solar modules need to be compared against one another to select the solar cell that has the least impact on the environment. The modules were compared based on 3 types of analysis which are midpoint impact indicator, endpoint damage indicator and single score based on perspective.

a) Midpoint Indicators

Figure 32 shows the midpoint impact indicator comparison graph of all 4 types of solar module. For midpoint impact indicators, the impact indicators that were severely affected by the life cycle of the 4 types of solar modules are metal depletion, fossil depletion and climate change. In metal depletion, amorphous silicon (a-Si) solar module has the highest contribution with a value of 0.32, followed by poly-crystalline silicon (Poly-Si) solar module with a value of 0.22, then mono-crystalline silicon (Mono-Si) with a value of 0.20 and lastly cadmium telluride (CdTe) solar module with the least contribution of 0.15. This indicates that a-Si silicon uses more metal like steel, copper and aluminium compared to other solar modules. Besides that, in order to manufacture a-Si solar module that produces 1 kW power, the area of the module and area of roof mounting for the module is larger compared other modules which causes the usage of large amount of metal to manufacture the module.

For fossil depletion, Poly-Si solar module has the highest contribution with a value of 0.28, followed by Mono-Si solar module with a value of 0.24, then a-Si with a value of 0.23 and lastly CdTe solar module with the least contribution of 0.15. Poly-Si and Mono-Si solar module have higher contribution towards fossil depletion compared to a-Si and CdTe as both silicon modules uses a large quantity of fossil fuels like fuel oil, petroleum gas, coal, coke, diesel and charcoal to harness the energy required to process the silica into solar grade silicon. The amount of fossil fuel used by Poly-Si is higher compared to Mono-Si which makes the normalised value of Poly-Si towards fossil depletion to be higher than Mono-Si.

For climate change impact indicator which affects human health, Poly-Si and Mono-Si both have equal contribution with a value of 0.14, followed by a-Si with a value of 0.13 and CdTe with a value of 0.07. Poly-Si and Mono-Si have a high value because they have high emission of carbon dioxide, carbon monoxide, nitrogen oxides, sulphur dioxides and other metallic components to the atmosphere. These substances which are emitted to the air can have adverse effect to the atmosphere which could then lead towards human health damage.

However, it can be seen that CdTe solar module has the lowest contribution to the impact indicators compared to the other solar modules. This indicates that CdTe solar module has the least impact on the environment compared to Poly-Si, Mono-Si and a-Si. The reason is because CdTe is a thin film cell which only uses a small amount of metals and materials to be manufactured. Besides that, the only significant emissions that exist in the whole inventory is the emission of cadmium ion to water in which the amount is very much lower compared to the emissions of other solar modules.

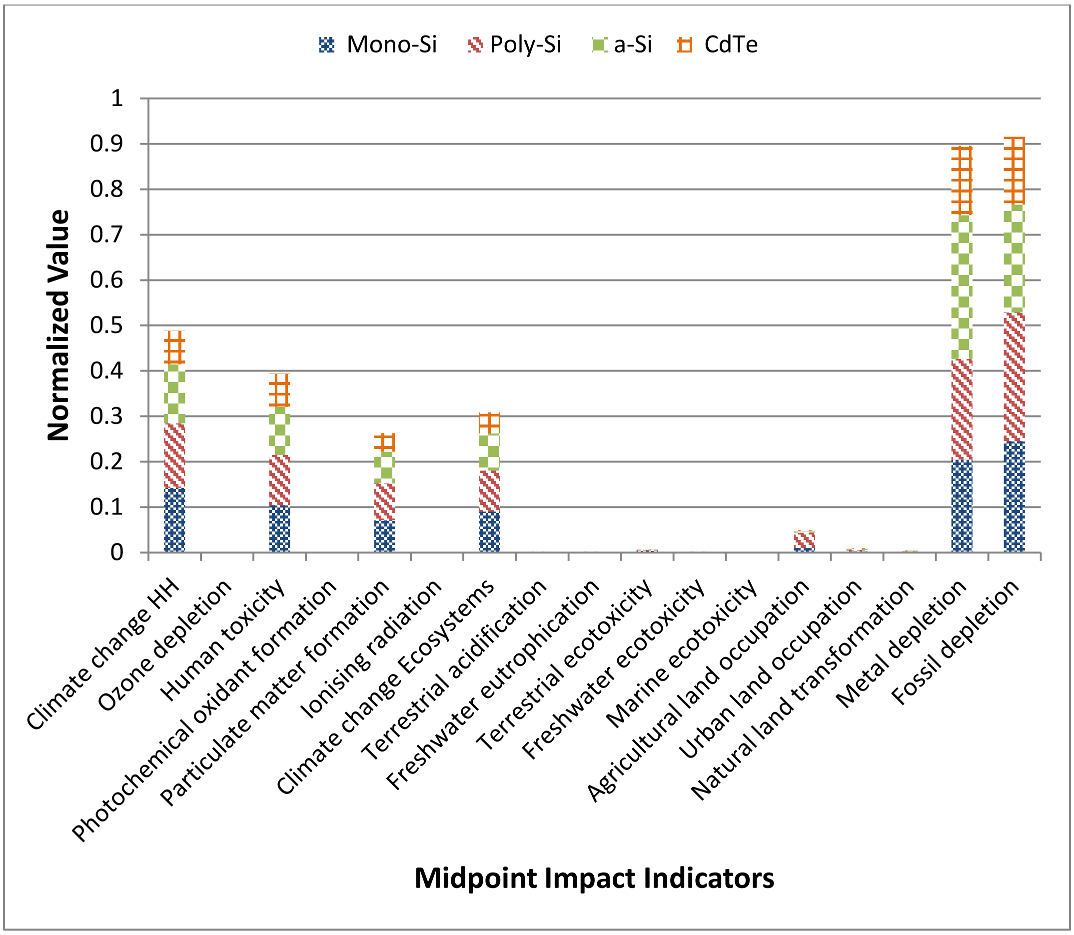

Figure 32: Solar Module Comparison for Normalised Midpoint Impact Indicator

b) Endpoint Damage Indicators

Figure 33 shows the endpoint damage indicator comparison graph of all 4 types of solar module. For the endpoint damage indicator, the 4 types of solar modules were compared against one another for their damage towards human health, ecosystem and resources. The highest damage was towards resource. For damage towards resource, a-Si solar module has the highest contribution with a value of 0.55, followed by Poly-Si with a value of 0.51, then Mono-Si with a value of 0.45 and CdTe with a value of 0.30. Damage towards resource is usually resulted from the effect of metal depletion and fossil depletion. Amorphous silicon (a-Si) has the highest damage towards resource due to its high contribution towards metal depletion and fossil depletion. In order to produce a solar module of 1 kW, the manufacturing process of a-Si uses high amount of steel, aluminium, copper and fuels which contributes towards resource depletion. On the other hand, CdTe solar module has the lowest contribution towards resource depletion as it only uses a small amount of copper, chromium and natural gas as fuel to be manufactured.

The next one is damage towards human health. For human health, Poly-Si solar module has the highest contribution with a value of 0.34, followed by Mono-Si with a value of 0.32, then a-Si with a value of 0.31 and CdTe with a value of 0.19. The value for damage towards human health is formed from the severity of impact categories like ozone depletion, human toxicity, ionising radiation, photochemical oxidant formation, particulate matter formation and climate change. Poly-Si and Mono-Si have a high damage towards human health compared to a-Si and CdTe due to their severe contribution towards climate change, human toxicity and particulate matter formation. This is due to high emission of carbon dioxide, carbon monoxide, nitrogen oxides, sulphur dioxides, particulate matter and other metallic components to the atmosphere. For CdTe, it has the lowest contribution towards human health damage as its inventory consist of only small amount of cadmium emission to air and water where the amount is very much lower compared to the emissions of other modules.

The least damage is damage towards ecosystem. For damage towards ecosystem, Poly-Si solar module has the highest contribution with a value of 0.13, followed by Mono-Si with a value of 0.11, then a-Si with a value of 0.09 and CdTe with a value of 0.05. The damage towards ecosystem is resulted from impact indicators like terrestrial ecotoxicity, terrestrial acidification, agricultural land occupation, urban land occupation, natural land transformation, marine ecotoxicity, freshwater eutrophication, marine eutrophication and freshwater ecotoxicity. Poly-Si had the highest contribution compared to other solar modules because it has the highest amount of metal ions, organic halogen and organic carbon emission to water and air compared to other modules. CdTe has the lowest contribution as it only has a low amount of cadmium emission to air and water.

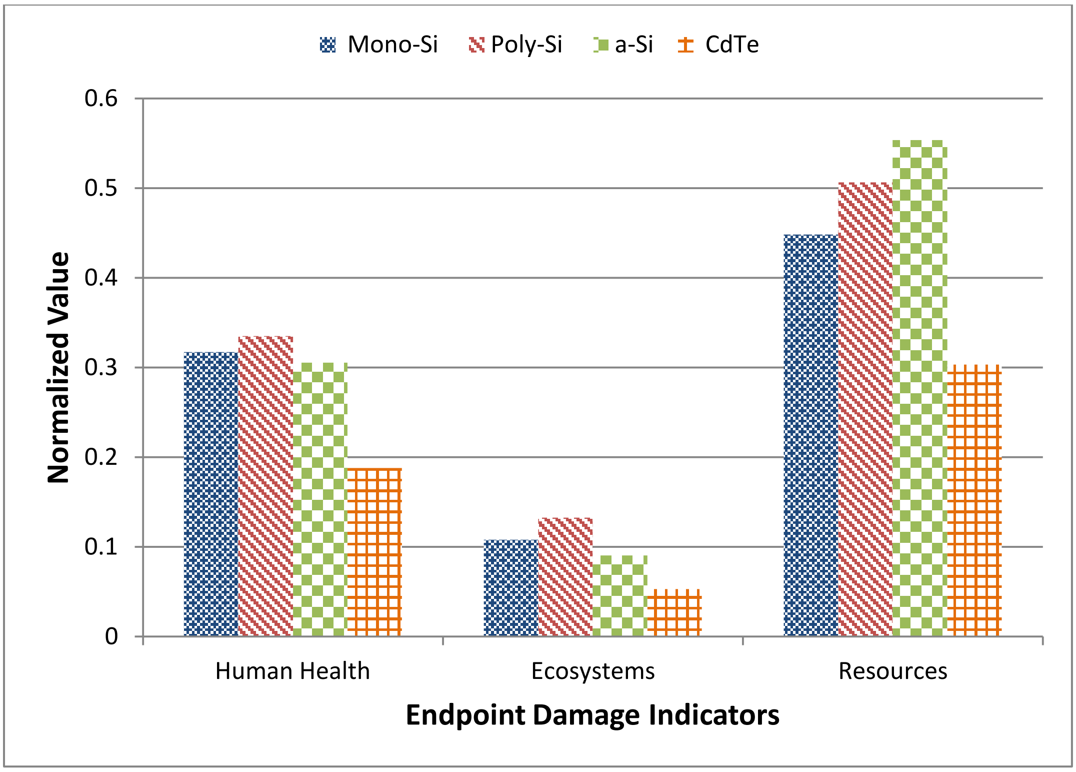

Figure 33: Solar Module Comparison for Normalised Endpoint Damage Indicator

c) Single Score

For single score the solar modules were assessed in 3 types of perspective which are hierarchist, individualist and egalitarian. These perspectives actually represent a set of choices on issues like time or expectations on proper management or future technology development that can avoid future damages. The first one is hierarchist perspective which is the most common policy principles with regards to time-frame and other issues.

Figure 34 shows the graph for solar module single score comparison based on hierarchist perspective. Based on hierarchist perspective, Poly-Si solar module has the highest score of 288 Pt which is the summation of the damage scores where the damage towards human health has an indicator score of 134 Pt, damage towards ecosystem has the score of 53 Pt and the damage towards resource has a score of 101 Pt. The solar module with the lowest single score value is CdTe module with a score of 157 Pt which that summation of the damage scores where the damage towards human health has an indicator score of 75.2 Pt, damage towards ecosystem has the score of 21.2 Pt and the damage towards resource has a score of 60.6 Pt.

As it can be seen from Figure 32, Poly-Si has the highest score compared to other solar modules which shows that Poly-Si has the highest environmental impact compared to Mono-Si, a-Si and CdTe. This is because hierarchist perspective which has an intermediate time frame and follows the most common principles which considers human health damage more compared to ecosystem damage and resource depletion. Poly-Si has high emission of metals and gases to the atmosphere which increases the damage of the solar module towards human health. This causes Poly-Si to be the least environmental friendly solar module based on hierarchist perspective. On the other hand, CdTe has the lowest score compared to other solar modules which makes it the most environmental friendly solar module based on hierarchist perspective. This is because CdTe has a low number and amount of emission substance compared to other solar modules. This causes CdTe to have a small impact on human health damage which reduces the overall score of the module.

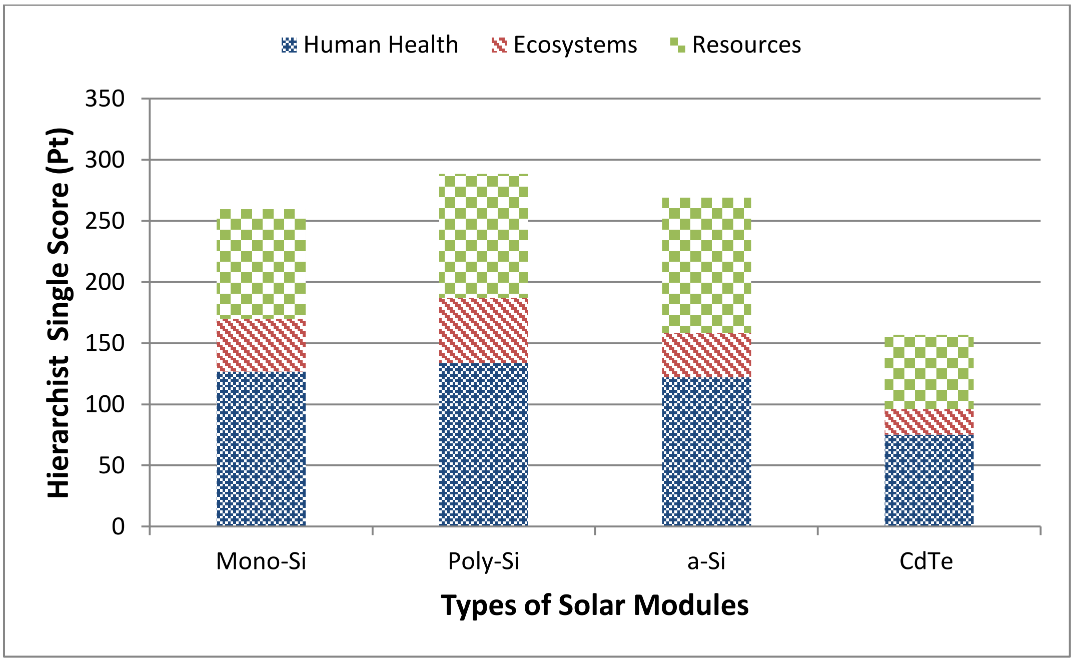

Figure 34: Solar Module Comparison for Single Score based on Hierarchist Perspective

Figure 35 shows the graph for solar module single score comparison based on individualist perspective. Individualist is based on short-term interest, impact types that are undisputed, technological optimism as regards human adaptation. Based on individualist perspective, a-Si solar module has the highest score of 295.3 Pt. The single score is the summation of the damage scores where the damage towards human health has an indicator score of 75.4 Pt, damage towards ecosystem has the score of 36.5 Pt and the damage towards resource has a score of 183.4 Pt. CdTe solar module has the lowest score of 159.2 Pt which was the summation of the damage scores where the damage towards human health has an indicator score of 43.7 Pt, damage towards ecosystem has the score of 21.5 Pt and the damage towards resource has a score of 94 Pt.

For individualist perspective where it only considers a short time frame, a-Si solar module has the highest score which shows that this solar module has the highest environmental impact compared to other solar modules. Individualist perspective focuses more on the damage towards resource. Even though a-Si has a lower number of materials or emission used in the inventory compared to Poly-Si and Mono-Si, the area of a-Si module required to produce 1 kW power is higher compared to Poly-Si and Mono-Si which makes the amount of resource materials like metal and fossil fuel used to be higher than other modules. This causes a-Si to be the least environmental friendly solar module in terms of individualist perspective. It can be also seen from the figure that CdTe has the lowest score among all which makes it the most environmental friendly solar module based on individualist perspective. This is because CdTe has a small contribution towards resource depletion which makes the overall score for CdTe to be lower than other modules. CdTe only uses a small amount of metal and natural gas as fuel to be manufactured.

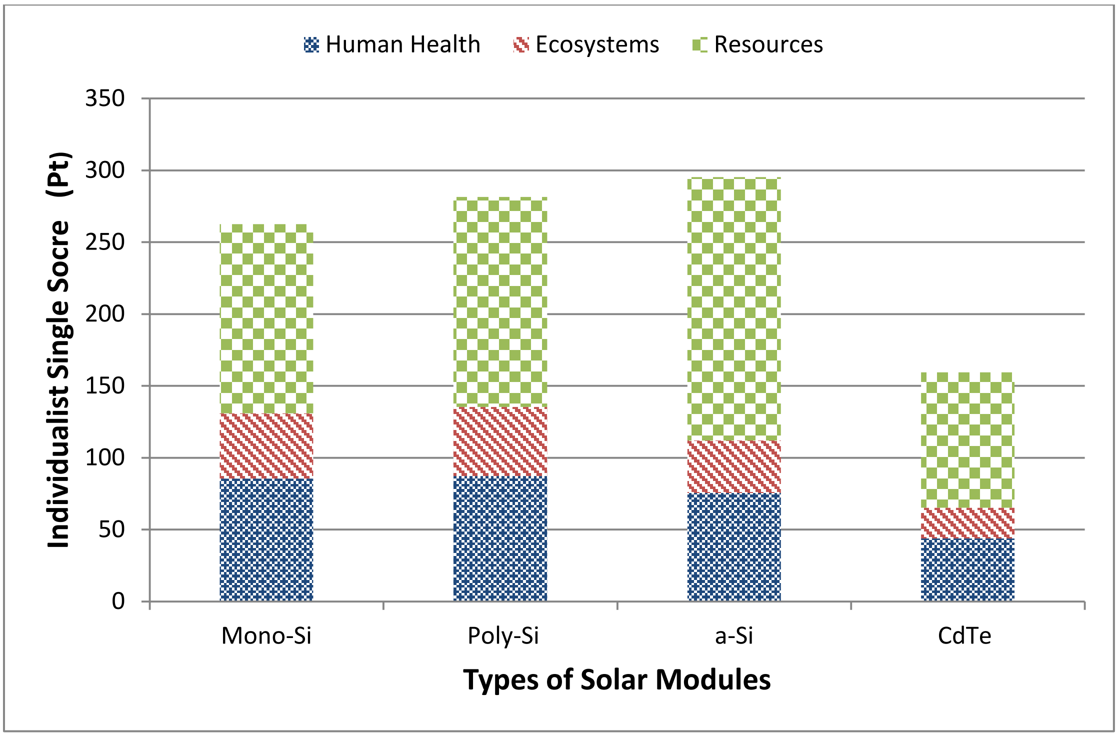

Figure 35: Solar Module Comparison for Single Score based on Individualist Perspective

Lastly is egalitarian perspective which is the most precautionary perspective which takes into account the longest time-frame. Figure 36 shows the graph for solar module single score comparison based on egalitarian perspective. For egalitarian perspective, a-Si has the highest score of score of 1.184 kPt. The score for damage towards human health is 0.9745 kPt, damage towards ecosystem has the score of 0.099 kPt and the damage towards resource has a score of 0.1107 kPt. CdTe has the lowest total score of 0.794 kPt where the score for damage towards human health is 0.675 kPt, damage towards ecosystem has the score of 0.584 kPt and the damage towards resource has a score of 0.606 kPt. This shows that as the time frame increases, the production of solar module would cause a higher damage towards human health.

According to egalitarian perspective where it considers the longest time frame, a-Si is the least environmental friendly solar module compared to Poly-Si, Mono-Si and CdTe. The egalitarian perspective focuses highly on the damage on human health. This is because as the time frame increases, the emission of hazardous gases and metallic component to water and atmospheric will first have adverse effect towards ecosystem which will eventually affect human health as well. In order to produce 1 kW power, a-Si has the largest module and mounting area compared to other solar modules which causes an increase in the amount of substances released to the environment. This will then lead towards the damage towards human health in future which causes the overall score to increase significantly. This makes a-Si to be the least environmental friendly solar module in terms of egalitarian perspective. The figure also shows that CdTe has lowest score which means that CdTe is the most environmental friendly solar module in terms of egalitarian perspective. The reason is because the manufacturing process has lower impact on human health compared to other modules where only small amount of cadmium are emitted to the atmosphere. This makes CdTe less dangerous to the environment and human population in long term perspective.

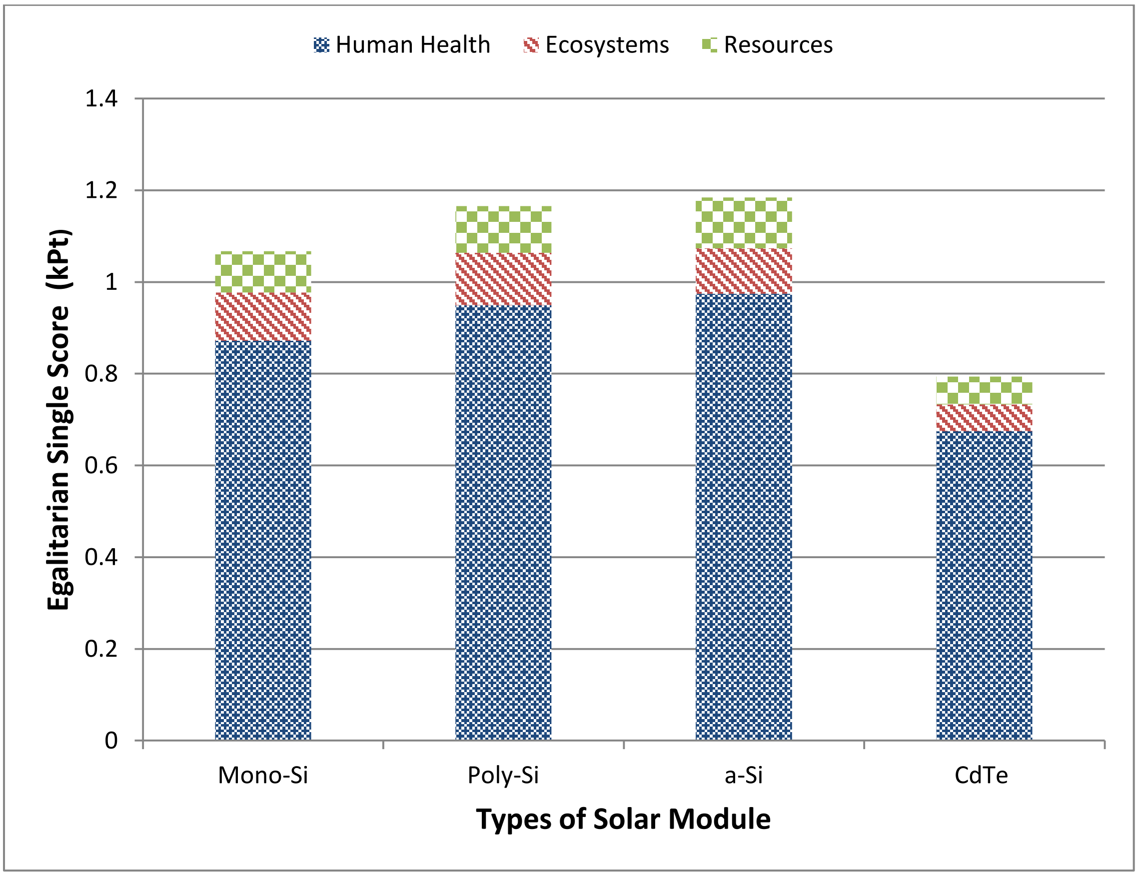

Figure 36: Solar Module Comparison for Single Score based on Egalitarian Perspective

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

As a conclusion, this project has fulfilled its objectives which are to use ReCiPe method to conduct life cycle assessment (LCA) on solar modules and to come up with a solar module that has the least impact on the environment. Solar module is becoming one of the most efficient types of renewable energy and has a promising future in the energy industry. This shows that it is important that the solar module used does not have any major effect on the environment which would lead to greater problems in future.

This project conducted LCA on 4 types of solar modules which are mono-crystalline silicon (Mono-Si), poly-crystalline silicon (Poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe) where their impact to the environment were addressed. Besides that, the materials or emissions in the inventory that lead to the environmental impacts were also addressed. This analysis can help to guide the decision making process of solar modules companies in determining the process or material that should be used to manufacture a solar module. This analysis can also help them to understand the effect of each process or material towards the environment.

From the LCA, cadmium telluride (CdTe) solar module was chosen as the module with the least impact on the environment. The LCA shows 3 types of results which are midpoint indicators, endpoint damage indicators and single score. In all 3 results, CdTe had the least impact to the environment and human population. Besides that, the modules were also analysed in different time frame or perspective and CdTe proved to have least environmental impact regardless of short term usage or long term usage. This makes CdTe the most environmental friendly solar module compared to Mono-Si, Poly-Si and a-Si. Furthermore, CdTe solar module is also less expensive compared to crystalline silicon module as it is a thin film module which requires less material to be manufactured compared to crystalline silicon solar modules.

Even though CdTe solar module is more environmental friendly and less expensive, crystalline silicon solar modules are still the most popular type of solar modules used in industrial and domestic sector. The reason is because crystalline silicon solar module has a higher efficiency compared to thin film solar module like CdTe. This means that crystalline silicon solar module like Mono-Si and Poly-Si produces more power per unit area compared to CdTe solar module which makes it more preferable for power generating industries and domestic users.

For future recommendations, the photovoltaic production companies should try to increase the power generating efficiency of CdTe so that they would be more appealing to the consumers as CdTe is less expensive and more environmental friendly. In terms of project recommendation, life-cycle assessment research should be done on solar cells by increasing the scope of study to other types of solar cells. Besides that, it is recommended that the result of this research is used to come up with new innovations like implementing the CdTe solar module on solar-powered cars which would promote the development of green technology.

CHAPTER 6

REFERENCES

1. Acero A. P, Rodriguez C. & Ciroth A. (2014). *'LCIA Methods: Impact Assessment Methods in Life Cycle Assessment and Their Impact Categories'*. Green Delta.

2. '*Typical PV System Components*'. (2014). Solar Direct. Retrieved June, 13, 2014 from http://www.solardirect.com/pv/pvbasics/pvbasics.htm.

3. Bekkelund K. (2013). '*A comparative life cycle assessment of PV solar systems*'. Norwegian University of Science and Technology.

4. Cherrak M. &Kirci M. (2012). *'Comparison of Different Photovoltaic Modules within the Framework of a Technical and Cultural Project'*. Design Project – SIE.

5. Jungbluth N, Stucki M, Flury K, Frischknecht R. & Busser S. (2012). *'Life Cycle Inventories of Photovoltaics*'. ESU-Service Ltd.

6. Budavari Z, Brown N, Peuportier B, Zabalza I, Krigsvoll G, Wetzel C, Cai X & Staller H. (2011). *'Indicators and Weighing Systems Including Normalisation of Environmental Profiles'*. LoRe-LCA.

7. Fthenakis V.M. & Kim H.C. (2011). *'Photovoltaics: Life – cycle Analyses'*. Science Direct.

8. Fthenakis V, Kim H. C, Frischknecht R, Raugei M, Sinha P & Stucki M. (2011). *'Life Cycle Inventories and Life Cycle Assessment of Photovoltaic System'*. IEA International Energy Agency.

9. *'How a Photovoltaic Cell Works'*. (2011). The NEED Project. 43.

10. Bengtsson J. & Howard N. (2010). *'A Life Cycle Assessment Part 1: Classification and Characterisation'*.

11. Chamsilpa M. & Tanongkiat K. (2010). *'Life Cycle Assessment of Amorphous Silicon Solar Cell Power Plant Using Activity-Based Approach'*. International Journal of Renewable Energy.

12. Sherwani A. F, Usmani J. A &Varun. (2010). '*Life Cycle Assessment of Solar PV Based Electricity Generation System: A Review'.* Renewable and Sustainable Energy Reviews.

13. Goedkoop M, Heijungs R, Huijbrefts M, Schryver A D, Struijs J and Zelm R. V. (2009). *'A Life Cycle Impact Assessment Method With Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level'*. ReCiPe 2008.

14. Williams A. S. (2009). *'Life Cycle Analysis: A Step by Step Approach'*. ISTC Reports. University of Illinois.

15. Bertolli M. (2008). *'Solar Cell Materials'*. University of Tennessee. Spring.

16. Stoppato A. (2008). *'Life Cycle Assessment of Photovoltaic Electricity Generation'*. Science Direct. 224-232.

17. Stubbs R. (2008). *'Basics of Solar Power'*. Solar Power Answers. Retrieved June, 6, 2014 from http://www.solar-power-answers.co.uk/basics.php.

18. Fthenakis V.M. & Kim H.C. (2007). *'Greenhouse-Gas Emission from Solar Electric and Nuclear Power: A Life-Cycle Study'*. Energy Policies. 2549-2557.

19. Fthenakis V. M. (2004). *'Life Cycle Impact Analysis of Cadmium in CdTe PV Production'*. Renewable and Sustainable Energy Reviews. 303-334.

20. Rebitzer G, Ekvall T, Frischknecth R, Hunkeler D, Noris G, Rydberg T, Schmidt W. P, Suh S, Weidema B. P & Pennington D. W. (2004). *'Life Cycle Assessment Part 1: Framework, Goal and Scope Definition, Inventory Analysis and Applications'.* Environment International. 701-720.

21. FSEC PVDG Division. (2003). *'Grid-connected Photovoltaic System Design Review and Approval'*. Florida Solar Energy Centre. University of Central Florida.

22. Duda M. & Shaw J. S. (n.d). *'Life Cycle Assessment'*. Social Science and Public Policy. 39-43.

23. Glunz S. W, Preu R. & Biro D. (n.d). *'Chapter 1.16: Crystalline Silicon Solar Cell – State Of The Art and Future Development'*. Fraunhofer Institute of Solar Energy System.

24. *'What is Life Cycle Assessment?*'.Quantis Sustainability Counts. Retrieved June, 6, 2014 from http://www.quantis-intl.com/life_cycle_assessment.php.