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FACULTY OF TECHNOLOGY

LIFE CYCLE ASSESSMENT OF GROUND MOUNTED PHOTOVOLTAIC PANELS

LINH TRAN

ENVIRONMENTAL ENGINEERING

Master's thesis

July, 2019

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Prof. Tobias Viere
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Dr. Jean Nicolas Louis

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ABSTRACT FOR THESIS

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Abstract

Nowadays, the problem of carbon emission attracts a lot of attention from people in the world. To solve this problem, many solutions are proposed to get the target of Greenhouse Gas emission reduction. Among of all, the increase of the share of renewable energy is known as a feasible and promising approach for achieving this goal. Solar power and wind power is considered as two dominant renewable sources having a significant contribution to the power generation as well as reducing CO_2 emissions. In this study, ground mounted photovoltaic plant is taken as a approach for achieving this target.

The objective of the study was to answer three research questions: (1) What are the life-cycle environmental impacts of ground-mounted photovoltaic (GMPV) systems; (2) What are the missing data to perform life cycle assessment (LCA) of GMPV? and (3)What are the future development projections for GMPV and how would they impact on their LCA? Furthermore, the state of the art of GMPV technology is also reviewed.

The thesis is based on the data of Ecoinvent v3.3, available in open LCA, associating with six cases studies on GMPV, will give an evaluation about the state of the art of technology, the data gap of GMPV in Ecoinvent v3.3. The LCA method is known as a quantitative approach which is utilized to make an evaluation of whole process of a product. The four steps of LCA are goal and scope definition, inventory analysis, impact assessment and interpretation

Based on the six case studies from literature, the data gaps were recognized regarding the power output, number of modules, performance module and degradation rate, and the materials in the mounting system. These data gaps are very important because they have the significant impacts on the implementation of LCA approach. If these data gaps were filled, operators would be likely to have a more precise evaluation of GMPV systems.

It was concluded that multicrystalline silicon module is the commercially available material with highest efficiency but, because of their high cost, the development is shifted towards CdTe thin film materials. CdTe thin film is gradually proving its position in the photovoltaic (PV) commercial market because of growing efficiency and reasonable cost, which are very important when applying in the large scale of GMPV systems. Finally, it was suggested that the third generation technology, which is the combination between Generation I technology and Generation II technology with the feature of high efficiency and reasonable cost, has the highest potential for applying in utility scale PV systems.

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Also, from bottom of my heart, I extremely would like to pay my gratitude for the collaboration between University of Oulu and Pforzheim University to give me the opportunity to join in the project InNoGys and partly make a contribution to the project.

Last but not least, I would like to say thankful my parents and especially my brother, who is beside me when I was in trouble in the time of doing Master thesis, always encouraged me, motivated me to keep moving forward and no giving up to achieve the thesis completion.

I am really happy when finally I can complete this topic thesis despite the difficulties and sometimes I used to have a thought of giving up. However, finally I am also proud for what I did.

July 23rd 2019, Oulu My Linh Tran

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ABBREVIATIONS AND DEFINITIONS

BOS	Balance of System
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
EPBT	Energy Payback Time
EU	European Union
FU	Functional Unit
GHG	Green House Gas
GW	Gigawatt
GWP	Global Warming Potential
GMPV	Ground mounted photovoltaic
IEA	International Energy Agency
NREL	National Renewable Energy Laboratory
LSRE	Large Scale Renewable Energy
LCA	Life cycle assessment
PV	Photovoltaic
kWp	kilowatt peak

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1. Introduction

1.1. Background

Nowadays, the problem of CO_2 emission along with the demand of electricity is attracting a lot of attention and discussion from many countries. All members in European Unions are on the pathway of action for getting the target of 2050 about cutting 80-95% greenhouse gas emission comparing with the level in 1990 (European Commission 2012). To achieve the goal of successful energy transition, the report of IRENA (2018a) determined six core areas that decision makers should focus on. The first is cooperating between renewable energy and the energy efficiency. Secondly, expanding the share of renewable energy in electricity generation. Then, improving electrification for vehicles in transportation, heating system in building and industry, but still underway finding more feasible renewable approaches such as geothermal, bioenergy, solar thermal align with the practice of policy framework. The following goal is relating to invest in the technology innovation and research which significantly contributes to reach the higher efficiency of energy yet still be cost-effective. Besides of technology, the establishment a solid structure of socio-economy and fostering the investment in energy transition is also highly required. Last but not least, it is essential to even between the gaining and cost for energy transition.

Taking insight into the state of CO_2 emission in recent years, in 2016, the emission of CO_2 reached 32.31 Gt, of which Asia reached the highest emission level of 17. 43 Gt CO_2 emission, three times higher compared to the level of the emission in 1990 (IEA 2019). In contrast, the trend of CO_2 emission from 2016 in European Unions (EU) tended to decrease to 5 Gt CO_2. The reason for the curtailment of CO_2 emission is the expansion from the share of renewable energy in various different sectors, especially in electricity generation. Furthermore, currently, all members in EU are on the way to shift to the natural gas combustion instead coal burning for power generation (IRENA 2018). According to IEA (2019) in Europe, the sector of electricity and heat accounted for the largest part of CO_2 emission with the amount of 2.09 Gt. To curb the CO_2 emission from the main emission source, in Roadmap 2050, it is indicated that the main pillar for getting the optimal solution of 90% GHG emission will come from renewable energy and energy efficiency (European Commission 2012). Renewable energy will not only participate in power generation, but it also engages in different sectors including the energy used in buildings, industry and transportation.

Apparently can be seen that, standing at the edge of natural resources depletion caused by over-extraction for industry, land corruption for building, tourism and even for transportation, it is highly required to find a good approach to prevent the discharge of GHG from these activities and figure out the other alternative resources instead of fuel combustion.

The success of energy transition in power sector is achieved essentially depending on the share of renewable energy with the expected growth three times higher from 2017 to 2050 (25% to 85%), especially with the contribution from solar and wind energy generation (IRENA 2018).

Traditionally, most of the electricity model in many countries stays at the form of fuel combustion for electricity generation. However, due to the high emission level of carbon dioxide, many countries in EU decided to change the electricity model to decarbonization with the focus on lowering fossil fuel and increase the share of renewable energy. The role of renewable energy is also involved to reduce the dependence of import electricity also the fuel especially oil and gas in EU. The high import of energy from foreign countries urged EU countries to take action in the integration of renewable energy into the directive policies through year by year since 2001. The increasing of use renewable energy in EU countries witnessed a significant progress with the remarkable development in 10 years since 2007 in renewable energy generation about 64%. Taking the leading position belongs to wood and solid-biofuel with the share of 42% of primary production. Meanwhile, the solar energy occupied for 6.7% of primary production (European Commission 2019). In conclusion, the diminishing of energy import and self-develop electricity production by integrating the role of renewable energy will be considered as feasible approaches for security of energy supply.

Concerning about the renewable energy in electricity generation, two types of renewable energy sources should be taken to account for including photovoltaic and wind power generation with the target of raising electricity from 25% in 2017 to 85% by 2050 (IRENA, 2018). In 2016, renewable energy electricity accounted for more than a half of final energy consumption with the largest share of hydropower (36%) meanwhile solar power only occupied 11% (EEA, 2018). However, the year of 2017 witnessed the dramatic growth of cumulative installed capacity from global PV solar panels with the addition 100 GW of new installed capacity, resulting in the price drop from $4 per Watt in 2007 to only 0.35 $ per Watt in 2017, even if comparing with the period of 2008-2013 then this price is reduced up to two-third in the power market such as Germany and Italy. It can be assured that PV currently dominate the renewable energy market about the installed capacity also the competitive price. For wind power, there is a significant increase of 47 GW whereas offshore wind power takes account for 4 GW (IRENA, 2018a).

1.2. Aim of the thesis

In this thesis, as the target is researching about the life cycle assessment studies of ground mounted photovoltaics plants so, it is essential to have a detail at utility scale of photovoltaics installation. First of all, take a look at the large scale of renewable energy definition. Large scale of renewable energy (LSRE) are known as utility scale renewable energy. Normally, the installed capacity of LSRE is from megawatts to million megawatts. The role of large scale of renewable energy often contributes to make higher amount of electricity loading into grid. Furthermore, it is highly cost-effective because of the size of utility scale, the wholesale price for installation or the marginal cost for production such as buying the materials or machines will be significantly lower, resulting in the electricity price provided for consumer will be much cheaper competitive with the price for small scale system (World Resource Institute 2019)**.** The LSRE projects often refers to the energy sources which have ability to provide a huge amount of electricity for an utility and receive the subsidy and support from government, some typical LSRE systems inclusive to solar farm, wind farm or hydropower.

Regarding large scale of PV panel, it is defined as a huge collection of ground mounted solar arrays with the role of supply electricity for a large community in an area. The minimum requirement capacity for the large scale photovoltaic is at least of 1 MW. Although concerning about the share of PV power production, the type of small-scale system (< 3 kWp) dominates the large scale system, but the expansion of installations utility scale PV panels in market still take the leading position (Beylot, Payet, Puech, Adra, Jacquin, Blanc, and Beloin-Saint-Pierre 2014). The installation of PV panels in large scale is considered as an environmental-friendly, economic beneficial and high energy efficiency. However, to achieve the goal of tracking the depletion of CO_2 emission, it is necessary to have a method to assess the whole-life cycle of photovoltaic ground mounted process. In this project, the goal is focusing on the data collection of Life Cycle Assessment (LCA) about ground mounted PV detail in installation phase and take account for the efficiency from each types of PV materials.

LCA is generally known as a common method for environmental assessment of the whole process of a specific product starting from basic stages of material mining, assembly of components until the last stage of end-life product. In the LCA implementation, it is required to carry out four steps: identifying the goal and scope of the product assessment, the second step is named as life cycle inventory relating to have a determination of system boundary of product, input and output flows for the process of production. The following step is life cycle environmental assessment, which is inclusive about environmental indicators. This indicators will be evaluated basing on the normalization and weighting. The last step is data interpretation. In general, the process of ground mounted photovoltaic life cycle assessment starts from material extraction, material processing such as purification, production phase, application and operation phase, deactivate components, landfill or recycling phase (Brandon Kiger 2016). There are two main benefits from using LCA approach for ground mounted photovoltaic. The first benefit is through the support of LCA method, there will be the solution for system optimization concerning several specific aspects of economy, environment, CO_2 emission and other relevant factors. For the other benefit of LCA in photovoltaic is making evaluation of the state of the art of technologies about performance of different materials, types of installation or electricity generation technologies (Ito 2011). In this study, the LCA method will primarily concentrate on making comparision of GMPV technologies especially relevant to installation phase.

The study also concentrates on the specific research questions:

- What are the life-cycle environmental impacts of ground-mounted photovoltaic (GMPV) systems

- What are the missing data to perform life cycle assessment (LCA) of GMPV?
- What are the future development projections for GMPV and how would they impact on their LCA? (focus on potential technology development)

1.3. Structure of the thesis

The thesis is organized into the consistent outline with five main parts: introduction, theoretical part, experimental part, conclusion and the last reference. The introduction includes two subsection with the first subsection for the purpose of thesis and the second section is for the outline of thesis. In the first section, there is an overview of current state of CO_2 emission in European countries, since then, through the roadmap of 2050 goals , the increase of renewable energy share to get the target of GHG emission reduction is one of the most promising and feasible solution. Photovoltaic instllation is mentioned with the primary role of contribution to the elevation of renewable energy share. The approach life cycle assessment of photovoltaic is also reviewed in general and the advantage that LCA method in this study is indicated to make comparision between literature studies about state of the art of technology and also the data gaps of this.

In the theoretical part, there are two large parts for reviewing about the photovoltaic with first about photovoltaic effect and second about photovoltaic system. In the photovoltaic system, it is divided in to two categories including photovoltaic part and balance of system part which is mostly associated with the support structure and electric devices.

Also in the theoretical part, the method applied in this study is also reviewed with the general framework of the method and stages to make a whole implementation of LCA.

The thirst part is experimental section. This section includes the description of project InNOSys, target of the experimental part, state of the art of GMPV technology, LCA of ground mounted system and the last is result and discussion. Concerning about the part of LCA for GMPV, two main section should be taken into account including source of data from ecoinvent and from literature articles. The second is about the state of the art of GMPV, which can be assured from the review of six case studies in the data table.

The part of result and discussion will point out the data gaps from the available data in the Ecoinvent v3.3 with the external case studies from artiles. Since then, giving the evaluation of the GMPV development in technology and the role of this development to the LCA of GMPV.

The ninth part is giving the conclusion for whole of thesis. The tenth part is the references.

THEORETICAL PART

2. Photovoltaic effect

Photovoltaic is known as the technique used to directly convert light from the sun to the electricity: DC current in watt or kilowatt in the semiconductor material (Luque and Hegedus 2011). The PV cells or solar cells have the common of denominator is p-n junction where the photovoltaic effect happens. Most of PV cells are made from silicon, thin film technology (Kreith and Goswami 2007). These materials are capable to take the energy that comes from the sun under the form of photons and convert them to different kind of energy, which is known as electricity. The electricity is produced in the solar cells by the movement of free electrons in the valance band to the conduction band. When receiving high temperature or energy from sunlight, these covalent bonds between electrons will be broken. These electrons will move away from each other under the impact of electric field. The electrons receiving the higher energy than the amount of energy inside them, will leave the valence band and create holes in which has the positive charge. The liberated electrons will move out of the atom and there is a moving-in from another neighboring electron to fill the positive hole. Thus, the movement of electrons will create electricity current.

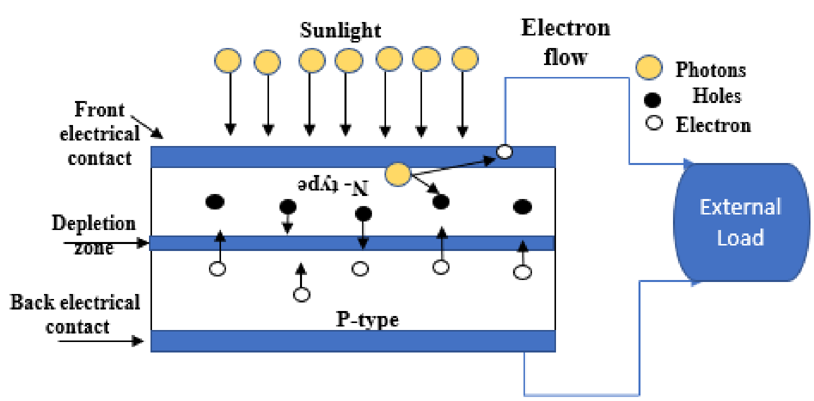

Figure 1 Photovoltaic effect (based on (Solar energy at home 2019))

The apparent advantage of solar cell is no requirement of high temperature for operation because photon absorption from direct sunlight will keep the solar cell warmer than the normal atmosphere temperature (Luque and Hegedus 2011).

3. Photovoltaic system

The system of photovoltaic components generally consists of two main parts: photovoltaic arrays and balance of system (BOS). Photovoltaic array is characterized by the basic units starting from solar cells in which the photovoltaic effect occurs, until the photovoltaic panel, and the last is photovoltaic arrays. In general, the main process of light conversion to electricity happens in solar cells, however, due to the high demand of electricity from residential also from community, thus, it is highly required to aggregate more power by connecting solar cells in series to make PV panels. These PV panels become main contributors for PV arrays in generating sufficient power for whole area.

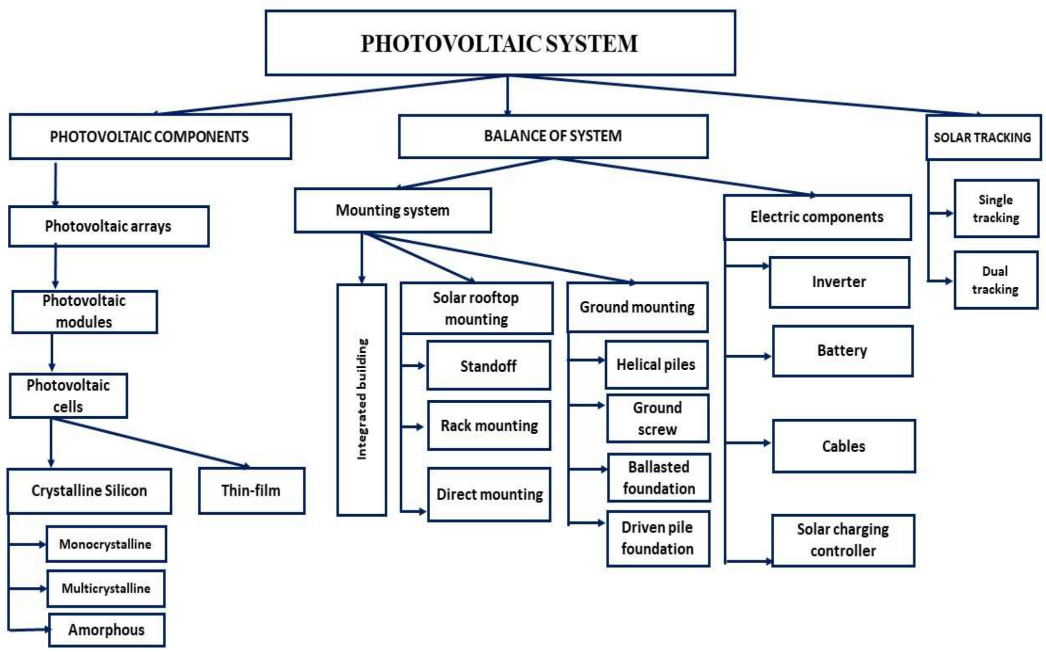

Figure 2 Scheme of photovoltaic system components

Another part which is known as high cost consumption in the solar system is balance of system (BOS). This subsystem consists of some electrical components such as cables, inverters, system controller, battery, electric meters and supporting materials consisting racking, frames, other different components.

3.1. Photovoltaic arrays

For the sake of providing a large amount of electricity for big communities or whole country, one solar cell or even one solar module is not sufficient. Thus, to achieve this goal, it is required to connect a significant number of solar cells to each other to create bigger photovoltaic modules or photovoltaic panels (Tiwari and Dubey 2010). These modules are assembled together to make photovoltaic arrays, which have ability to provide sufficient energy for the demands of a specific area. The power that solar panel produce is measured in watts of peak power (Wp). Thus, the power unit for a solar array is calculated in the total of watts peak from all of modules which constitutes to those arrays (Luque and Hegedus 2011). It also leads to that if taking consideration for a whole photovoltaic system, the power that can be totally delivered from the sunlight will be measured in kilowatts peak (kWp). Depending on the size of the system that there will be increase from some kWp in the scale of residential to several gigawatts peak in utility scale (Parida et al. 2011). Regarding about the materials of photovoltaic, most of photovoltaic cells are currently made from the crystalline silicon because of their economic and energy efficiency. There is an estimation that the dominance of standard silicon materials accounts for 80% in PV market, meanwhile this number for thin-film silicon is 5% and 6% for CdTe material (Tyagi et al. 2013)

3.2. Photovoltaic modules

Photovoltaic module is the connection of solar cells together to achieve the higher voltage for the system. The connection of solar cells can be ensembled in parallel or series depending on the required current value or voltage of system. The types of photovoltaic module are categorized basing on the types of solar cells including: crystalline silicon PV module (single crystalline silicon PV module and polycrystalline silicon PV module), amorphous PV module, thin-film solar modules. In general, the features of photovoltaic modules will be defined by the types of solar cells constituted that module. The common number of solar cell for each module ranges from 30 -36 solar cells with the voltage of each cell can be up 0.5V. Depending on number of cells that the voltage will be 15V use for charging 12-V battery without controller and the type of 18V will need a controller to avoid overcharging (Tiwari and Dubey 2010).

3.3. Photovoltaic cells

3.3.1. Production

Photovoltaic cells are the basic units of photovoltaic system, in which there is an occurrence of photovoltaic effect, converting sunlight to electricity. The material used for solar cells production are various however basing on the energy efficiency as well as the prevailing material, silicon is used as the dominant material for solar cell production (Bruton 2002, Blakers et al. 2013). The process of producing cell starts from obtaining metallurgical silicon (Metallurgical Grade), then the next steps are relating to purification of MG-Si. The degree of purity of polysilicon, which is used for solar cells, should reach 99.999% and determined as Solar Grade Silicon (SG-Si). The MG-Si will be underway the Siemen process in which MG-Si will react with HCL at high temperature with the participation of catalyst to form trichlorosilane ($HSiCl_3$). Trichlorosilane will be distilled to remove impurities and also decomposed at high temperature to have purely silicon. In this process, a significant amount of energy is consumed (Mertens 2018).

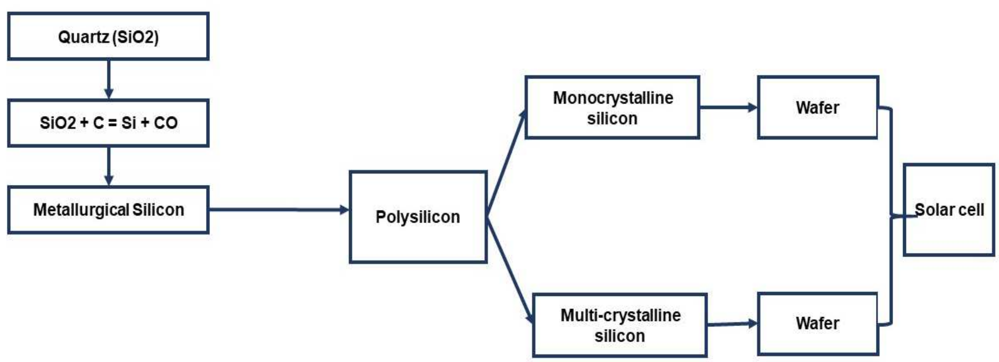

Figure 3 Process of crystalline silicon production (bases on (Mertens 2018))

To produce monocrystalline silicon, the conventional method is Czochralski process (Tyagi et al. 2013, Mertens 2018). This method includes the step of melting the polysilicon in a crucible at the elevated temperature and then, a seed crystal introduced into the melt silicon. There is a gradual growth of this seed in the melted silicon. When the crystal grows to a specific shape, the rod will be pulled upward in rotation (Halbleiter.org 2019). To doping the silicon, a little amount of boron or phosphorous atoms will be added into melt silicon (Tyagi et al. 2013). For the multi-crystalline silicon, the production method is simpler but the efficiency of multi-crystalline silicon material is not as good as the single silicon. The polycrystalline silicon is manufactured from the cast square ingots. This process is basing on the growing a crystalline seed in a crucible. The process starts from melting the raw polysilicon at high elevated temperature, nucleation crystalline silicon seed from the melted silicon, the development of crystalline seed in crucible and the final step is solidification (Zhang et al. 2015). The directional solidification cast technology is evaluated as the popular and low cost method for mc-silicon production (Chen and Dai 2012).

3.3.2. Types of photovoltaic cells

Regarding about the types of photovoltaic cell, it is divided into two main types including crystalline silicon cell and thin-film cell. Most of crystalline silicon material is used for PV module production, accounting for 80 - 90% the global PV market comparing with any other materials in last decade (Glunz et al. 2012). It is divided into two board categories including monocrystalline silicon cell and multi-crystalline silicon cell.

Monocrystalline silicon cell has some highlight characteristics such as free of grain boundaries, high purity, thus the ability of light conversion to electricity is more efficient than any other material (Energysage.com 2019). However, the disadvantage of this material is about the indirect bandgap of silicon, which results in the burden for contacting of electron hole pair comparing with the direct bandgap in thin-film CdTe (Irvine 2017). Due to this drawback, solar cell production from monocrystalline will require a thick wafer of silicon and not much economic though the conversion efficiency of a monocrystalline silicon is ranging from 14% to 25% until 2015 and this number is expected to reach about 26% in 2020 (NREL 2019a).

Multi-crystalline silicon cell is more cost beneficial than single crystalline cell because the method of production is much simpler, no requiring as much material as monocrystalline silicon but the light conversion efficiency is lower affected by the grain boundaries. Grain boundary is the interface between two grains in the polycrystalline silicon and this boundary forms the defect of the material, create the obstacles in the electricity conductivity. According to NREL 2019, the conversion efficiency of mc-Si is about 22.3% so far.

With the high efficient performance of crystalline silicon cell, it is widely applied for the utility scale photovoltaic plants (IRENA 2012). Normally, c-Si cell is much more efficient though the price is higher (IFC 2015). The degradation rate of crystalline silicon module also influent on their lifetime and the process of maintenance. The mono-crystalline silicon system has the longer energy payback time (EPBT) and higher GHG emission rate than multi-crystalline silicon system. Depending on the conditions such as solar irradiation, types of installation, modules size, the life time of mono-Si PV system ranges from 20 – 30 years such as mono-Si PV system under the irradiation of 1117 kWh/m^2/year in Switzerland, the EPBT is 3.3 years (Jungbluth et al. 2011). The common EPBT of mono-Si PV system ranges from 1.7 -2.7 years and GHG emission rate from 29 to 45g CO_2 g eq./kW h (Peng et al. 2013). Meanwhile, the value of EPBT of multi-Si PV system in South European under the irradiation of 1700 kWh/m^2/year is 3.2 years with the GHG emission rate of 60g CO_2-eq./kWh (Alsema 2000). Another case study in China with the solar irradiation of 1702 kWh/m^2/year, the EPBT for multi-Si PV system and GHG emission rate are 2 years and 43 g CO_2-eq./kWh respectively. These values are shorter than in mono-Si PV system with the EPBT of 2.5 years and GHG emission rate of 50g CO_2-eq./kWh (Ito et al. 2010). It is preferable to use multi-crystalline silicon panels for the cost benefit and environmental issue reduction.

Thin film solar cells are the second-generation solar cell which are produced from the deposition of a micron-thick semiconductor material with two main raw materials including SiH4 and H_2 on the low-cost substrate such as glass, metal or plastic (Messenger and Mcconnell 2007). The characteristic of thin-film is flexible and light weight. Thin-film solar cells are currently having three types including amorphous silicon thin film, Cadmium Telluride (CdTe) thin film and Copper Indium Gallium Selenide (CIGS) solar cells currently commercially applied in the most of PV panels installation (Bagher et al. 2015).

Amorphous silicon thin film is known as the oldest thin film, which is known as non-crystalline material. This material is made from vapor depositing a thin layer of silicon about 1 micro-meter on the surface of inexpensive materials such as glass, stainless steel, or plastic (Bagher et al. 2015). The advantages of this material are no requiring much silicon as crystalline silicon material, substrate material is cheap, very flexible and lightweight. Because there is dangling bonding in the structure of amorphous solar cell, thus, this material not allows the doping other material on that. To get higher solar collection performance, the Si in this solar cell can be alloyed with Ge, C and N in glow discharge evaporator (Irvine 2017).

CdTe thin film solar cell is produced from the light absorbing semiconductor material called cadmium telluride. It has direct bandgap semiconductor with the energy level of bandgap about 1.5eV (Energy.gov 2019). The bandgap energy is the minimum energy to excite electron break their bound to be liberated and moving to the conduction band. The bandgap also points out the energy required for electron excitation and energy for electric generation (PVEDUCATION 2019a). Thanks to the bandgap energy level, CdTe leads the highest position of thin-film technology of energy efficiency because it is likely to capture almost visible light ranging from $10^4 \div 10^5$ cm^{-1} with only requiring 1µm thickness layer (Bosio et al. 2018). According to the research of CdTe solar cells of NREL, a typical schematic of superstrate CdTe solar cells is illustrated that the top layer is glass which allows the sunlight to go through. The next layer is transparent conductive oxide (TCO) such as Cd_2SnO_4 keeping the role as electricity transmission. CdS is the intermediate layer to transmitting the electric current from TCO layer to CdTe. The electric field is created between CdTe layer and TCO layers. The last substrate is in charge of being as electric contacts connecting to the external electric equipment such as metal or carbon paste with copper. Concerning about the environmental assessment of CdTe thin-film, it is indicated that there will be toxicity when this material is underway of combustion. Other emission can be discharged from the purification process of CdTe, recycling of CdTe modules and landfilling of some unrecycled CdTe modules. In the study of Fthenakis (et al. 2008), the amount of atmospheric Cd emission from the CdTe overall life cycle stays about 0.02-0.3 g Cd/GWh, much less than 2-3 g Cd/ GWh from coal burning power plants. Furthermore, comparing with the conventional solar cell of crystalline silicon, the emission from CdTe is lower because the manufacturing process of CdTe requires less energy, resulting in the less emission of some toxic gas such as SO_x, NO_x, or heavy metals. About energy payback time for ground mounted installation , CdTe modules installed at high irradiation has the EPBT about 0.5 year shorter than EPBT of sc- Si about 2.8 years (Leccisi et al. 2016).

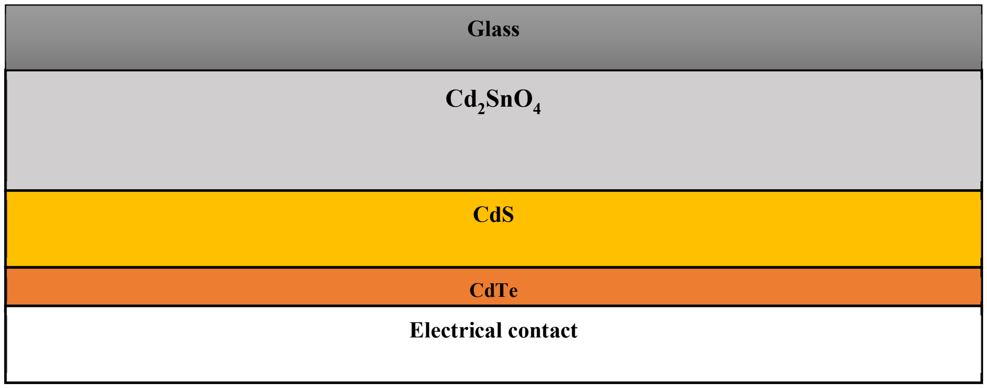

Figure 4 CdTe solar thin film structure

CdTe is potential thin-film technology though it still has the issue of the availability of Tellerium and Cadmium. The supply of Tellerium is in the limitation because this element is not much available in production and extraction. The main source for Tellerium provision comes from the by-product of smelting prime metals such as Cu, Pb and Au (Zweibel 2010, Fthenakis 2016). Currently, a large number of researchers also found the Tellrurium sourcing from bismuth ore in Mexico, Sweden and China with approximate concentration of 20% (Zweibel 2010). To solve the problem of Tellurium availability and retain the effective performance of CdTe solar cell, the solution is proposed to reduce the thickness of active layer and increase the efficiency of execution. Respecting to the environmental term, CdTe module is evaluated as the most eco-friendly solar module because of their lower values of EPBT and GHG emission rate comparing with different solar modules (CTFSOLAR 2018) . In the study of Fthenakis and Alsema (2006) about the EPBT and GHG emission rate of crystalline silicon module and CdTe thin-film which are applied on the rooftop under the average irradiation of 1700 kWh/m^2/year indicated that CdTe thin-film had EPBT and GHG emission rate lower than multi-crystalline silicon.

CIGS solar cell is a thin-film material converting sunlight to electric power, belonging to the group of the second generation technology solar cell.

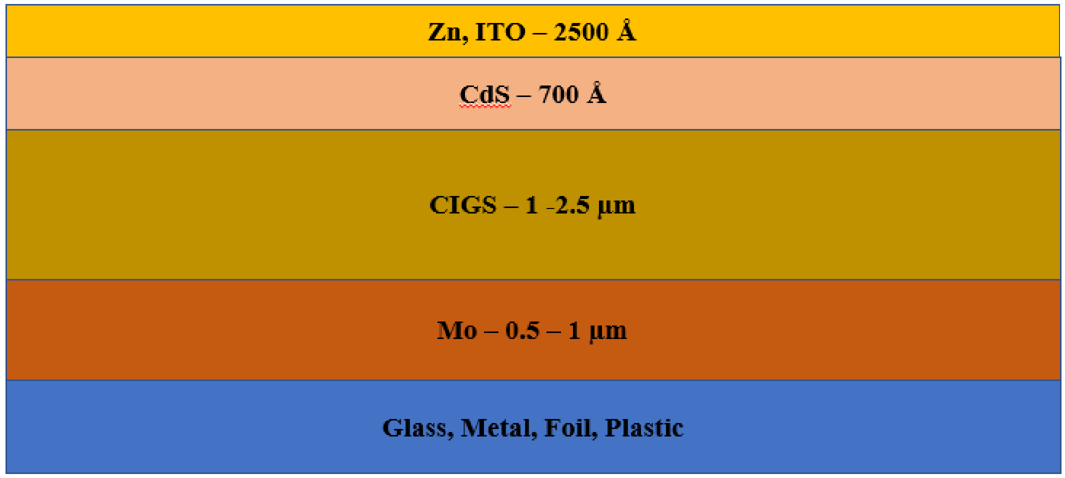

Figure 5 CIGS thin-film structure (based on (NREL 2019b)**)**

The feature of CIGS solar cell is the semiconductor produced from depositing the materials of group I, III, VI including copper, indium, gallium, and selenium on the surface of glass at the elevated temperature. About the structure of CIGS, it is constituted of the direct bandgap as CdTe thin film and amorphous-Si thin film. CIGS is considered as the most effective alternative solar cell used in utility-scale photovoltaic system (NREL 2019a). CIGS cell is take accounted of being as a high efficient thin-film solar cell with the efficiency reaching about 20% .

3.4. Balance of System (BOS)

3.4.1. Roof-top mounting system

The mounting system of photovoltaic panels in roof-top depends on the type of roof such as flat or sloping roof, or the types of mounting can base on the way they are supported. In the process of rooftop PV panels installation, there are some aspects need particular attention paid to:

The physical and electrical characteristics of PV modules concentrate on the size, weight, frame or composition of laminate. These characteristics will define the proper roof or mechanical structure applicable.

Thermal and electrical performance relates to the impact of operation temperature. Depending on the types of module materials that the useful lifetime of PV panel will be reduced when the operation temperature is elevated. Regarding about electrical performance, changing temperature in operation will influence on the performance of PV arrays. In detail, according to Barkaszi and Dunlop 2001 then increasing 10 ˚ C will reduce 5% of power output for crystalline silicon PV arrays. Even, the rise in temperature coefficient also lower half the height of standoff mounting array from the surface of roof to the top of module (Barkaszi and Dunlop 2001).

Site conditions impacts on the efficiency of PV arrays performance especially relevant to shading. The cause for shading is likely to come from trees, buildings or daily time of solar irradiation. There will be a significant reduction of output power when a part of system affected by shading.

Installation and maintainance goes along together with the condition that the design and installation of PV panels on the roof only require little or even no maintainance. The PV system should be flexible to adapt with any field conditions .

Environmental and material issues are also mentioned in the criteria for PV rooftop installation. Depending on the different location of mounting, leading to the difference in environmental conditions, that requires the use of different types of fasteners or metal supporting components. For example, using the stainless steel fasteners and aluminum insullated from contacting with steel will reduce the problems of material corrosion.

In addition to the conditions of installation, it is important to pay attention to the types of rooftop installation. There are four different of support structure: stand-off mounting, direct mounting, integrated mounting and rack mounting.

Standoff mounting PV panels or building attached PV are commonly applied for the sloping roof with the support of brackets made from metal (Barkaszi and Dunlop 2001). The standard distance from the array to the roof surface is calculated from 3 inch to 6 inch (Kreith and Goswami 2007).

Rack mounting are majorly applied on flat roof by mechanical attachment or using ballast to shield wind (Kreith and Goswami 2007) .The operation temperature in rack mounting system is generally lower comparing with other mounts because of the convection from front to back of panels.

Integrated mounting or called as building integrated photovoltaics (BIPV) are in charge of two functions including becoming the covering for the building and the second is generating electricity. The configuration of BIPV includes: PV modules, a charge controller to avoid the overcharge in battery, power storage system, inverter converting DC to AC, backup power system in case of blackout, support components such as mounting equipment, cables. The energy production from BIPV depends on some factors relating to the intensity of solar radiation, types of photovoltaic panels, position of panels and the tilt angle of panels (Takeda et al. 2005). Furthermore, about the design and application of PV modules for building, there are some application such as solar cell integrated into façade of building, integrated into awning which can directly expose to the sunlight, applied in skyline system create the economical values (Steven Strong 2016). **Direct mounting** is applied for the most standard solar panel with the target of reducing the cost of aluminum racking. The direct attachment is using clips integrated with roof mounts shared by adjunction modules but the ability for withstanding the force of this attachment is still need to more research.

3.4.2. Ground mounted system

Foundation is the part for supporting the panel and also embedded into the ground for installation. In the section of ground mounted PV installation, it is required to have implementation of the geographical technical examination and the second is structure engineering. Regarding the geographical technical examination, it is necessary to inspect the suitability of land characteristic to find out the suitable types of mounting racking system. Ground mount is the firm attachment of panel to the ground through a rack and metal posts. Normally, the ground mount PV panels are often installed in large scale area (Paradise solar energy 2019). Before deciding which foundation suitable or not, it is highly required to have an investigation of soil characteristics and geotechnical analysis. The investigation is divided into two phases including soil drilling and testing laboratory. Test boring requires using the standard penetration test (SPT). This common method is applied on-site for determining geotechnical engineering of subsurface soil and carried out in borehole (Houk and Berglin 2017). The advantage of SPT in testing is useful for checking the bearing capacity of soil for attachment of piles. The method will use a 63.5 kg hammer falling down with the distance of 0.76 meters from the ground surface. The estimation for the drilling hole ranges from 60 to 200mm (El-Reedy and El-Reedy 2017). The drilling is used to dig the hole with the specific depth and then, when drilling equipment is removed, the sampler is driven by the hammer blows. Regarding the laboratory testing, the soil samples are collected and sent to the laboratory to test the characteristics of soil to figure out whether soil is suitable for the PV installation or not.

For example, to check the allowance of ampacity for burying the cables underground, lab technician will need to test thermal resistivity of soil. If it is required to test the impact of soil on the metal post, steel, it is necessary to have chemical analysis to test the corrosion. After determining the characteristic of soil, there will be types of foundation mounts including helical piles, ground screw, driven piles and ballasted foundation

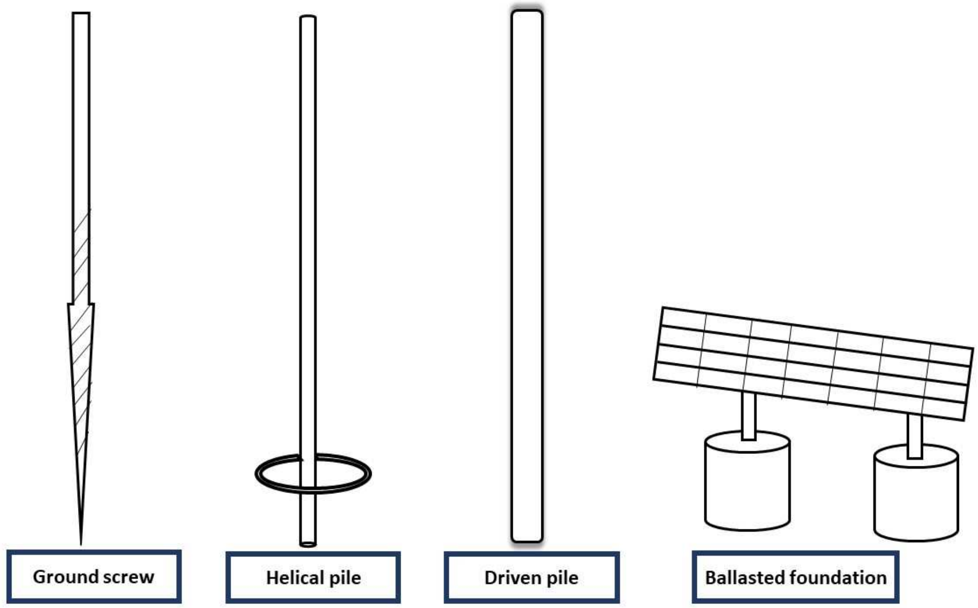

Figure 6 Types of ground mounting foundation (based on (Bushong and Worden 2014)**)**

Foundation mounts or helical piles

Foundation mounts or helical piles are the most common mounting type of PV panels. The feature of this mounting is attaching pipes or tubing to the ground and being fixed by concrete foundation. The installation is very suitable with the poor soil cohesion. After installing, the piles will be in charge of locking the structure into the soil (VERMEER 2018). There are a lot of benefits coming from helical piles including time-saving for the concrete cure after installation, easily adapt with under weather conditions, not require grading of soil, noise reduction comparing with driven piles, installing with most equipment with the head of hydraulic drive.

Ground screw is that using a screw drilling into the soil. It is mostly applied in the loose soil, sandy soil and bedrock because it has a high contact surface between screw and soil (Bushong and Worden 2014). The outside of screw footing is galvanized by zinc to prevent from corrosion and rust. The common material for ground screw is mostly applied for photovoltaic mounting framework is low-carbon steel and aluminium (Messenger and Ventre 2004). To increase the anti-corrosion ability for steel, the common method is hot-dip galvanizing. This method is considered as more superficial comparing with many different coating approaches for steel because of the low cost for coating material such as aluminium or zinc, light weight, high durability (Shibli et al. 2015). The advantages of ground screw for solar panels installation are the fixing to the ground more firmly, longer lifetime because of anti-corrosion, cost reduction because it has no requirement for concrete or excavation activity. This foundation is also eco-friendly as there is no significant impacts on the ecosystem surrounding, the product is likely to be reused (Bushong and Worden 2014) . Furthermore, the application of ground screw is wider for different types of soil and larger scale. If using ground screw for the rocky soil, it is highly required to use pilot holes. The drilling for pilot holes will encounter the extra cost requirement comparing with other typical foundations. In case of the soil belonging to softer soil group, it is no requirement for drilling pilot holes but need to dig deeper for screw.

Ballasted foundation

Ballasted foundation has the supporting posts surrounded by concrete frame so as to make the post footing harden (Margulies 2015). Ballasted foundations are suitable for the soil having high refusal rates and low soil cohesiveness or high water. These types of foundation are good alternatives in case for earth-screws or helical piles not applicable. The characteristic of ballasted foundation is having a concrete to keep the footing of pile to the ground and preventing the overturn of module in case of storm weather. Previously, ballasted foundation is not cost effective resulting in the fact that they are not popularly favorable in the mounting system comparing with helical piles or earth-screw. However, in recent years, the price of this ballasted foundation is decreasing thus they are becoming good options in the case that helical piles and earth-screw are not effective.

Driven piles foundation

The characteristic of this foundation is the steel – feet foundation galvanized by zinc by dipping the steel feet into bath of hot zinc (Bushong and Worden 2014)**.** Zinc coating prevents the rust and corrosion of steel under the water or wet conditions. This foundation is very suitable to the clay, low water table, cohesive soil. The advantage of this foundation is quick installation, adapted with large scale projects, high accuracy and low cost (Bushong and Worden 2014). The feature of driven piles foundation is suitable for frame or frameless modules. It is cost beneficial because it is operated by pile-driven machine.

3.4.3. Inverters

Inverters are generally applied indirect current system. When supplier needs to load the electricity from PV system to local or national grid, inverter works as converting DC currents to AC currents. According to Solar Power World Online 2016, there are four main types of solar inverters including:

String inverters are constituted from the connection a specific number of photovoltaic strings together. String inverters work in three phases variation. The problem of string inverter relates to shading issue. The shading from trees or chimney casting on one panel can virtually reduce the entire performance or output of system (Energy sage 2019a). It is estimated that in Germany, about 41% of rooftop PV installation is significantly impacted from the shading issues, resulting in losing 10% energy performance. The solution is using a power optimizer installing beside the inverter or using Maximum Power Point Tracking, which is known as the device to optimize the most useful power from PV system. String inverter are often widely applied in the residential and commercial area, even, with the small utility scale less than 1 MW, it is more competitive and effective than central inverters.

Central inverters are defined as a large version of string inverter with the connection of many large PV panels to an inverter (Çelik et al. 2018) . The typical size of central inverter ranges from 125kW to 2.5 MW, majorly specializing in utility scale PV system application (Trina Solar 2018). The drawbacks of these inverters are the same as the faults in string inverters about shading condition. These inverters are unable to deal with the situation of partly shading when there is a shortage of connection and control between

MTTP with each strings (Çelik et al. 2018). Even, according to Energy informative 2019 if the shading occupies 9% of solar system then there will be 54 % reduction of power output for central inverter. The central inverters has a larger footprint than string inverter because of the maintenance and installation from a large number of components in the system (Trina Solar 2018). In addition to disadvantages, the advantages of central inverters are the convenient applications for the photovoltaic utility scale, high efficiency and saving cost (Çelik et al. 2018). Otherwise, the capital price per watt from central inverter is low resulting the popular adoption of this inverter in large scale PV system. However, it is required to have a high cost investment for installation. The large size of central inverter is likely to make the system better efficiency but also exerting noise matters.

Micro inverters are becoming popular and favourable in the photovoltaic market by their effectiveness, reliability and higher production. The principal working of micro inverter is converting DC to AC right at each solar panel. The micro inverter can be integrated into the solar panels or installing besides in case of mounting system. The power rating of micro inverter ranges from 50 to 400W (Hasan et al. 2017, Çelik et al. 2018). Micro inverters work independently and optimize total energy from single panel with conversion efficiency approximate of 90% (Çelik et al. 2018). Furthermore, their reliability is present at the feature that if there is any problem of shading or operation happening in one panel then the entire system is not affected.

3.4.4. Battery bank

Battery plays as the important role in energy storage of PV system and produce energy when there is a requirement from the grid. Generally, in PV system, the excess energy will be charged to the battery and withdrawn from battery if needed. There are many situations that PV system is unlikely supply sufficient electricity to the grid due to the weather conditions or high demand of power from consumer. When it comes to batteries, some important characteristics should be concerned: Battery life times, depth of discharge, capacity and power, round-trip efficiency (Energysage 2019b).

Battery capacity is determined by the maximum amount of electric energy available in battery. The unit of battery capacity is usually Ampere hours (Ah), kilowatt hours (kWh) or Watt hours (Wh) (Markvart and Castañer 2003).

Depth of discharge (DoD) is relating to battery capacity when discharge and recharge. In detail, it measures the amount of electricity loss when battery is discharged. In the case of battery full of discharge, the DoD is 100% (Spiers 2012).

Cycle life is identified that one cycle is one time of fully discharging of battery. It is estimated for the charging and discharging times of battery in the whole life of that battery (McEvoy et al. 2012). Cycle life of battery is relevant to DoD. The battery with the higher DoD value has

Battery lifetime is about how long a battery can be effectively charged or drain in a specific period time of warranty which is proposed by manufacturer. As a rule, the capacity of battery will degrade significantly due to sulfonation and shedding of active material (PVEDUCATION 2019b). Both of these issues are determined by the cause from overcharging or undercharging of battery. Another key feature impacting on the solar battery lifespan is the number of cycle charging. It is estimated about 300 to 700 cycles if it is a flooded battery. Even, in lithium batteries, this number can reach up to 2000 cycles (Solar light manufacturer 2019). Temperature is also assessed that having a significant impact on the battery lifespan such as when temperature is higher, the battery cyclic life will decrease. However, if operated in the elevated temperature, the performance of battery increases but the lifespan will be reduced. It is estimated that about five to fifteen years for the lifespan of solar batteries (Sunrun 2018).

There are two primary types of batteries in photovoltaic system including lead acid battery and lithium battery

Lead acid battery is composed of two electrodes: the cathode is electrode connected to a spongy load plate and the other electrode connecting to lead-dioxide. Both of these electrodes are deepen in sulfuric acid solution electrolyte (Hyperphysics 2019). The voltage is created by chemical reaction between lead and lead oxide with the sulfuric acid electrolyte. The typical charge time of lead acid battery ranges from 8 to 16 hours (Battery university 2019).

For the photovoltaic system, lead acid battery is widely applied under the role electricity storage off-grid photovoltaic system. Depending on the rated nominal voltage and rated capacity that the connection of lead-acid batteries is in series or parallel.

Lithium ion battery is a rechargeable battery with the same configuration as lead acid battery with one cathode with lithium oxide, one anode with and an electrolyte playing as the role of conductor(Batteryuniversity 2019). The performance of Li-ion battery in discharge is the movement of lithium ion from cathode (positive) to anode (negative). The charging will be reversed comparing with discharging (Battery university 2019).

3.4.5. Solar charging controller

Due to ensure the longer lifetime of battery, it is essential to equip a solar charging controller in the photovoltaic system. The role of solar charging controller is manage the power charging or discharging from the battery bank, ensuring that there is no overcharging for battery bank (Altestore 2019). There are two different kinds of solar charging controllers including Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). Concerning about the PWM solar charging controller, this device is connected directly to the solar arrays and the voltage going out from the arrays will be reduced when charging to the battery bank (Altestore 2019). For MPPT solar charging controller, it measures the Vmp voltage output of the arrays and also converting down it to equal to the battery voltage (Altestore 2019).

3.5. Solar tracking system

The solar tracking system is the system that enhances the efficiency of the solar system electricity through utilizing the movement of solar panels following the position of sun under the adjustment of tilt angle. Solar tracker helps to maximize the solar energy extraction, optimizing the PV panels performance by minimizing the angle of light incidence. The narrower the angle of incidence which are created by the sun light striking on the surface of the solar panel, the more energy a photovoltaic panel can produce, majorly, the common efficiency have not surmounted 13% in common solar tracker (Tudorache and Kreindler 2010, Hafez et al. 2018) The position of solar panels on solar trackers being perpendicular to the solar irradiation will give the best energy efficiency results (Hafez et al. 2018).

Utility-scale and large projects usually use horizontal single-axis solar trackers, while dual-axis trackers are mostly used in smaller residential applications and locations with high government Feed-In-Tariffs. Vertical-axis trackers are suitable for high latitudes because of their fixed or adjustable angles.

The solar tracking system not only exists in the power and efficiency gains and increase compared to the fixed systems, but also in the economic analyses of the large-scale solar energy applications. The systems are oriented with optimal tilt angles towards the equator from the horizon to maximize the solar radiation reaching to the PV panels.

When it comes to the basic structure and components of solar tracker, there is a presence of light dependent resistors (LDR) for measure intensity of the sunlight. LDR continuously monitors the solar irradiation and there will be a transmission of collected data to the motor through a micro controller, in there, the signal is translated to language program and lead to that the motor will move the panels to the optimum position (Chhoton and Chakraborty 2017).

The categorization of solar tracking system includes basing on the number of axis with single -axis and dual-axis or another criterion for classification is about the activity types with active or passive solar trackers. The tracking collectors improve the energy efficiency from 10% to 20% comparing with the fixed solar panel system. In one report of USA, it is proved that the potential working of solar tracker in summer reaches the high efficiency with two specific figures in summer of over 50% and in autumn time over 20% (Tudorache and Kreindler 2010).

3.5.1. Single – axis photovoltaic tracker

Regarding about the rotation axis, single-axis tracker is used for moving the panels in two direction from north to the south or from east to west. Meanwhile, the dual axis is used for tracing the solar irradiation in both horizontal and vertical direction. Single - axis tracker is applied mostly for the PV small power plants. The working principle of single – axis solar tracker uses an electric motor to rotate the PV flat panels in the trajectory following the sun pathway. In detail of a solar tracking control circuit, there is a presence of light sensor called LDR which is highly sensitive to sunlight intensity. The resistance of LDR stays normally at 2MΩ which changes reversely with the sunlight intensity with increasing value of resistance when there is a reduction of light intensity falling on the LDRs mirrors (Tudorache and Kreindler 2010). Single-axis solar tracker is very suitable for being installed at the location whose position nearby the Earth equator because there is no significant difference of sunlight angle (Ali 2016). Another hardware component of this tracker is a geared bidirectional DC motor with the role of moving the panel to the required position. The third component is potentionmeter, which is used for identifying the position of panel by giving the resistance data of the position of panel , then informing the signal to the controller system and calculating the suitable angle for rotating the panel accordingly the angle of panel is measurable (Kabalc 2015).

3.5.2. Dual axis solar tracking system

As the movement of sun includes daily movement and annual movement that single-axis solar tracker only possibly takes a charge of tracking the sun from east to west. Accordingly, dual-axis solar tracker is designed to take an accurate tracking of solar pathway, result in increasing the efficiency of solar panels, especially in the cloudy days. The components of two-axis solar tracker consist of a Global Positioning System (GPS), an electric microcontroller which manages all of operations in the system, DC motor, photosensor, control circuit unit, motor driver with relay (Wang and Lu 2013, Seme et al. 2017).

4. LIFE CYCLE ASSESSMENT

Life cycle assessment method is known as a quantitative analytical method used for evaluating the overall life cycle of a product basing on the aspect of environment: Starting from material extraction, processing of product until to the end-life of product (Lee and Inaba 2004). Furthermore, LCA method will include waste management, assessing even about the human contribution to the process. Basing on the LCA, producer can figure out what material is suitable, cost efficient but still assuring for the low emission to environment. It can be assured that one of the most important application of LCA method is enhance the quality of the product and corresponding services (Rebitzer et al. 2004). The LCA method includes four main steps with the framework (Rebitzer et al. 2004, Curran 2013)

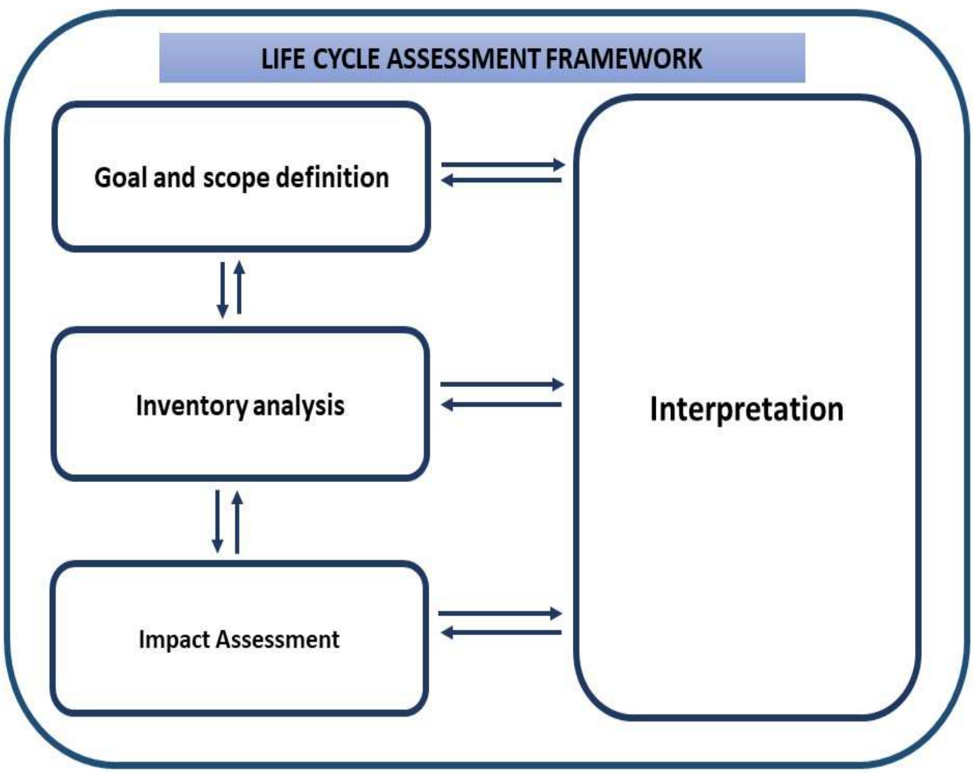

Figure 7 LCA framework (based on (Guinée 2002)**)**

Step 1: Determining the goal and scope and implying the functional units and system boundaries.

Step 2: Inventory analysis including determining the input including raw material, electricity, water and the output relating to pollutants and discharged waste.

Step 3: Environmental Impact Assessment about the evaluation potential human and ecosystem impacts

Step 4: Data interpretation comparing the results gained from step 2 and step 3 since then propose the solution which technologies, materials or processes are economically beneficial, eco-friendly, highly efficient.

In addition, LCA also needs to involve in sustainability evaluation through the cost analysis, technical specification and any relevant social issues.

4.1. Goal and scope definition

It is the first step in LCA process, which determine the objective of overall procedure, propose any questions about the application of the evaluation, the intended audience that the LCA report to such as: consumer, stakeholder and other targets (Rebitzer et al. 2004). In this part, there is a requirement to list the participants involvement to the LCA projects including: LCA commissioner, researchers, target audience, reviewers, supervising board (Guinée 2002). The apparent goal of LCA will decide the system model appropriately. After determining the goal, the scope of definition is about the determination of time, location and also technology employed during the product manufacture. According to requirements in ISO 14044, there is need to implementation of finding functions of product, identifying functional unit and also the system boundaries (Guinée 2002).

4.1.1. Functional unit

Functional unit is description about the function of unit product relating to amount, weight, application. When making a comparison between with the alternative product, the functional unit of each product should be equivalent. Depending on the objective of end-use of product obeying cradle to gate or cradle to grave, the functional unit of product should be as closely as the end-use process. The size of functional unit is not obligator. The way to identify a function unit of product will follow the Handbook on life cycle assessment of (Guinée 2002).

Step 1: Give a short description about the product.

Step 2: Determine the functions of product. Making priority for the primary function. Pointing out the additional functions which are ignored.

Step 3: Make a selection for functional unit based on the SI-unit in a specific time.

Step 4: Sizing the function of product by choosing the arbitrary amount of product but the actual figure is a good preference.

Step 5: In term of substitute products, it should meet the requirements from the function of product and having any superior benefits comparing with any other ones which are not in the list of alternative selection. Furthermore, including the reference flows in relevant to the respective alternatives.

4.1.2. System boundary

System boundary is including the processes happening relating to the system. Depending on the goal and scope of LCA, each system can connect with other system, exerting a great deal of unit processes such as when it comes to the LCA a product, it can include the unit processes from the raw material extraction till the processes occurred within the production (Guinée 2002, Rebitzer et al. 2004). The system boundary is built to help the targeted audience or researchers acknowledge about the limitation of the life cycle of the product for assessment. The system can be categorized into five types consisting of: Gate to gate, cradle to gate, cradle to grave, gate to grave, cradle to cradle (Vertech Group Sarl 2015).

Gate to gate is a system boundary approach commonly applied for the unit process because there is only a focus on the process starting from receiving material, material in use, manufacturing products, product ready for users without stepping further for distribution and other activities (Vertech Group Sarl 2015).

Cradle to gate approach goes further inside to the production process. Furthermore, it also considerations about the step of extraction materials, first distribution, transformation and transportation steps (Vertech Group Sarl 2015).

Cradle to grave approach is a full life cycle study with the starting assessment from the material exploitation until the disposal stage of product.

Gate to grave approach is a minor part of the system boundary with the common application on market study because in this approach, the researcher can attain the information about the product distribution to consumers, application of product and end-life product management (Vertech Group Sarl 2015). In this approach, instead of being disposal, the product will be underway of recycling process so as to reduce the environmental impacts (Balaman and Balaman 2019).

Cradle to cradle is a circular process including all of life product cycle from exploitation of material resources to product processing, to the end life product and the remaining for recycling coming back to the first stage, being utilized as the materials for the next production. This method goes beyond the conventional approach, include the appearance of recycling stage. It is a promising approach with the goal of making economic development of product relying on the eco-friendly design, manufacture in clean industrial ecosystem and underway the loop cycle from starting to come back the initial stage of being a raw material (McDonough and Braungart 2002). The product will not be for sale but for use. The company will be not dependent on the price of raw material or shortage of raw material availability because the material of products after use will be recycled to the first stage (EPEA-Hamburg 2019) .

4.2. Life cycle inventory

In the part of inventory analysis, there is a more detail of system boundaries. There are three types of system boundaries including: The first is between product and environment, the second is between the internal system with other external other system which are not relating to the product (cut-off) and the third is the boundary between the product system and other product system.

In the inventory step, the system is defined including data collection for input and output (Rebitzer et al. 2004). The data is relevant to raw material acquisition, energy consumption for operation, water consumption and waste discharge. The data should be set the target for quality such as about time coverage, geographical area of data collection, technological relevance of data (Lee and Inaba 2004). The basic activity in this step is unit process. Unit process is known as the activity for producing any economic valuable output.

There is an inquiry about the data requirement, the source of the data, the quality of collected data, the model of product system, the aggregation of data and uncertainty handling.

4.3. Life cycle impact assessment

Data after being collect in the step LCI, LCI results will be firstly categorized into impact categories corresponding with each environmental indicator (Zucaro et al. 2015). After being classification, the data results are underway of analysis and translating the data results to make calculation the degree of impacts caused from waste emission to human health and ecosystem.

The compilation will primarily focus on evaluation of the degree of influence from the environmental potential impacts through quantifying the data of some environmental categories such as: fossil fuel consumption, water use, energy consumption and environmental emission.

ReCiPe method is known as one of the most popular method majorly and widely applied in pointing out the indicators relevant to environmental impact assessment of LCA approach. The purpose of ReCiPe approach is interpretation of the huge data results from Life Cycle inventory to the limited number of indicator scores, with two approaches: Midpoint impacts include eighteen factors and the endpoint part consists of three factors (RIVM 2018). The midpoint part in ReCiPe method contains the largest number of midpoint factors. The feature of midpoint in ReCiPe is characterized by factors: climate change, ozone depletion, terrestrial acidification, human toxicity, particulate matter, agriculture land occupation, freshwater ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, land use or transformation, marine ecotoxicity, ionizing radiation, urban land occupation, natural land transformation, depletion of mineral resources, depletion of fossil fuel resources, depletion of freshwater resources, freshwater eutrophication, marine eutrophication, photochemical oxidant formation. Meanwhile, the endpoint part will be characterized by three factors: resource scarcity, human health, quality of ecosystem (Huijbregts et al. 2017).

The focus on the detail environmental impact of ReCiPe method is illustrated in this graph:

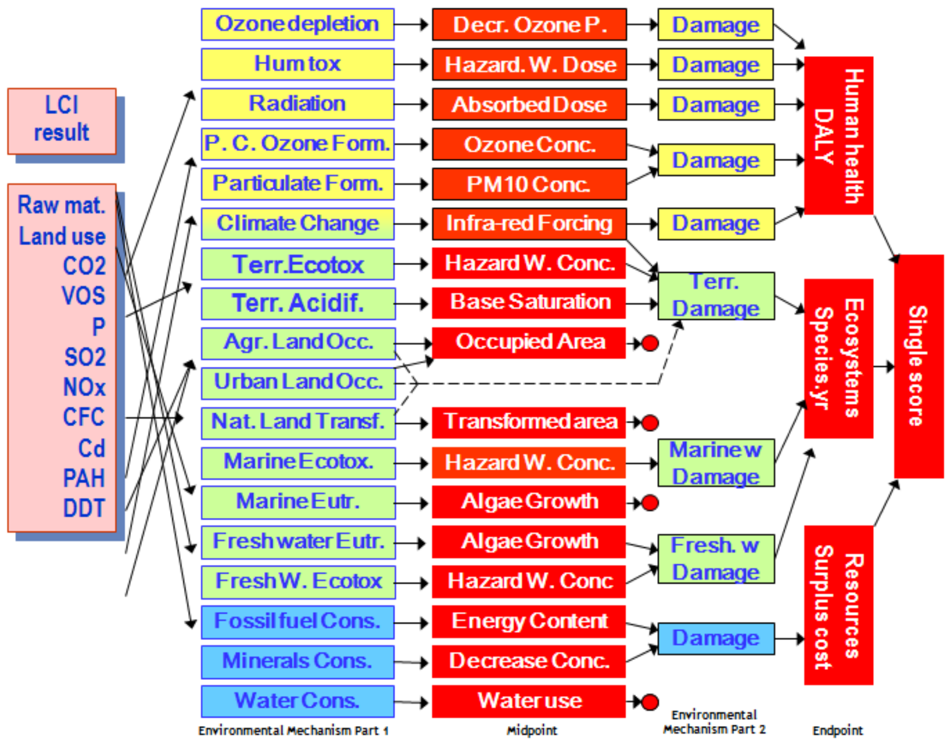

Figure 8 ReCiPe method in LCA (based on (Goedkoop et al. 2009)**)**

As can be seen from the framework, there is a necessary condition for the calculation of midpoint and three endpoint indicators to estimate the magnitude of impact indicators from each level. However, because of the robust number of categories in midpoint level and the uncertainty in endpoint factors, thus, users need take careful consideration when making decision for selection of impact categories.

4.4. Impact categories of GMPV

In normal, the comparison between the rate of GHG emission reflects the efficiency of technology PV in term of global warming. Although using the PV panels is considered as a potential alternative for the fossil fuel but during the manufacture, transportation, material extraction and the end – life step, there is a significant amount of GHG emission to environment. A large number of studies about environmental impact assessment of PV plant base on the LCA framework and focusing on specific environmental indicators including: primary energy demand, energy payback time and greenhouse gas emission

Primary energy demand is referred to the cumulative energy demand, meanwhile, the primary energy is known as the raw energy existing in natural resources and need to be harvested to convert to secondary energy (Jungbluth et al. 2011).

Energy payback time relates to the range of time that the photovoltaic system will produce the same amount of energy which is generated in the beginning time. The calculation formula for this is based on Jungbluth et al. 2011

Energy Payback Time (EPBT)= $(E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})/((E_{agen}/\eta_G) - E_{aoper})$

E_{mat}: Primary energy demand to produce materials comprising PV system

E_{manuf}: Primary energy demand to manufacture PV system

E_{trans}: Primary energy demand to transport materials used during the life cycle

E_{inst}: Primary energy demand to install the system

E_{EOL}: Primary energy demand for end-of-life management

E_{agen}: Annual electricity generation

E_{aoper} :Annual energy demand for operation and maintenance in primary energy terms

η_G : Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

CO_2 Greenhouse gas emission rate

In normal, the comparison between the rate of GHG emission reflects the efficiency of technology PV in term of global warming. Although using the PV panels is considered as a potential alternative for the fossil fuel but during the manufacture, transportation, material extraction and the end – life step, there is a significant amount of GHG emission to environment.

Regarding about the GHG emissions, it should be taken to consideration about global warming potential. According to EPA, Global Warming Potential (GWP) is fostered as a technology to estimate the amount of energy absorbed by 1 ton gases in a specific time, detail in the PV life cycle then using time period of 100 years (GWP_{100}). All GWP is calculated equivalent to CO_2.

Depending on the type of gases, there will be a GHG conversion factor equivalent. There are some concerned gases emission in the processing of PV panels including CH_4, N_2O, Chloroflourocarbons. 1kg CH_4 = 23kg CO_2-eq, 1kg N_2O= 296 kg CO_2-eq, 1kg Chloroflourocarbons = 4600 – 10600 kg CO_2-eq

EXPERIMENTAL PART

5. PROJECT InNOSys

The thesis is a part of project InNOSys. The goals of this project relates to establishing the qualitative modelling and researching of energy scenarios, orienting to sustainable energy system in Germany. The pathways for evaluation can base on the relevant criteria of economic, social and environmental aspects. The project is the collaboration of parties including DLR, GWS, INEC, ZIRIUS, ITAS and INATECH with the common target developing the assessment methods about the sustainability of energy tranformation scenarios in Germany with multicriteria relevant to economy, ecological and social perspectives. The second goal is analyzing and make comparison of the transformation scenarios with the combination of methods, modeling and competences of project partners. The third purpose is optimization of development and expansion of power sector in Germany. Next is determination and analysis of conflicting goals, trade-off between different sustainability indicators happening in the process of transformation. The last target is giving the conclusion of policy and society relating to alternative solutions.

There are some questions raised from the project

- How to implement sustainability assessment basing on the coupling of complex modeling about the energy scenarios and life cycle assessment methods
- What new insights into the design of the energy system transformation can be gained with this instrument, and what are the differences between the new insights and make comparison with the current insight?
- How can alternative infrastructure development paths be compared in scenarios and what are the specific advantages and disadvantages depending on the target size?
- Which renewable share in the energy supply can be described as optimal if several indicators are taken into account? Which conflicting goals emerge?
- Which evaluations result for scenarios under consideration of specific regional boudary conditions in individual federal states or regions?

In this project, the method of life cycle assessment is applied and access data from ecoinvent version 3.3. The role of LCA method in this project achieving the goal is help to make evaluation of GMPV in economic, ecology and social aspect. The data from openLCA ecoinvent and also from research literature will assist the project for the overview of the state-of – the art of GMPV technologies. Furthermore, the data also supplies the information about the upstream and downstream process, from material extraction, production, then operation and the final step of disposal of materials. Beside of technical matters, LCA is also virtually in charge of environmental assessment of GMPV through the assistance from ReCiPe framework with environmental indicators are identified and their impacts on the ecology system, human health. In term of data ecoinvent, there is inclusive of material cost of different solar system with different materials such as Multi-crystalline silicon, single-crystalline silicon, Cd-Te thin film, amorphous silicon. After researching the data of GMPV in ecoinvent of latest version, there is only the exist of data ecoinvent about ground mounted PV with the nominal power of 570 kWp open ground. Therefore, in this study, it is necessary to supplement more data collected from literature research.

6. Targets of the experimental part

The target of the experimental part is study about the state of the art of ground mounted photovoltaic technologies relating to installation and use phase and figure out the way to fulfill the data gap of GMPV. The process of study will be based on the scientific literature of life cycle assessment, since then identifying the data gaps corresponding to the installation and use phase. In term of the installation, the data gap will be relevant to identify the scale of the photovoltaic plant, types of photovoltaic modules applied, number of photovoltaic modules for the area of the photovoltaic plant. Concerning about structural support system, the data gap will be about the frame and legs including the amount of aluminum used, the number of inverters, types of inverters, cables and other electronic equipment connecting to the grid, the obstacles and challenges for GMPV development. The second target of the experiment is basing on the literature to find the data gap of ground mounted photovoltaic with different materials and which materials brings the most promising benefits for the utility scale.

In this study, to close the gap of the data, it is necessary to find out the data of the nominal power for different materials such as multi-crystalline silicon, monocrystalline silicon, Cd-Te thin film at different power plant with the different electricity generation. The target data should be found: the area for installing of PV panel with the specific amount of electricity generation for power plant, the number of panels of each materials should be applied, the number of inverters should be used, the length of cables for connection, amount of aluminum, amount of concrete, amount of steel for ground mounting system. This dataset only focus on the PV plant installation not relevant to the electricity consumption for the construction of mounting system. Regarding of life cycle inventory of mounting system production, due to the scarcity of data about process emission, therefore there is no focusing on the field of life cycle impact assessment.

7. State of GMPV technology

7.1. Current state of GMPV technology

Photovoltaic technology is developing in fast track with several critical aspects including: cost reduction, government subsidy and company investment for material enhancement, open policy and especially relating to achieve the goal of higher reduction for GHG emission. When it comes to the progress of PV technology, there are two main aspects should be taken to account including the PV module and BOS system technology. Before take a detail insight to the future development of GMPV technology, it should be concerned about the available GMPV technology, which is popularly applied in the GMPV system.

7.1.1. Current state of PV module in GMPV technology

When concerning about the PV module technology, there are detail three generation technologies including silicon PV material with two major materials multicrystalline silicon and monocrystalline silicon. The second generation technology is about thin film with two particular material CIGS (Copper Indium Gasnium and selenium) and CdTe thin film (Cadimium Telluride). The third generation technology is a new extent with the reseach of organic PV material, hybrid solar cell . Among of these module materials, the design silicon PV module for power generation accounts over 90% the share of commercial modules market though this material is very conventional, whereas, the current share of CdTe thin film technology still stay at the progressing with being comparative with mc-Si and sc- Si technology with the potential price and promising performance (Gangopadhyay et al. 2013, Bosio et al. 2018).

Crystalline silicon PV module is still having the highest conversion efficiency with the value according to the best research of cell efficiency chart of NREL for single crystalline silicon of 26.1% meanwhile this value for multicrystalline silicon 22.3%. Explaining for the higher efficiency of single crystalline silicon module comparing with mc-Si module is from the grain boundaries. The interfere of grain boundaries in the mc-Si make this material require the thicker layer in the fabrication resulting in the lower performance in converting sunlight to electricity (Honrubia-Escribano et al. 2018). Furthremore, the cost of crystalline silicon PV module is relatively high and this foster many researchers orients to the different module technology material such as CdTe thin film or even organic PV module.

Thin film module second generation technology is known as a potential alternative for c-Si module technology because of their improving efficiency, reasonable cost, less material requirement. Currently there are three prevailing major thin film solar cells including CIGS (Copper Indium Gallium Selium), CdTe thin film and amorphous Silicon. Among of three technologies, amorphous silicon cell is the most traditional, lower performance comparing with the two remaining materials. The superior feature of this material technology is light weight with only 1kg/m^2, high flexibility so easily to apply for the curving structure thanks to without using glass , high voltage output based on the serially connected structure of amorphous silicon cells (Sakurai and Sakai 2010).

The favourable thin film technology for the utility scale ground mounting photovoltaic plant application is CdTe. This solar cell is known as the low cost and high absorption efficient material with the cell efficiency of 22.1%, which is recorded by NREL 2019a

The conversion efficiency of CdTe according to the best cell efficiency research of NREL 2019a reaches the value at 22.1%. In the report of FRAUNHOFER ISE 2019 about photovoltaic, CdTe is indicated as the most promising and popular technology applied for utility scale photovoltaic (Munshi et al. 2018a). Also, there is a comparision between the power output of GMPV using CdTe material and crystalline silicon material installing in the same shading condition in the study of Munshi for the CdTe technology. The result demonstrates that the power output of the GMPV system using CdTe is higher 1.6 kW than the GMPV system using multicrystalline silicon PV panels (Munshi et al. 2018a). Besides of the out-standing of CdTe thin film performance for GMPV system, the range of degradation rate values of CdTe modules and Crystallin silicon module in the study the degradation rate of CdTe modules for one year less than comparing with this average value of crystalline silicon modules (Munshi et al. 2018a). When the degradation rate of CdTe module is lower meaning the energy requirement for the operation of this kind of module will be reduced and having the benefit of cost consumption. In the study of (Munshi et al. 2018b), when implementation the comparision of CdTe module performance and polycrystallint silicon module under the shading condition, the results pointed out that crystalline silicon module consume there is a loss of electricity more than for the CdTe thin film technology. Thanks to these advantages, nowadays, CdTe thin film module is increasingly attracting the interest of operator, becoming the dominant materials for large scale GMPV compating with Generation I technology crystalline silicon thin film.

The third generation of GMPV technology is known as an emerging technology with the popular types of module including perovskite solar cells, copper zinc tin sulphide .

7.1.2. Current status and development of BOS system in GMPV

When it comes to the BOS system in GMPV, it is essential to have an attention to the part of mounting system. When it comes to the mounting system photovoltaic panel in open ground, it should be concerned about the typical types of foundation including: Helical piles, ground screw, ballasted foundation and driven pile foundation. The description of this foundation is performed in the part of BOS system ground mounted system in this thesis. However, it is necessary to have a detail insight to the current situation of PV support stand eriction in GMPV.

Also in the part of supporting system technology, it should be taken consideration about the types of metal posts, which plays a vital role in the PV mounting. Thanks to the hot dip galvanizing method meaning a steel or iron piles likely to be coated by zinc to prevent the corrosion caused from extreme weather conditions, resulting in the longer lifetime of mounting post from 20 to 30 years (Euro format steel 2019). Besides of the outside protective metal post, the technical design in mounting system for safety ensurance also attacts a large attention. In detail, in the study of Datsios and Mikropoulos (2013), it is highlighted that the ground mounting electrodes should be taken careful consideration in the installation stage because these metal parts protect the GMPV system from the ground resistance.

7.2. Future state of GMPV technology

7.2.1. Futre development of PV module technology

Concerning about the photovoltaic module which contributes a vital role in the efficiency of GMPV performance. In most of studies about installation of GMPV system, the typical and common photovoltaic modules mainly come from silicon material. Nowadays, the generation technology of PV module is developed not only with crystalline silicon or thin film but also extension to the field of organic PV technology, hybrid solar cells. From the year 2000 to 2010, it witnessed a remarkable increase of PV cell production in the world. Among of that, China led the first position in the PV cell production. The solar cell production in 2009 in China reached at over 4000MW . The performance of polysilicon is increased . Furthermore, in the report of photovoltaic trends 2018 of IEA (IEA 2018), the development of photovoltaic module is indicated detail in the material production technology with two criteria about energy consumption and production efficiency. In detail, since 2017, the amount of energy consumption for PV module production is reduced 12% from 2009 with the amount of 120 kWh/kg to 2017 with amount of 40 kWh/kg.

The development of CdTe thin film

CdTe thin film is known as a promising alternative comparative with polysilicon PV module. In the study of thin-film technology to track the performance of this technology with different materials in the same condition of installation, in detail about the ground mounting. CdTe has a dominant performance than crystalline silicon when being installed in ground mounting with the power generation in one day about 19.4 kWh meanwhile this number for polycrystalline silicon is 14.1 kWh (Munshi et al. 2018a). Concerning about the degradation rate of module, it is lower comparing with the crystalline silicon so it explains for that CdTe thin film will require less energy consumption for the system and also the life time of module will be longer.

The future of PV module should be taken consideration about the third generation technology modules. It is very potential for application in utility scale GMPV system because of its reasonable price and high performance (Brown and Wu 2009).

7.2.2. Development of GMPV balance of system

Electronic devices

Regarding about the BOS technology of GMPV, it should be get attention to the development of electronic devices and mounting structure. To optimize the PV system performance, a device is integrated into system inverter named Maximum power point tracking, playing the role to solve problem about shading or any others matter which reduce the efficiency of PV. To operate this MPPT, an alogarithm is applied but instead of the traditional method, which is very high cost consuming,low efficiency then in the study of Manju and Sagar (2017), the intelligent control devices are supposed to use for optimize the non-linear current voltage output PV and improve the quality of the output such as Artificial Neutral Network.

About the inverter, it makes a significantly important role to the electricity conversion and loading to the grid. For GMPV in utility scale, most of applicable inverters possess the power rate from 2 MW to 5 MW.

Support structure

Regarding about the support structure, from the report of utility scale solar in the United States (IFC 2015), in many utility scale project about GMPV, the using of helical piles and ground screw is preferable because the energy consumption for two types of ground mounting is low because it no requires to use the concrete foundation, which consume a lot of energy.

8. LCA for ground-mounted systems

8.1. Ecoinvent data

In latest Ecoinvent data (Ecoinvent v3.3) in open LCA, the only available data set is about a 570 kWp open ground multi-silicon PV installation. It consists of a photovoltaic mounting system, for 570kWp open ground module. The available data includes input and output categories.

Table 1 Ecoinvent data of 570 kWp power plant

	Category	Flows	Unit	Amount
Input	Manufacture of electric equipments	Inverter 500kW	Items	3.126
		Photovoltaic panel, multi-Si wafer	m^2	4401.705
	Construction	Photovoltaic mounting system, for 570kWp open ground module	m^2	4273.5
		Photovoltaic plant, electric installation for 570kWp open ground module	Item	1
	Electric generation, transmission and distribution	Electricity, low voltage	kWh	36.033
	Demolition and site preparation	Diesel burned in building machine	MJ	7673.0
Output	Construction	GMPV 570kWp	item	1

Basing on the available data on the table as long as researching more about the data in the literature articles, the following table summarizes the information about GMPV from different countries at different capacity and plant size. From the available data and studied data from literature articles, the data gap for state of the art about technology in GMPV will be proposed. There are three tables with three small section: The first section will be about the general information of six case studies including authors, title, year of publication, country, LCA purpose, temperal data coverage, database for background data, functional unit and the capacity of plant. The second section will display data about photovoltaic module installation concerning about material, power of module, total number of modules, size of all modules, performance ratio, performance of module, degradation rate. The third section will mention about the components in BOS with two part electronic components and ground mounting structure.

8.2. Data from literature review

8.2.1. General information

This table 2 indicates first three case studies in Intaly, China and United States with the year in 2012 and 2017. In this three case studies, the purpose of case study 1 and case study 2 is similar, relevant to environmental impact assessment of PV module also inclusive about the BOS system meanwhile in the case study 3, the purpose mostly orients to the support structure and electronic devices installation. . The functional unit is not found in the case study 2 and case study 5, in contrast to the data of FU in case study 1, case study 4, case study 6, the functional unit is 1 kWh electricity generation. Meanwhile, this value for the case study focus on the BOS for 550MWc CdTe utility scale PV system.

Table 2 Summary table about general information of first three case studies

	Unit	Case study (*)	Case study	Case study
		1	2	3
Authors		Umberto Desideri Stefania Proietti Francesco Zepparelli Paolo Sdringola Silvia Bini	Peishi Wu, Xiaoming Ma, Junping Ji, Yunrong Ma	Parikhit Sinha Mariska de Wild-Scholten
Title		Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems (Desideri et al. 2012)	Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study (Wu et al. 2017)	Life cycle assessment of utility scale CdTe photovoltaic balance of system
Year of Publication		2012	2017	2012
Country		Italy	China	United States
LCA purpose		LCA of ground mounted PV installation	Assessment about the environmental impact of multicrystalline silicon PV ground mounting in China	Assessment of ground mounted BOS for planned thin-film CdTe 550MW Topaz Solar plant in southest United States.
Temporal coverage		2008, 2009	2005/2006	2011
Data base for background data		. From technical documentation from TerniEnergia . From on site measurements during the construction of the photovoltaic field. .Ecoinvent Idemat 2001 BUWAL 250 ETH-ESU 96	Wild-Scholten, M.J. de and E.A. Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production, version 2, status 2005/2006, 2007	International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines for life cycle assessment (LCA) of PV Ecoinvent v2.2
System boundary		Installation phase	PV technolgy production to grate	BOS installation phase
FU		1 kWh	N/A	BOS for 550 MWac CdTe utility scale PV system
Capacity	kWp	1778.48	1000	550000

Concerning about the data source, six case studies commonly use the data from Ecoinvent or literature articles, from on-site measurement. In the table 2a, for the case study 1, the data source is taken from diversified sources such as the document of Tenni Energia, from field trip of construction field, Ecoinvent, Idemat 2001, BUWAL 250, ETH-ESU 96. The case study 2 happening in China with the capacity of 1MWp have the data source from the literature of Wild Scholten and Alsema, as well as the data from the environmental life cycle inventory of crystalline silicon photovoltaic module production version 2. Furthermore, the LCA in this case study covers all the PV technology of system also with the BOS system installation and operation phase and electricity generation. The LCA in this case study mostly focus on calculating the energy requirement from each phase, since then having an estimation of EPBT. In the case study 3, the data stems from the literature IEA PVPS Task 12 guidelines for LCA of PV and also inclusive to Ecoinvent 2.2. The capacity of case 3 is considered as the very big capacity of a specific GMPV solar system with the use of CdTe thin film module with the boundary system focusing on the BOS installation phase.

In the table 3, there is a display of next three case studies with the region distributed from the United States, Malaysia. The case study forth aims at to use LCA for the BOS of multicrystalline silicon GMPV system at Tucson Electric Power Springerville, AZ field PV plant. The capacity is the second largest with 3.5 MWp. The boundary system of this case study starts from the BOS production to the end-life management of components in BOS system. The database of this case study is rather old, ranging from 1998, 2000 to 2004 and gathered from LCI database, Franklin Association 1998 , LCI of metals – Final report of Ecoinvent 2000 and US LCI project data. Concerning about the case study 5, LCA approach is used to evaluate the environmental impacts of GMPV installation with the capacity of 5 MW and with the different support structures. In this case study, only scenario 1 with the fixed mounting structure, primary alimunium support is taken consideration. The data is collected in 2008 and

2012 with the database of Ecoinvent v2.0. The boundary system of this study mostly range from infrastucture production, plant installation, use phase decommissioning.

Table 3 Summary table about general information of second three case studies

	Unit	Case study	Case study	Case Study
		4	5	6
Authors		Mason J.E, Fthenakis, V.M. , Hansen T., Kim H.C.	Antoine Beylot et al	Hyoungseok Kim et al
Title		LCA of the balance of system (BOS) components of the 3.5 MWp multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant. (Mason et al. 2005)	Environmental impacts of large-scale grid-connected ground-mounted PV installations (Beylot, Payet, Puech, Adra, Jacquin, Blanc, and Beloin-saint-pierre 2014)	Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems (Kim et al. 2014)
Year of Publication		2006	2012	2014
Country		Arizona, United States	China, Europe	Malaysia
LCA purpose		LCA of the balance of system (BOS) components of the 3.5 MWp multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant.	Characterizing the environmental impacts of large-scale grid-connected GMPV installations (5 MWp), considering one module technology (mc-Si) with different structures and types of supports	Use LCA approach to evaluate the envi-ronmental performance of the CdTe PV system
Temporal coverage		1998, 2000, 2004	2008 and 2012	2008, 2010
Data base for background data		USA LCI database Franklin Association 1998, LCI of metals - Final report ecoinvent 2000, US LCI project data	Ecoinvent v 2.0	AIST (National Institute of Advanced Industrial Science and Technology), JAPAN ; Ecoinvent D/B, National LCI D/B; First Solar, Inc, KACO New Energy Photovoltaic power plant (Shinan, Taean, Samnangjin, Yeongwang, and Hadong)
System boundary		Cradle to grave of BOS	Infrastucture production plant installation use phase decommisioning	Cradle to grave
FU		N/A	N/A	1 kWh of electricity
Capacity	kWp	350000	5000	100

For the case study 6 in the table 2b about the LCA of Cadmium Telluride photovoltaic system with the capacity of 100 kW, the background data collected in 2008 and 2010 with the source from AIST (National Institute of Advanced Industrial Science and Technology), JAPAN; Ecoinvent, National LCI, KACO New Energy Photovoltaic power plant. The system boundary of this case study is inclusive to the pre-production, production process, installation and operation stage. The functional unit of this case study is identified with 1 kWp of electricity

8.2.2. Summary data about photovoltaic module installation

Regarding about the photovoltaic module installation in first three case, it can be seen that for the case study 1 and 2, the type of material is multicrysline silicon, which is very popular applied in commercial area. Meanwhile, the material used in the case study 3 is CdTe. In detail, the mc-Si module of case study 1 is 235 W, less than the power rate in case 2 with 270W.

Table 4 Summary data about photovoltaic module installation in first three case studies

Categories	Unit	Case study (*)	Case study	Case study
		1	2	3
Material		mc-si	mc-si	CdTe
Power rate	W	235	270	N/A
Number of modules	items	7568	4568	N/A
Size of total modules	m^2	12362.3	7537.5	N/A
Performance ratio		N/A	0.835	0.812
Module degradation rate	%/year	N/A	0.7	0.67
Performance of module	%	14.4	17.5	12.6

The number of modules and the size of total modules in the case study 1 is respectively 7568 modules and 12362.3 m^2. The performance of mc-Si in the case study 1 is 14.4%. For the case study 2, with 4568 modules, the size for modules installation is estimated to

7537.5 m^2. The values for performance ratio, module degradation rate and performance of module is respectively 0.835, 0.7%/ year and 17.5 %. In the case study 3, there is only three remaining available data including performance ratio of 0.812, module degradation rate of 0.67 and the performance of module CdTe of 12.6 %, which is lower than comparing with two previous case studies with using mc-Si material.

For the table 5, the case study 4 and 5 possess the same material: multicrystalline silicon but case study 6 apply the material of CdTe thin film. For the case study 4, the performance of module is 12.20% meanwhile this value for case study 5 and 6 are respectively 14% and 11.2 %. The size of total modules in case study 5 is 35714 m^2 amd for case study 6 is 892.957 m^2. The performance ration of case study 5 is 0.855 and for the case study 6 is 0.8. For the module degradation rate, there is an available data in case study 6 with the value of 0.8%/ 30 years.

Table 5 Summary data about photovoltaic module installation in second three case studies

Categories	Unit	Case study	Case study	Case study
		4	5	6
Material		mc-si	mc-si	CdTe thin film
Power rate	W	N/A	N/A	N/A
Number of modules	items	N/A	N/A	N/A
Size of total modules	m^2	N/A	35714	892.957
Performance ratio		N/A	0.855	0.8
Performance of module	%	12.20	14	11.2
Module degradation rate	%/year	N/A	N/A	0.80/30years

8.2.3. Summary data about BOS installation and energy flow

Besides of PV modules installation data, BOS installation along with the data about energy flow also have a significant influence to the life cycle assessment of GMPV. In the term of BOS installation, for the table 4a, for the case study 1, there is an availability of data about the electronic components. In this study, the data not only covers from inverter with 6 items with three inverters with the power of 300kW and two remaining inverter having the power of 250kW that it also the type of inverter: multi string inverter. There are two three-phase transformers applied in the system with the power rate of 1000 kVA. There is no information about the cables. The components of mounting system, the components are aluminum cross bars used hot dip galvanizing. For the case study 2, there is data very detail about the cables meaning the weight of material per meter square size. For the case study 3, the mounting components of system are inclusive to steel, aluminum, synthetic rubber and all of these categories are calculated by amount of material by kilograms per square meters.

Table 6 Summary data about BOS installation and energy flow in first three case studies

Categories	Unit	Case study 1	Case study 2	Case study 3
Electric components		Yes	No	No
Inverter	items	6	N/A	N/A
Transformer	items	2	N/A	N/A
Cables		No	Yes	Yes
Installation of mounting system		Yes	No	Yes
Components of mounting system		Aluminum cross bars Hot dip galvanizing	Fixed mounting	Steel, aluminum, synthetic rubber
Parameters				
Irradiation	kWh/m2/year	N/A	2017	2199/1700
Wind load	km/hours	N/A	N/A	137
Snow load	kg/m2	N/A	N/A	24
Energy flow				
Total amount of used energy	kW h	9469394	5 431 888.89	N/A
Power production	kW h	45701377	213333.33	N/A
EPBT	years	4.17	2.3	0.21-0.37 (for BOS system)

For the section additional parameters in the table 6, there is no available any data for case 1 but the irradiation in case study 2 is estimated about 2017 kWh/m^2/year and this number for case study 3 is 2199 kWh/m^2/year or 1700 kWh/m^2/year. In the case study 3, the good data about wind and snow load is very helpful because it will help the LCA method can give the suitable evaluation for decision maker choosing the suitable of mounting at the suitable soil area and climate condition.

For the energy flow term, the case study 1 has the data of energy consumption for useful lifetime in 25 years with the power consumed is 9469394 kWh per year meanwhile the power production 45701337 kWh. Since then, the EPBT of PV system is 4.17 years. For the case study 2, the total amount of used energy is 5431888.89 kWh meanwhile the power production is 213333.33 kWh. The EPBT of this system is only 2.3 years. For the case study 3, it only concentrate on the BOS system so the available data of EPBT ranges from 0.21 to 0.37 years.

Table 7 Summary data about BOS installation and energy flow in next three case studies

Categories	Unit	Case study 4	Case study 5	Case study 6
Electric components		Yes	No	Yes
Inverter	items	N/A	N/A	N/A
Transformer	items	N/A	N/A	N/A
Cables		N/A	N/A	N/A
Installation of mounting system		Yes	Yes	Yes
Components of mounting system		One foot long nail without concrete foundation	Fixed mounting primary aluminum support	Ground mounted sheet iron and aluminum posts
Parameters				
Irradiation	kWh/m^2 /year	N/A	1700	1810.4
Wind load	km/hours	193	N/A	N/A
Snow load	kg/m2	N/A	N/A	N/A
Energy flow				
Total amount of used energy	kW h	N/A	N/A	N/A
Power production	kW h	N/A	N/A	4344960 kW h w/o degradation 3910464 with degradation
EPBT	years	N/A	N/A	0.98 (for BOS)

The data of next three case studies about BOS installation and energy flow is displayed in the table 7. For the case study 4 5 6, there is no detail about the number of electronic components in the PV system, only mentioning about the installation of mounting system with the respective types for each study 4 5 6 are one foot long nail without the concrete foundation support, fixed mounting with the primary aluminum support and the last is ground mounted sheet iron and aluminum posts.

For the energy flow, there is only available data in the case study 6 with the amount of power production is 4344960 kWh without considering degradation of system meanwhile if there is degradation, this value is 3910464 with degradation.

Table 8 Full table of literature data with 6 case studies

	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case Study 6
Authors	Umberto Desideri Stefania Proietti Francesco Zepparelli Paolo Sdringola Silvia Bini	Peishi Wu, Xiaoming Ma, Junping Ji, Yunrong Ma	Parikhit Sinha Mariska de Wild-Scholten	Mason J.E, Fthenakis, V.M. , Hansen T., Kim H.C.	Antoine Beylot et al	Hyoungseok Kim et al
Title	Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems	Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study	Life cycle assessment of utility scale CdTe photovoltaic balance of system	LCA of the balance of system (BOS) components of the 3.5 MWp multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant.	Environmental impacts of large-scale grid-connected ground-mounted PV installations	Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems
Year of Publication	2012	2017	2012	2006	2012	2014
Country	Italy	China	United States	Arizona, United States	N/A	Malaysia
Temporal coverage	2008, 2009	2005/2006	2011	1998, 2000, 2004	2008 and 2012	2008, 2010
System Capacity	1778.48 kWp	1000kWp	550000kWp	350000 kWp	5000 kWp	100kWp

§	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case Study 6
LCA purpose	LCA of ground mounted PV installation	Assessment about the environmental impact of multicrystalline silicon PV ground mounting in China	Assessment of ground mounted BOS for planned thin-film CdTe 550MW Topaz Solar plant in southest United States.	LCA of the balance of system (BOS) components of the 3.5 MWp multi-crystalline PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant.	Characterizing the environmental impacts of large-scale grid-connected GMPV installations (5 MWp), considering one module technology (mc-Si) with different structures and types of supports	Use LCA approach to evaluate the environmental performance of the CdTe PV system
Data base for background data	. From technical documentation from TerniEnergia . From on site measurements during the construction of the photovoltaic field. .Ecoinvent Idemat 2001 BUWAL 250 ETH-ESU 96	Wild-Scholten, M.J. de and E.A. Alsema, Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production	International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) Task 12 guidelines for life cycle assessment (LCA) of PV Ecoinvent v2.2	USA LCI database Franklin Association 1998, LCI of metals - Final report ecoinvent 2000, US LCI project data	Ecoinvent v 2.0	AIST (National Institute of Advanced Industrial Science and Technology), JAPAN ; Ecoinvent D/B, National LCI D/B; First Solar, Inc, KACO New Energy Photovoltaic power plant (Shinan, Taean, Samnangjin, Yeongwang, and Hadong)
System boundary	Cradle to grave	PV technolgy production to grate	BOS installation phase	Cradle to grave of BOS	Infrastucture production plant installation use phase decommisioning	Cradle to grave
FU	N/A		BOS for 550 MWac CdTe utility scale PV system	N/A	N/A	1 kWh of electricity

	Unit	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case Study 6
Photovoltaic module installation							
Material		Polycrystalline silicon	Multi-crystalline silicon	CdTe thin film	Multi-crystalline silicon	Multi-crystalline silicon	CdTe thin film
Power	W	235	270	N/A	N/A	N/A	N/A
Number of modules	items	7568	4568	N/A	N/A	N/A	N/A
Size of total modules	m2	12362.328	7537.5	N/A	N/A	N/A	892.957
Module degration rate	% /	N/A	0.7	0.67	N/A	N/A	0.8 / 30 years
Performance ratio	%	N/A	0.835	0.812	N/A	0.855	0.8
Performance of module	%	14.4	17.5	1.1	12.20	14	11.2
Detailed inventory data available for …							
Electric components		Yes	No	Yes	No	Yes	Yes
Inverter							
Number	items	6	N/A	N/A	N/A	10	1
Transformer							
Number	items	2	N/A	N/A	N/A	5	N/A
Power rating	kW	1000	N/A	1000	N/A	1000	N/A

	Unit	Case study 1	Case study 2	Case study 3	Case study 4	Case study 5	Case Study 6
Cabling, Mouting system and its material							
Cabling		No	Yes	Yes	No	Yes	Yes
Installation of mounting		Yes	No	Yes	No	Yes	Yes
Component of support structure		Aluminum cross bars Hot dip galvanizing	Fixed mounting	cdTe thin film	N/A	Fixed mounting primary aluminum	Galvanized sheet iron, aluminium post frame and concrete
Parameters							
Irradiation	kWh/m2/year		2017	2199/1700	N/A	1700	1810.4
Degradation rate	%/year			0.67			0.80/30years
Wind load	km/hours	N/A	N/A	137	193	N/A	N/A
Snow load	kg/m2	N/A	N/A	24	N/A	N/A	N/A
Energy flow							
Total amount of used energy	kW h	N/A	5 431 888.89	N/A	N/A	N/A	N/A
Power production	kW h	45701377	213333.33	N/A	N/A	N/A	4344960 no considering degradation
EPBT	years	4.17	2.3	0.21-0.37	N/A	N/A	0.98
Fuel consumption for	J	683.1	N/A	N/A	N/A	N/A	0.221 MJ/kWh

9. Results and discussion

The way to figure out the data gap comparing with the avaidable data in Ecoinvent v3.3 is implemented by literature research through studying six case studies of life cycle assessment of GMPV with different capacity. It can be seen that, in the ecoinvent data v3.3, the capacity of GMPV system stay at 570 kWp with very rare data of different categories in PV installation. It is only relevant to the data input including inverter with power rate and the size of total PV modules, the size of construction GMPV system, the diesel burned in machine belonging to the category of demolition and site preparation.

Basing on the tables of data collected from the six articles and comparing with the available data in the Ecoinvent 3.3, it can be clearly seen that the gap data mostly about the photovoltaic module installation, BOS installation technology. In detail, in the part of photovoltaic module installation, there is lacking of data about performance of module, degradation rate of module, performance ratio, number of modules, system boundary, power rate of module. The impact of the lacking these types of data will make the LCA approach find difficult to identify the limitation to give the evaluation or taking data when there is a lacking of identification of system boundary. The LCA method is also negatively affected by the data shortage about degradation rate of module because the degradation rate of module will reflect the importance either in economy and also in technical term. In the economy aspect, the degradation rate of the module will reflec the power output of system. When the degradation rate of module is high then the power generation will be lower, negative impact on the financial benefits. Otherwises, in the term of technology,

Concerning about the data gap of BOS installation technology, similar to other studied articles, the available data is only about the number of inverters and power rate. Meanwhile, the data of cabling which is calculated by kg/m^2, is not available in the ecoinvent. There is a data gap of transformer, associating with power rate and number of transformer.

The ecoinvent data also need the additional data about the components of mounting structure installation, information about the snow and wind load. The data about the irradiation also play an important role for the LCA used to evaluate the performance of module, power generation, since then affecting on the EPBT of PV system. Furthermore, to enhace the LCA performance in the GMPV system, it also should pay attention to the data gap of land preparation because it will partly reflect the types of soil, which are highly useful for operators when adopting the area for installing GMPV system or choosing suitable types of mounting system.

To close the data gaps in the Ecoinvent data 3.3 for the power plant with capacity of 570kWp

- The first data gap is the power output of GMPV 570 kWp
- The second data gap is about the number of modules for the GMPV system. To calculate this number of modules
- The third data gap is about the degradation rate of module
- The forth data gap is about the performance of module or conversion efficiency

Meanwhile, the area for the 570kWp GMPV panel is 4401.075 m^2 so the power output produced from the specific number of modules with the support of the inverter 500kW . Also, according to the IEA PVPS report task 12 for the ground mounting photovoltaic system with capacity of 570 kWp in Spain, the electricity yield for each square meter is 198 kWh/m^2*a (Fthenakis et al. 2011), since then if applying this number for the calculation to find the data gap of power output in ecoinvent v 3.3, the value is 871 412.85 kWh, approximately the annual power generation is 871 MWh.

The second gap data, which should be fulfilled in the ecoinvent v3.3 is the number of modules. To have this number, it is necessary to have the size of one module and the total size of the module. Because the shortage of the data about the size of module, therefore, the data from the case studies in the table 4, and table 5 providing about the size of each module. Supposing that neglection about the distance between modules. According to the case study 1, the size of module calculated will be 1.6335 m^2 with the power module of 235 Wp. Thus, the number of modules will be 2694 modules. In case of this module, the total electricity generation will be changed and the power output in this scenario is 633090W , equivalent to 633.090 kWp.

In the scenario 2, with the size of module is 1.65 m^2 then the number of modules will be 2667 modules. With the power of module is 270Wp, the power output for this case will be 720090W equivalent to 720 kWp.

Table 9 Scenario for number of modules calculation

	Unit	Scenario 1	Scenario 2
Total size of modules	M^2	4401.075	4401.075
Size each modules	M2	1.6335	1.65
Number of modules	Items	2694	2667

The third data gap very important for life cycle assessment of GMPV is degradation rate of module. The reason is that the high degradation rate of module will reflect the high electricity consumption of modules and even the life time of module will be lower. This low quality of module will result in the environmental problems, energy consumption, the cost for operation and maintenance. Therefore, the degradation rate of module will be a good element for operator using LCA approach to make the evaluation in detail and more precise. To close the gap of this data, it can be based on the types of module from the research studies. In case of using multicrystalline silicon module case study 2, the degradation rate of this module will be 0.7%.

To bridge the data gap of performance of the module. In the case of using the multicrystallin silicon cell in case study 1, the conversion efficiency is 14.4%. For the case study 2, this value will be 17.5%. However, if using the case study thin film solar module, the conversion efficiency will be reduced (12.6 % for case study 3 and 11.2% for case study 6).

10. Conclusion

Photovoltaic system can be regarded as a potential alternative source for electricity production instead of using fossil fuels. The study focused on the ground mounted photovoltaic system, which is currently developing in many countries and the life cycle of whole photovoltaic system has many significant impacts on the environment, human health and also the development of economy. The thesis has a detail description about the photovoltaic system starting from the fundamental unit solar cells to the whole system. Two main parts in the photovoltaic system including photovoltaic panels and balance of system also are detail analyzed. The state of the art of photovoltaic system relevant to GMPV technology is indicated. Although crystallin silicon still leads the position in highest conversion efficiency but CdTe thin film is still the dominant material for GMPV panels because of the competitive price and growing conversion efficiency. For the balance of system, the development of technology is presented at the metal posts which is covered by the zinc and aluminum outside to preven the corrosion though the up to date technology hot dip galvanizing.

Because the development of GMPV installation, the approach life cycle assessment needed to be implemented to make evaluation about the impact of GMPV. However, the data available in the latest ecoinven is not sufficient for operators using LCA approach to make an evaluation. Therefore, the task of the thesis is about closing the data gaps for the data ecoinvent of 570kWp GMPV system. There are six case studies reviewed with the different values of photovoltaic panels also the balance of system. However, there is still the shortage of data resulting in the closing the data gaps is not completely progressing.

The thesis answered the research question about the missing data of GMPV. The data gaps include: power output generation, number of modules calculated based on the different module from case study 1 and case study 2, since then the power output is also changed according to the power module so the value of the power generation is changed. The power output when the electricity yield of 198 kWh/ m^2 is 871 MWh. For the using two different modules from case study 1 and case study 2. The respective power out put is 633.090 kWp and 720 kWp. The literature study also supports to find the performance of module and degradation rate. The result data gap for performance module of case study

1 is 14.4% and for the case study 2, the data gap will be 17.5%. If using the material panel of CdTe thin film, the performance of module is 12.6% for using case study 3 and 11.2 % for using the case study 6. Furthermore, the degradation rate is also important data gaps which have significant impacts on the implementation of LCA approach. The degradation rate if using multicyrstallin silicon in case study is 0.7%/year.

About the future development of GMPV technology, it can be assured that the CdTe thin film technology is becoming the dominant material technology with the feasible price, growing efficiency and eco-friendly. Other types of material GMPV technology is relevant to organic PV modules but it is still on progressing of research.

For the balance of system, the metal post with using hot dip galvanizing plays an important role in the safety for the GMPV supporting system. Furthermore, using the types of helical pile or screw without needing of concrete will partly reduce the energy consumption and firm attachment to the ground but however, it depends on the condition of soild and climate condition to give the decision for choosing suitable ground mounting system.

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