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Life Cycle Assessment of Photovoltaic Systems in the APEC Region

APEC Energy Working Group

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Prepared by:

Dr. Norasikin Ahmad Ludin (Project Overseer)
EWG06 2017A: Economic and Life Cycle Analysis of Photovoltaic System in APEC Region towards Low-Carbon Society,
Solar Energy Research Institute (SERI),
National University of Malaysia (UKM)
Tel: (60) 89118586 | Fax: (60) 89118574
Email: sheekeen@ukm.edu.my

Produced for:
Asia-Pacific Economic Cooperation (APEC)
35 Heng Mui Keng Terrace
Singapore 119616
Tel: (65) 6891-9600 | Fax: (65) 6891-9690
Email: info@apec.org Website: www.apec.org

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KEY ABBREVIATIONS

APEC	Asia-Pacific Economic Cooperation
EWG	Energy Working Group
LCA	Life Cycle Assessment /Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCCA	Life Cycle Cost Assessment/ Life Cycle Cost Analysis
LCOE	Levelized Cost of Energy
EA	Environmental Assessment
EPBT	Energy Payback Times
GHG	Greenhouse Gases
PV	Photovoltaic
ISO	International Organization for Standard
SAPV	Standalone Photovoltaic System
SRPV	Solar Rooftop Photovoltaic System
SFPV	Solar Farm Photovoltaic System
IRR	Internal Rate of Ratio
PB	Payback Period
ROI	Return of Investment
GWP	Global Warming Potential
O&M	Operation & Maintenance
ILCD	Life Cycle Data System
BOS	Balance of System
IPCC	Intergovernmental Panel on Climate Change

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FOREWORD

Environmental impact issues must never be neglected in managing energy supply and demand responsibly. These issues have been studied and investigated through Environmental Assessment (EA) method, namely the Life Cycle Assessment (LCA) which was developed in the early 90's. LCA is the assessment of the environmental impact of a given product or service throughout its lifespan and it is one of the most well-known analysis methods providing guidance on assuring consistency, balance, transparency and quality to enhance the credibility and reliability of the results. LCA is a completely structured, comprehensive and internationally standardized method. It quantifies and qualifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues.

Associated to LCA, another study of which covers the economic assessment upon implemented paradigm is the Life Cycle Cost Assessment (LCCA). LCCA is a process of evaluating the economic performance of a system over its entire life. Sometimes known as whole cost accounting or total cost of ownership, LCCA balances initial monetary investment with the long-term expense of owning and operating the project. LCCA is based upon the assumptions that multiple design options can meet programmatic needs and achieve acceptable performance, and that these options have differing initial costs, operating costs, maintenance costs, and possibly different life cycles. In other words, LCCA will assist in providing the bigger picture of the project from economic point of view as well as environmental cost incurred throughout the project lifetime.

The EWG06 2017A Project, Economic and Life Cycle Analysis of Photovoltaic Systems in APEC Region towards Low-Carbon Society aims to prepare a documentation for APEC Member Economies especially APEC financial ministries can embrace and implement its applicability based on their respective circumstances according to these objectives:

I. Develop recommendation for report & guideline of economic and life cycle assessment of solar PV system for future development;
II. Creating a network of solar PV players and financial institutions in APEC economies for multilateral and regional cooperation;
III. Increase knowledge of participants and society on the environmental impact of solar PV systems through workshop and publication.

The project aligns with the APEC Member Economies undergoing policy and programme shifts to promote development of sustainable communities across the region. Furthermore, it follows the Energy Working Group's (EWG) Strategic Plan 2014-2018, which aims to promote energy efficiency and sustainable communities. The report and guidelines recommendation are intended to be develop using Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) tools to identify the most viable photovoltaic systems both in terms of environmental impact and economic.

The project is expected to be completed within timeframe of 11 months from January to November of 2018 with the following benefits:

- Enhancing cooperation among international energy agencies in utilizing LCA and LCCA report as reference tools in the PV industry.
- Policy recommendation to be based on LCA studies, analysis and issues.
- Strong communication highway as the report & guideline will be made accessible.
- Increase awareness among the PV industries & society on the environmental impact of the solar PV systems.

The Expert Meeting and Workshop are expected deliverables as a platform to discuss, review and agree on a set of guidelines for the project as a whole whilst taking into account APEC regional expert's point of views in term of best practices and success stories sharing from public and private sectors of APEC economies. This involvement shall promote capacity building among project beneficiaries and APEC economies experts which furthermore widen the scope of applied LCA & LCCA studies through real industrial player's case studies.

This report provides an update of the life cycle analysis (LCA) framework as well as the complete analytical result of photovoltaic system case study assessment result and discussion of the subject.

EXECUTIVE SUMMARY

This report focuses on the Life Cycle analytical assessments of Photovoltaic (PV) Systems; Solar Farm system, Solar Rooftop system and Solar for Rural electrification system. In particular, this report provides comprehensive descriptions of methods and models used when analyzing the PV systems life cycle from cradle-to-grave.

The main objectives of this report are:

1) To propose the best practices and viable type of PV systems based on their life cycle assessment.
2) To determine and understand the PV systems impact and contribution towards the low carbon society.
3) To analyze the new PV systems technology life cycle and best practices to draw out highlighted issues for viability.

In the first section, 'APEC Region Photovoltaic Context', best practices in PV systems within the APEC economies are documented. In addition to describing general approaches and listing common reference documents by selected economies which are Malaysia, Thailand and Indonesia, the section outlines solar photovoltaic policies overview of each economies.

In the second section, 'Framework', comprehensive guidelines on how the study is carried out, based on real case study of the three economies. The section emphasizes the specific goal, scope and methodology of the whole life cycle assessment of the systems. The framework are agreed on by field experts during the EWG06 2017A Expert Meeting held on March 2018.

The majority of presented methods and tools can be applied irrespective of particular technology and systems. However, a whole life cycle assessment over three different systems would require some considerations, as outlined in a dedicated chapter on 'Foreground Case Study Extraction'. In particular, Solar farm, Solar rooftop and Solar for rural electrification have been analyzed in this study comparing real case study data to the experimental data using the Eco-Invent database software, as one whole system.

The extracted data of both indirect and direct energy consumption of the system life cycle energy input are described in the fourth chapter, 'Life Cycle Inventory (LCI)'. This section outlines each type of PV system designs divided into five phase in the life cycle system boundaries, which are the Manufacturing phase, Installation phase, Transportation phase, Operation and Maintenance phase, and Dismantling and Disposal phase. Finally, Energy payback of the whole system shall be discussed together with the cumulative energy demand as the basic approach of real-time data processing is described as a means to optimize system output by increased responsiveness to outages.

The measures that are used for midpoint impact assessment from the Eco-Invent database are discussed in depth according to few environmental impact indicators through this section, 'Life

Cycle Impact Assessment (LCIA)'. Several environmental impact analyses such as Global Warming Potential (GWP), Greenhouse Gases Protocol (GHG), and Individualist Midpoint Recipe are thoroughly discussed for each PV systems providing deeper insight into the pitfalls and merits of various system design options.

The analyzed result of each system are compiled and compared to layout the PV systems performance and viability over each design. To this end, the goal of LCA is that the environmental performance of products and services be compared as well as succeed in choosing the least burdensome.

1.0 APEC Region Photovoltaic Context

Cities cover just two percent of the world's land mass but accounted for 70% of global Gross Domestic Product (GDP), more than 70% of energy consumed and over 70% of the greenhouse gas emissions are from human activities. APEC's 21 member economies as listed Table 1 represent 41% of the global population, 49% of international trade and 56% of the world's GDP. Half of the world's megacities (more than 10 million people) are in APEC, with an aggregate population of 231.4 million people. This growth poses enormous infrastructure and service challenges for urban areas [1].

Table 1: APEC Member Economies and Economy Gross Domestic Product

	Member Economies	**Date of Joining**	**Economy GDP 2017 (Millions of Int$)**
AUS	Australia	Nov 1989	1,235,297
BD	Brunei Darussalam	Nov 1989	32,958
CDA	Canada	Nov 1989	1,763,785
CHL	Chile	Nov 1994	452,095
PRC	People's Republic of China	Nov 1991	23,122,027
HKC	Hong Kong, China	Nov 1991	453,019
INA	Indonesia	Nov 1989	3,242,966
JPN	Japan	Nov 1989	5,405,072
ROK	Republic of Korea	Nov 1989	2,026,651
MAS	Malaysia	Nov 1989	926,081
MEX	Mexico	Nov 1993	2,406,087
NZ	New Zealand	Nov 1989	185,748
PNG	Papua New Guinea	Nov 1993	30,839
PE	Peru	Nov 1998	424,639
PH	The Republic of Philippines	Nov 1989	874,518
RUS	The Russian Federation	Nov 1998	4,000,096
SGP	Singapore	Nov 1989	513,744
CT	Chinese Taipei	Nov 1991	1,175,308
THA	Thailand	Nov 1989	1,228,941
USA	United States	Nov 1989	19,362,129
VN	Viet Nam	Nov 1998	643,902

Source : World Bank 2015

In 2009, half of the world's megacities were in APEC economies, with 231 million people and 60% of global primary energy demand as shown in Figure 1. The energy demand has doubled since 1990 for 11 out of 21 APEC economies. Energy imports to APEC economies are projected to increase by approximately 92% between 2000 and 2013 as domestic supplies fail to keep pace with expanding energy demands [2].

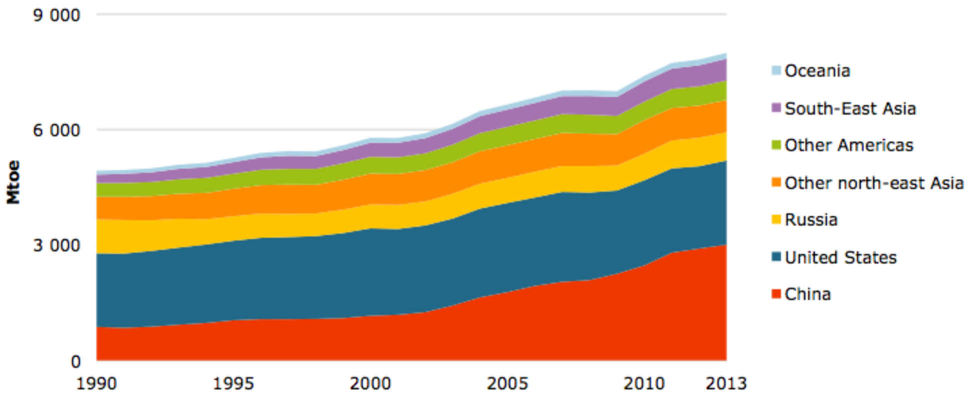


Figure 1 : Total primary energy demand by APEC regional grouping, 1990-2013

Source : IEA (2015)

APEC energy demand has been rising since at an average annual growth rate (AAGR) of 2.1%, slightly above the global energy demand rate of 1.9% [3]. The largest leap in APEC's total primary energy has come to 8,000 million tonnes of oil equivalent (Mtoe) in 2013 which is about 62% hike compare to 1990 level as illustrated in Figure 2.

Net additions of coal (673 GW) and gas (794 GW) exceed those of wind (420 GW) and solar (470 GW) [4]. Capacity is expected to increase for both gas-fired and coal-fired generation; gas-fired plants because of lower emissions and easier siting, coal-fired plants because of their cheap and relatively stable fuel supply. Even though there is a significant increment in coal from the total primary energy supply by fuel to 2013, the growth of other source of energy can also be seen in total contribute to the overall of 7995 Mtoe in 2013 [5]. This is proven by the rapid economic development in China that highly affect the growth in both APEC and global energy demand [5].

The International Energy Agency (IEA) estimates that, by 2050, PV will provide approximately 11% of global electricity production and avoid 2.3 Gt of carbon dioxide emissions per year [2]. IEA has indicated that energy technology revolution is under way and widespread deployment of low-carbon technologies will not only help address the climate change challenge but will also enhance energy security and economic development [6].

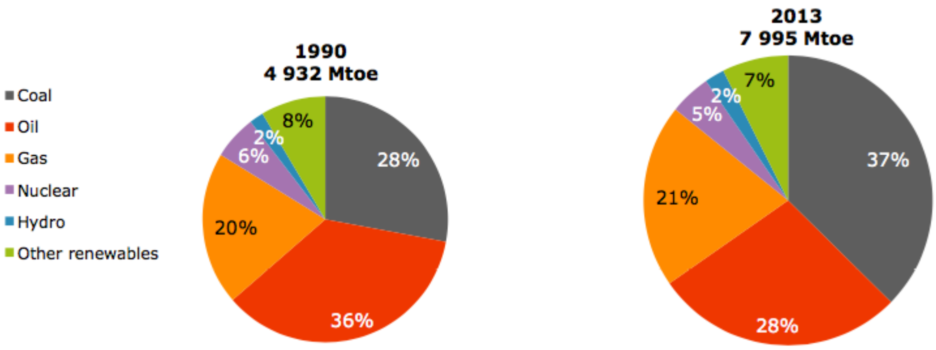


Figure 2 : APEC total primary energy supply by fuel, 1990 and 2013

Source : EIA (2015)

Meeting the growing energy needs of these 21 economies, particularly the rising demand for urban energy services, is a priority for APEC's Economic Leaders. Collectively, they have committed to increasing use of renewable energy to help in meeting the region's needs, led by three key market drivers [7]:

- Energy Security, to diversify a city's energy mix, reduce dependence on fossil fuels and provide a hedge against fuel price uncertainty.
- Climate Change, to ensure a cleaner environment by reducing CO_2, greenhouse gases and other harmful emissions. Renewable energy can be an essential element in city strategies to become low GHG or carbon neutral cities.
- Economic Development, to generate new and improved jobs, incomes, revenues and profits; diversify and strengthen local economies; and enhance the export base.

Renewable energy growing demand according the above driver is expected to double reaching 1360 Mtoe in 2040 (from 770 Mtoe in 2013) in a BAU scenario [5]. The renewable energy demand expansion satisfy two-thirds of the increase occurs in China, as the largest energy user in APEC. The share of renewables as shown in Figure 3, for China has rose to 52% in 2040 based on 43% in 2013 [8]. This followed by South-East Asia which is expected to add more than 105 Mtoe by 2040 and the United States adds 37 Mtoe [5]. Moreover, the other APEC members, The Russian Federation, other north-east Asia, other Americas and Oceania, all together add up to 68 Mtoe [5].

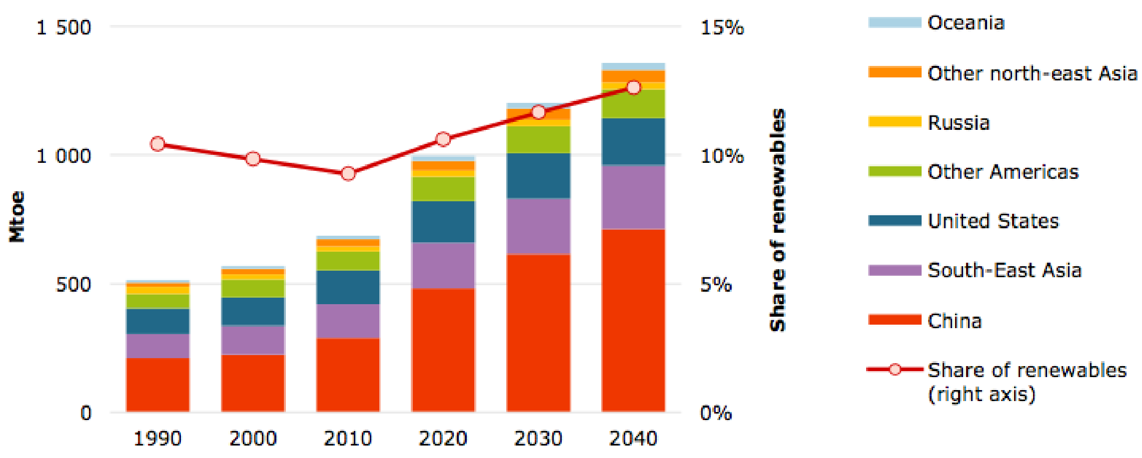


Figure 3: Renewable energy production by regional grouping, 1990-2040

Source : APERC and IEA (2015)

In most APEC economies, rising urbanisation drives up energy use. People in urban areas, particularly in developing Asia, consume significantly higher levels of energy than those in rural areas because of differences in lifestyles and demand for higher comfort levels. Thus, the bigger picture of environment and redirection of green energy technology has to support the global health issues.

Air pollution has become a big issue in causing ill health to humans and animal, particularly in cities and also towards the ecosystem whether directly or indirectly. The main contributor to this are known as the greenhouse gases that also leads to global warming in the near future. Carbon Dioxide (CO_2) is an active greenhouse gas that are released over simple combustion and as such, is difficult to control. Numerous studies have examined its effect and determined a range for the social cost of carbon which is USD 17 to USD 80 per tonne of CO_2. REmap assesses both outdoor and indoor air pollution using a methodology developed specifically for the purpose [9].

In most mature APEC economies, energy consumption per capita declines as economies shift towards the service sector and improve energy efficiency such as described by Figure 4. Some members adopted the APEC goal of improving energy intensity by 45% by 2035 such as Brunei Darussalam, Hong Kong, China, People's Republic of China and Thailand. Brunei Darussalam has targets by 2035 (2005 base) of 10% renewable electricity and energy intensity reduction of 45%; increase gas and oil production to 650 000 bbl/d [10].

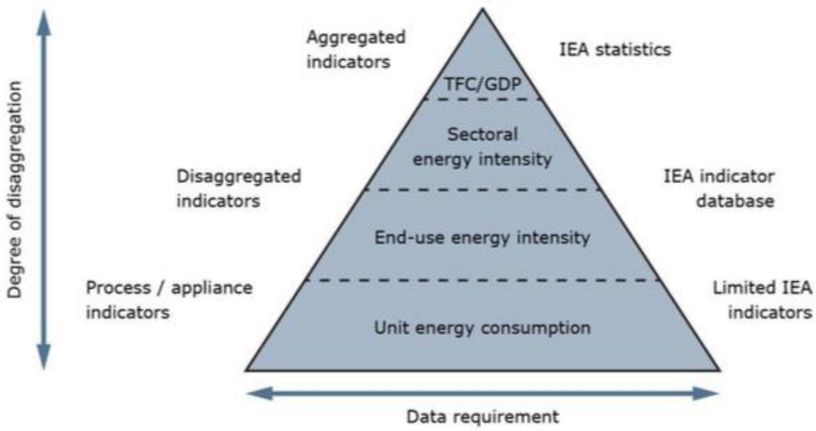


Figure 4 : Pyramid of Energy Efficiency

Source : IEA (2014)

For example, Hong Kong, China has targeted a 40% reduction in energy intensity by 2025 (from 2005 base); by limiting coal to no more than 10% of power mix, with gas reaching around 40%, renewables 3% to 4%, and remainder being imported nuclear power [11]. In the other hand, People's Republic of China has a rapid expansion of public transport systems, tightening of fuel economy standards and target of 5 million EVs and FCEVs in 2020; 60% to 65% reduction in CO_2 intensity by 2030 (2005 base), with CO_2 emissions peaking around 2030; non-fossil primary energy reaching 20% by 2030 [12]. Thailand has introduced fuel price reform; aiming towards 30% energy intensity reduction by 2036 (from 2005 base) and pushing for energy mix of coal up to 23% and renewables at 20% by 2036 [13].

Meanwhile, economies, especially in other north-east Asia such as Japan, Republic of Korea and Chinese Taipei, committed to energy efficiency goals well beyond the 45% target [11]. Japan has liberalise electricity and gas markets, strengthen energy efficiency measures, pursue power mix target of 20% to 22% nuclear, 22% to 24% renewables, 27% LNG, 26% coal and 3% oil; energy-related CO2 reductions of 25% by 2030 from FY 2013 [11]. Korea has maintained its nuclear share at 29% of capacity; renewables target of 11% of TPES by

2035. Chinese Taipei has consecutive decommissioning of nuclear power plants between 2018 and 2025; accelerate deployment of renewables with capacity target of 12.5 GW by 2030 [14].

Moreover, by using different target years or base years, or by measuring their energy savings in petajoules (PJ), several economies such as Canada, Chile, New Zealand and Peru have framed their goals in ways that are not directly comparable to the APEC goal [2]. Canada has strict regulations on coal-fired electricity and phasing out of nuclear as well as diversifying oil and gas exports. Chile has targeted 20% of electricity from non-hydro renewables by 2025; 20% energy savings goal by 2020; and 70% of electricity generation from renewables by 2050 [2].

Meanwhile, New Zealand plans to have 90% renewable electricity by 2025; enhanced building codes and minimum energy performance standards (MEPS) in their effort to further reduce energy demand. As for Peru, continuation in the development of major gas finds; blend rate of 5% for bioethanol and 2% for biodiesel; expanding the use of natural gas in power sector and increase electrification rate to 99% by 2025 [15] are among the efforts taken to meet the goal.

Modern energy services have to provide reliable high-quality and affordable electricity, fuels and thermal energy for all sectors of the economy while reducing the carbon intensity as well as the air and water pollution from traditional energy systems operations. These challenges apply to all APEC economies, with megacities presenting special requirements for infrastructure services. The imperative for making cities more liveable and better able to meet the needs of all of their inhabitants is reflected in the sustainable development plans of hundreds of cities throughout much of APEC.

2.0 Background

2.1 Approach

PV systems are still expensive sources of electricity compared with fossil fuel generation, financial incentives, either direct or indirect, are often necessary for application. Support for use of PV systems in APEC economies such as subsidies, green electricity promotion, net metering, enhanced feed-in tariffs and loans with reduced rates or tax credits are required. Policy makers and financial institutions, who will be involve in making decisions on providing the supports require knowledge of economic and LCA of these systems in order to make an informed decision. This project will directly benefit the all players in solar PV industries, financial institutions and indirectly give benefit to the society to be more proactive in reducing carbon emission by using the solar PV systems.

Therefore, this report focuses primarily on commercial application of photovoltaic system energy technologies, such as solar farm, solar rooftop and solar stand-alone. The report is the product of extensive studies using a variety of primary and secondary data sources. These included private communications with professionals active in relevant fields and industries, as well as documents and web sites from a variety of international agency, government, private sector, non-government, financial and academic organizations. Secondary sources included published reports, journal articles, reports in renewable energy newsletters and magazines, workshop proceedings and on line news reports. The compilation of data analysis is done with SIMAPro software and Eco-Invent database.

Notably, several recently published reports provide new data and insights on barriers and lessons learned to the widespread diffusion of renewable energy systems and technologies.

2.2 Objectives

a) To develop an impact assessment of photovoltaic systems framework through Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) from cradle-to-grave.

b) To identify the most viable photovoltaic systems (Solar Farm, Solar Rooftop and Stand-alone Solar) based on impact assessment indicator Global Warming Potential (GWP) and Return of Investment (ROI).

c) To infuse Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) as a tool for photovoltaic systems policy development within the APEC region.

2.3 Goal and Scope Definition

The goal & scope definition are stated as to understand the overall life cycle impact of the solar technology systems from manufacturing towards its end-of-life (cradle-to-grave). The life cycle study shall be a process based method. Project case studies include three photovoltaic system which are a Solar Farm with power production more than 1MWp and are set up on land, a Solar Rooftop with power production within the range of 500kWp to 1MWp and a Stand-alone Solar for Rural Electrification with power production less than 100kWp to 500kWp. LCAs usually do not address such things as social impacts or financial considerations so must be used in conjunction with other decision support tools.

The system is set to be normalized over certain basis for comparison purposes which are :

- ✓ A polycrystalline or monocrystalline system,
- ✓ The systems are expected to be stable with at least 2 years of being operational,
- ✓ A commercial site, within the APEC economies only.

Furthermore, the three PV systems are to be compared between the global warming potential (GWP) and energy cycle. The analysis will be done using SIMAPro for LCA and Excel spreadsheet for LCCA.

The scope of study is to assume 25 years of lifetime for all photovoltaic system in three case studies based on a 2 years matured system. Referencing on Energy Commission of Malaysia, there will be a 21 years of licensing and renewal for the whole system. Other economies cases shall be taken into account in term of LCCA lookout. Obligatory properties consideration includes quantification of system's power production, environmental impact, energy and economic cycle. Positioning properties must meet the following criteria which is; a tropical climate economy within the equator. The functional unit is global warming potential (GWP) and energy cycle based on ISO standards on power production of 3 types of photovoltaic system under similar weather conditions with environmental impact according to Environment & Carbon footprint for 25 years of lifetime.

2.4 Framework

The functional unit of the Life Cycle Assessment study is the Global Warming Potential (GWP) and Energy Cycle based according to ISO standards [16] on power production of three types of Photovoltaic System under similar weather condition, with environmental impact according to Environment [16] and Carbon footprint [16] for 25 years of lifetime.

One of the aims of this project is to compare and forecast GHG emission for GWP between the three different systems. To enable us to study this, a standardize reference flow of functional unit is required. According to past studies on LCA, which only focus whole system as a reference, no comparison has been done between different operational systems. Taking into consideration of stand-alone feature and its energy production is 1 kWp, it would not be fair to compare this to larger higher energy production systems like the solar farm and roof top systems. Therefore, for comparison purposes, the reference flows of the functional unit are normalized at 1kWp power production from three photovoltaic systems.

Obligatory properties that are quantified in the functional unit are power production, monocrystalline photovoltaic, polycrystalline photovoltaic, environmental impact, economic cycle, Balance of System (BOS) and Maintenance. Meanwhile, the positioning properties are tropical climate economies, 25 years of lifetime and transportation. These properties are clearly stated in setting the boundary for the study.

The study has such overall boundaries to keep on tract of the objectives, it covers eco-sphere (environment) affect but not techno-sphere (Human) affect and social. It only accounts for impacts related to normal operation of processes and products, assuming there is no spill, accident and natural disaster throughout the whole process. It does not take into accounts of health impact that products may directly exert on humans, workplace-exposure and indoor emissions. The study estimates through average of the three case studies for maintenance and replacement [17].

The project case study timeline are shown in Figure 5. The system boundary for all case studies is Cradle-to-Grave which include manufacturing, transport, construction, operation & maintenance and dismantling & disposal.

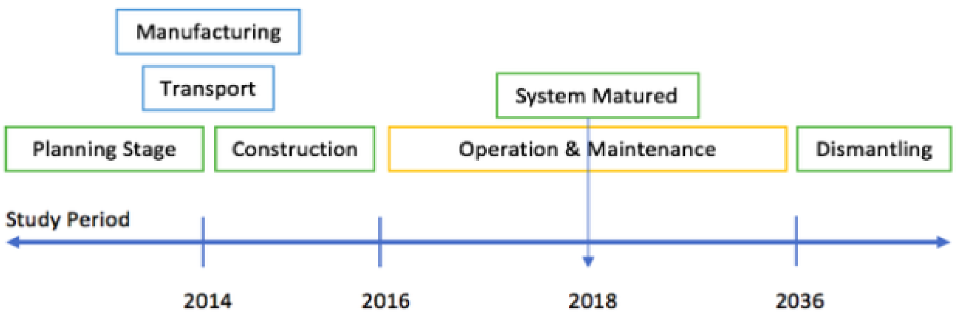


Figure 5 : Project Study Timeline

The system boundaries shown in Figure 6 is the primary data acquired from the site visit and first hand observation (primary data).The other is the secondary data that are acquired from the SIMAPro software databases which is an internationally approved databases.

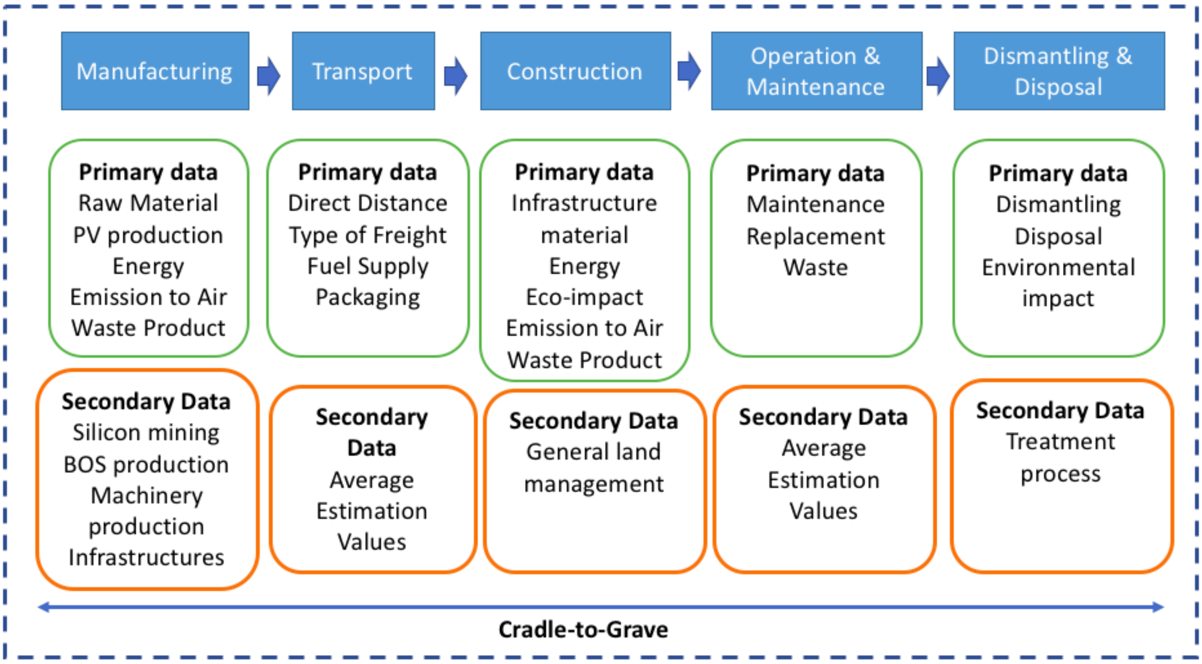


Figure 6 : System Boundary

Based on the system boundaries, the life cycle framework of the whole study is developed as shown in Figure 7 below. The framework covers all process flow and co-products for both LCA and LCCA.

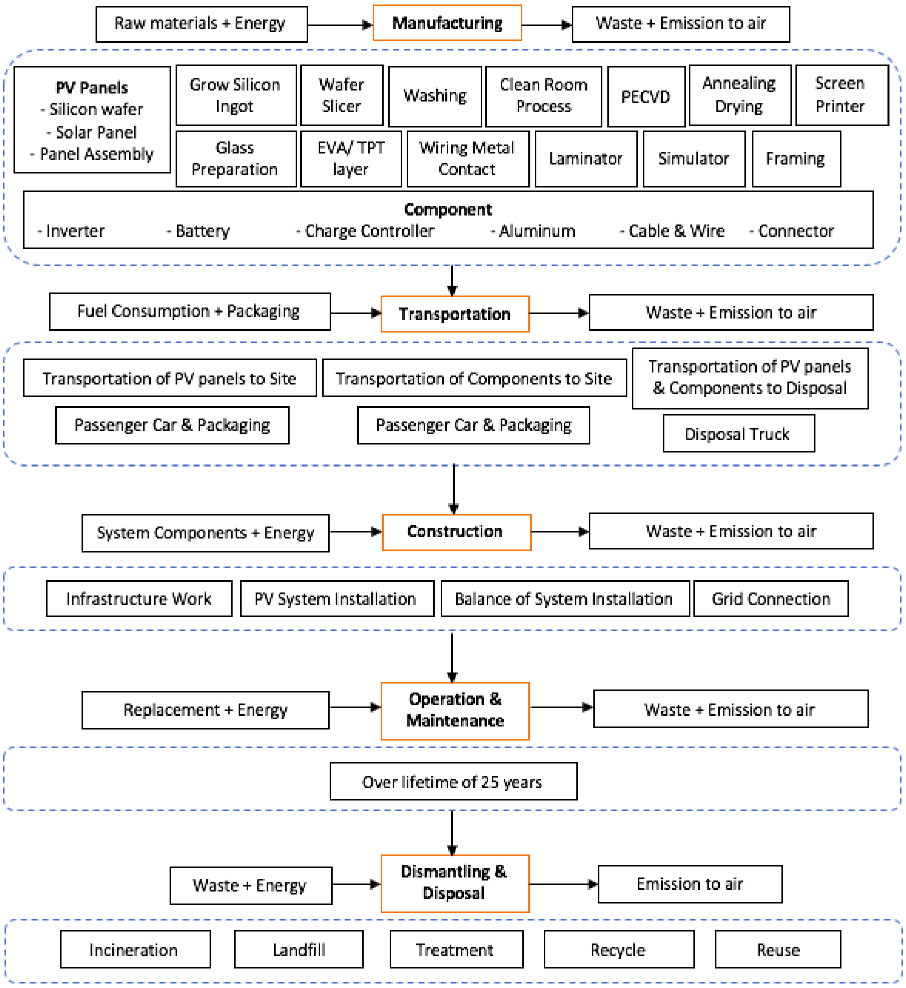


Figure 7 : Framework Study

The project LCA will also take into account all the phases which is commonly known as *Cradle-to-Grave* approach. Cradle-to-Grave includes assessment of 5 phases:

i. ***Manufacturing of Photovoltaic,***
ii. ***Balance of System Installation/Construction,***
iii. ***Transportation & Packaging,***
iv. ***Operation & Maintenance and***
v. ***Dismantling & Disposal***.

Manufacturing phase of photovoltaic shall involve production process, the use of chemicals, machinery, raw materials, energy consumption, solid waste and emission. The primary data collection will not include silicon mining, since the initiation from that stage also contributes to other product manufacturing, each BOS component production, machinery manufacturing and infrastructure manufacturing for the construction set up.

On the other hand, transportation takes account only the direct distance i.e. point A to point B. The type of transportation and fuel consumption for direct transfer will be accounted in terms of fuel efficiency and carbon emission. Packaging of product only includes the ones that are being disposed for waste. The transportation impact from each case study will be from the silicon feedstock supplier to manufacturing site, from manufacturing site to the case study site, from BOS manufacturing site to case study site and from case study site to disposal site.

Moreover, the construction will consider the infrastructure material (metal works, balance of system), energy consumption from machinery and eco-impact from land clearing. This phase will not consider social and geographical influence over general land management which means how they retrieve the land either from deforestation or any other methods. Assumption of land management will only be accounted in LCCA analysis, and not for LCA.

Furthermore, operation, maintenance and replacement phase will take an assumption of average function number of failure per 1kWp over 25 years of life span forecasted from 2 years of operational time span. The dismantling and disposal phase will include the disposal treatment process until it is inert and left in the landfill.

3.0 Foreground Data Collection

The data collection is undertaken on site of 3 economies chosen from the list of members in APEC region economies as shown in the Table 1 above. APEC has 21 member economies and it is called as 'economies' to describe the APEC cooperative process predominantly concerned with trade and economic issues, with members engaging with one another as economic entities. These economies varies in term of geography which is crucial for the Solar Photovoltaic system evaluation criteria.

The six case studies evaluated according to the methodology of study in Figure 8 were from Malaysia and other economies of similar climate as proposed by the experts, namely Indonesia and Thailand. This would allow evaluation of other APEC economies point of view and shall widen the policy review as well as measures taken for photovoltaic systems. Other than that, the capacity factor for usual solar PV site is only 16~17% from whole expected system outcomes will be taken into account for each case studies.

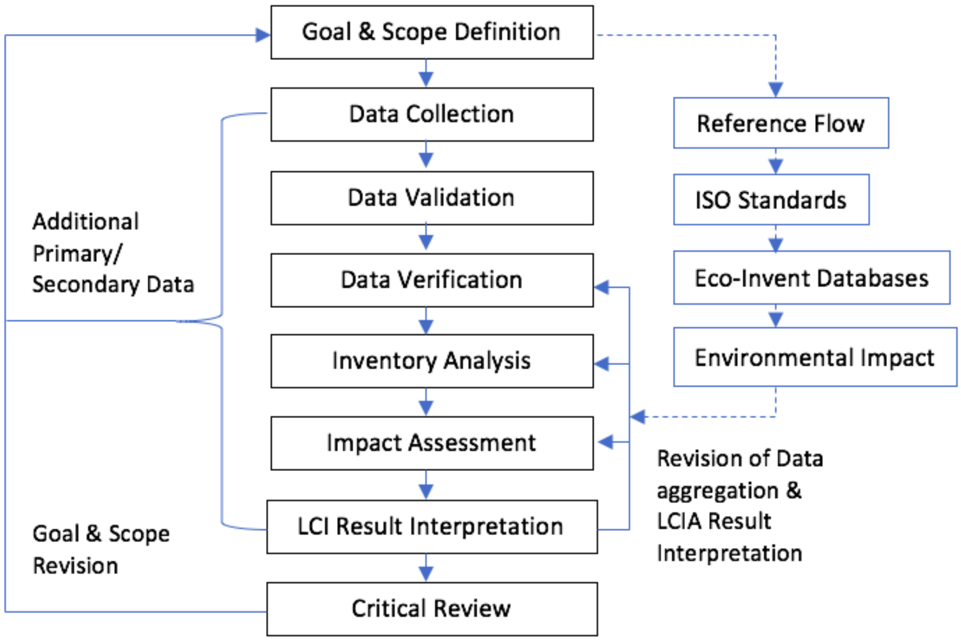


Figure 8 : Methodology of Study

The data collection is done on six case study site; solar farm, solar rooftop and solar stand-alone PV system over 3 APEC region economy of similar weather condition; Malaysia, Thailand and Indonesia.

The data collection on site is covered these life cycle phases:

i) Transportation and Packaging
ii) Balance of System Installation
iii) Operation and Maintenance

Moreover, data validation and verification are revised thoroughly with the reference flow as stated in the system boundaries, ISO standards for environmental and policy guidelines, Eco-Invent database for material value and environmental impact assessment.

The inventory analysis is concluded using all the data aggregation of primary data and secondary data from Eco-Invent database. Additional primary and secondary data are added and removed after being identified during the impact assessment and life cycle result interpretation. The reversible flows of methodology are possible due to the data availability and completion. The outcomes are critically reviewed by field experts and stakeholders to finalize the whole study findings.

3.1 Photovoltaic Panel Production

Silicon is the second most abundant element in the Earth's crust, compromising approximately 26% of it [18]. Silicon does not exist naturally in its elemental form, but as silicon dioxide (SiO_2) in sand, rock and quartz [19]. The silicon dioxide must be converted to elemental silicon (Si), with very low levels of contaminants in order to be useful in PV applications [20].

The silicon manufacturing method plays a big role in differentiating them into metallurgical-grade silicon (MG-Si), then into electronic silicon (EG-Si) through the Siemen's process or into solar-grade silicon (SoG-Si) through the modified Siemens process [19]. The first step in this purification process is to produce metallurgical grade silicon (MG-Si). A purity of 98-99% silicon for the MG-Si is not pure enough for solar cell application. The MG-Si has to be further purified in order to reach a high purity of 99,9999% (six nines pure). Silicon with this purity is called solar grade silicon (SoG-Si). Most of the MG-Si is commercial produced by carbothermic reduction of silicon dioxide [21].

There are currently two main purification methods; a metallurgical route and a chemical route which are Elkem Solar Silicon process and the modified Siemens process. The modified Siemens process is currently the most common method used for commercial SoG-Si production. Both the processes involve chemical purification of MG-Si, by thermal decomposition of trichlorsilane gas (SiHCl3, TCS).

The big drawback of the standard process as above is that a Siemens reactor is very expensive and the Siemens process itself requires a lot of energy. A number of new proprietary processes reduce the energy consumption and the capital costs for silicon production are Fluidized Bed Reactor and Vapor to liquid deposition. Though they are still similar to the traditional Siemens process, Fluidized Bed Reactor and Vapor to liquid deposition operates at much lower temperatures, does not produce by-products and faster extraction [22].

The crystal growing process starts from cylindrical ingot growing that is Czochalski process to obtain single crystals of semiconductor. It is a process which use massive amount of electricity and time since the process requires to operate at a very high temperature of 1400 - 2000°C.

Firstly, the grade silicon is melted into a quartz crucible. The molten intrinsic silicon is added with dopant impurity atoms such as boron or phosphorus. The quartz is then feed into an electric arc furnace or known as the ingot grower. A seed crystal, mounted on a rod, is dipped into the molten silicon. The seed crystal's rod is pulled upwards and rotated at the same time. By precisely controlling the temperature gradients, rate of pulling and speed of rotation, it is possible to extract a large, single-crystal, cylindrical ingot from the melt as illustrated in Figure 9 below.

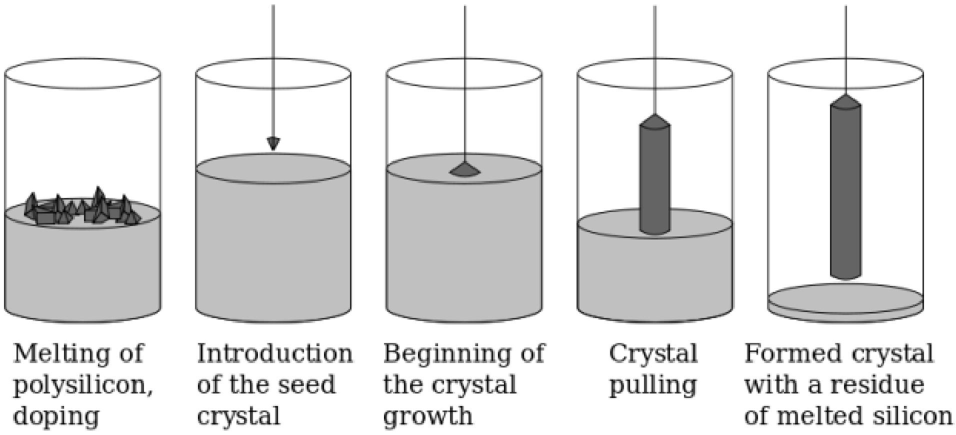


Figure 9 : Ingot Crystal Growing Process

The cylindrical ingot is 2 meter in length and about 200 mm to 300 mm in diameter. After the Czochralski process (for sc-Si) or other production process, silicon is made available for the solar cell production. The silicon ingot is needed to be sliced into wafer, one ingot can produce about 4000 wafer with each typically 0.75 mm thick.

Si-wafer based PV technology accounted for about 90 % of the total production in 2013. Silicon based photovoltaic cells can be three types are Monocrystalline, Polycrystalline and Silicon Ribbons, although all three cells are from the same silica material. The record lab cell efficiency is 25 % for mono-crystalline and 20.4 % for multi-crystalline silicon wafer-based technology [23].

- Monocrystalline wafer:

  Silicon with a single, continuous crystal structure is grown from a small seed crystal that is slowly pulled out of a polysilicon melt into a cylindrical shaped ingot (Czochralski process). The ingot is cut into wafers using a diamond saw. Silicon waste from the sawing process can be recycled into polysilicon.

- Polycrystalline wafer:

  Polycrystalline silicon consists of small grains of monocrystalline silicon. Cube-shaped ingots can be made directly by casting molten polysilicon, which are then cut into wafers similar to monocrystalline wafers.

There are few steps to be done for the wafer production which in this case study specifically of a monocrystalline cell production from Silicon Lab, UKM as illustrated in the Figure 10.

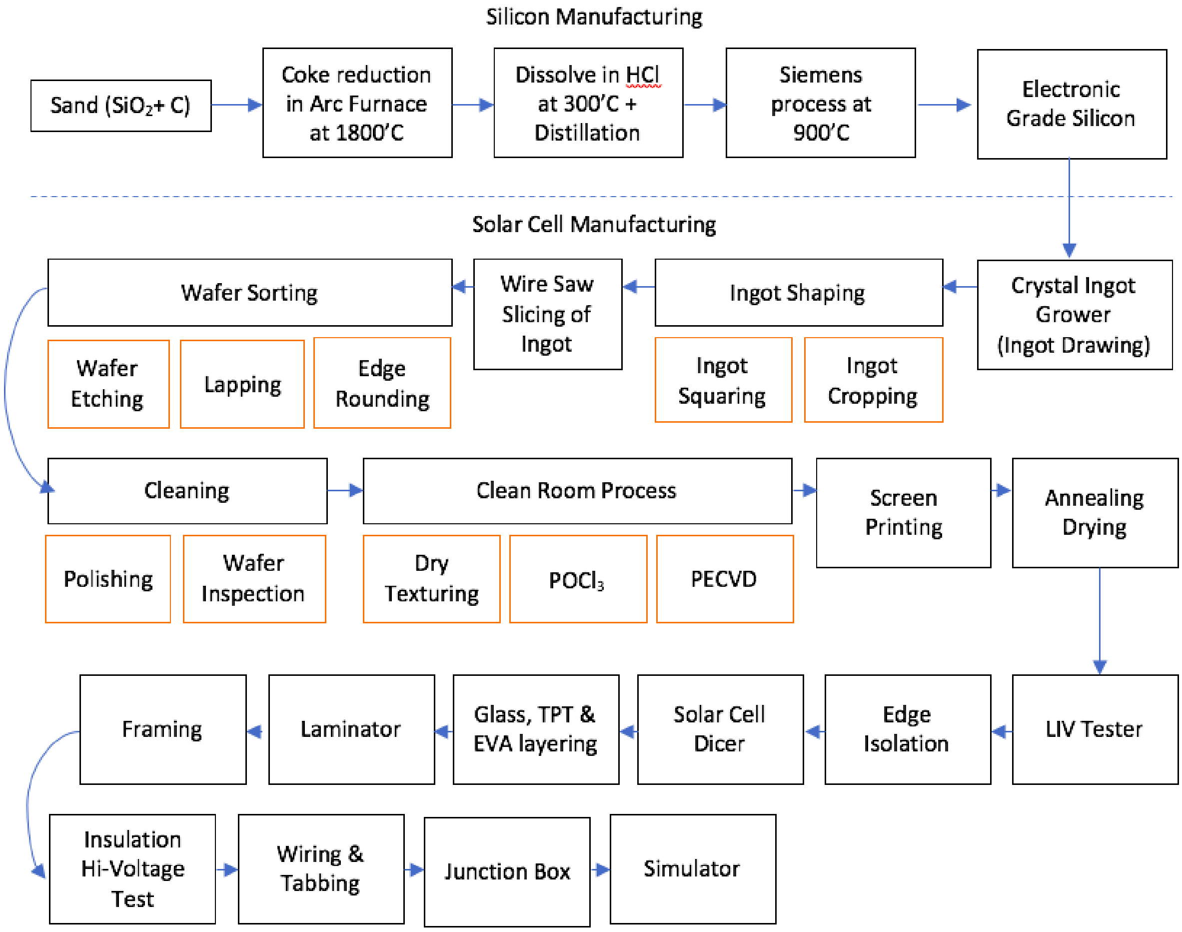


Figure 10 : Monocrystalline Photovoltaic Panel Production Step (Silicon Lab UKM)

This study focuses on the detail of real case study with an extended secondary data from ecoinvent database. The ingot need to undergo shaping process for cropping and squaring since it is initially round and indefinite in shape as illustrated in Photo 1 below. All of the cutting process will be done using a diamond-tipped saw for accuracy and clean after touch. While, the slicing of wafer will be done using thin SiC or Cu wire which are about 250 km long for one ingot since the wire can only be use once and not recyclable.

Photo 1 : a) Silicon Ingot, b) Cut part of Silicon Ingot and c) Silicon Wafer

Next, wafer sorting of edge rounding, lapping and wafer etching is included to sort out damage wafer and removing any remaining crystal damage using chemical. Other than energy demand, embedded energy is also a concern to life cycle assessment since it gives out schedule waste and emission contributes to the environmental impact. This covers both the cleaning and clean room process that plays an important role to perfecting the cell's aesthetic, appears blue with $POCl_3$ and smooth.

Finally, a proprietary surface texturing screen printing technique is used to enhance sunlight capture for electrical contact using Ag paste on both side of the wafer. After screen printing, the wafer undergo a firing process in a conveyor belt furnace at high temperature known as annealing drying process. This causes the metal electrodes to fuse with the silicon electrodes [24], forming a conductive path for the electrical current. There are also small amounts of glass in the paste which provide a good adhesion to the silicon surface [24]. The cell is tested using LIV test to ensure it is working properly.

Next is the panel assembly. Typically marketed monocrystalline PV is a 1.62 m^2 panel consisting of 60 wafer aligned in series as shown in Photo 2 [25].

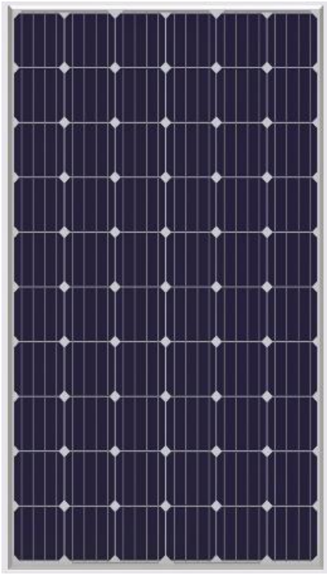


Photo 2 : Monocrystalline Photovoltaic Panel

The panel assembly includes back sheet, thin polymer sheets that provides physical protection from puncture and abrasion; moisture protection from low thermal resistance and prevent ingress of water or water vapor; electrical insulation to isolate the cells and connections from the environment; and improve efficiency through optimized internal reflection. Back sheet material varies according to the manufacturer and keep on improving through researches [26].

Intercell connections contained by the module shall be ready to allow for thermal expansion and to discharge mechanical stress. Intercell electrical contacts to the collector grid contact area of one cell and the back contact area of the next cell shall be provided. These connections shall be designed such that failure of any contact shall not degrade the individual cell electrical output by more than 5% from its output under Standard Test Conditions (STC). Solder shall cover the contact area where the intercell connection overlays the front cell area of one cell and the back contact area of the next cell [27].

The positive and negative of cell outputs usually drive through the back sheet of the module. After the positive and negative outputs are soldered onto the outside of the solar panel, it is essential to connect the positive and negative outputs with positive and negative output cables inside the Junction Box.

Glass cover on both front and back side of the panel usually uses anti-reflective tempered glass to be used as the protective shield for the active surface area of the module. To be carefully chosen for high impact and thermal shock resistance. The panel is then laminated, the laminate shall fill all spaces inside the module and shall adhere to the front glass and the back sheet. The encapsulant should be stable at elevated temperature and high UV exposure. Aluminum metal to hold the whole panel.

Junction box for each module will be of sealed type. This box shall not extend more than one and three-quarters inch (1¾") from the back sheet of the module. This junction box contain both the positive and negative output terminal posts and a small replaceable cover for easy access for replacement of the blocking diode. It will be completely filled with a soft, clear, removable, self-healing, room temperature curing, dielectric potting gel leaving no air gaps [26].

The complete PV monocrystalline panel is tested for approval using a simulator for its performance, efficiency and quality according to international standards such as IEC 61215, IEC 61730, CE, MCS, ISO 9001:2008, ISO 14001:2004, BS OHSAS 18001:2007, PV Cycle, SA 8000 etc [16].

3.2 Balance of System (BOS)

Balance of system is the mounting structure, wiring and cables, inverter, battery and other related electronic components depending on the type of system; ground-mounted, flat-roof mounted, slanted-roof mounted or building integrated system. According to IEA guidelines (2010), the market for PV systems are divided into four end-use-sectors:

- Residential systems: Mounted on individual buildings. Size up to 20kW.
- Commercial systems: Mounted on commercial office buildings, schools, hospitals and retail. Size up to 1 MW.
- Utility systems: Mounted on roofs or ground. Size from 1 MW and higher.
- Off grid applications: Not connected to the utility grid. Varying in size.

So far, the residential systems accounts for the largest share more than 40% of the global cumulative installed PV capacity [28].

The type of components use varies based on the system sizing and whether it is grid-connected or stand alone. For instance, the market share of string inverters is estimated to be 50 %. These kinds of inverters are mostly used in residential, small and medium commercial applications. The market share of central inverters, mostly used in large commercial and utility-scale systems, is 48 %. A small proportion of the market about 1.5 % belongs to micro-inverters (used on module level) [29].

The sizing method for PV system BOS can be list out based on such guidelines and formula [11].

- PV power array, $P_{array} = V_{array} \times I_{array}$
- Maximum current through controller, $I_{controller} = 1.56 \times I_{SC,\ array}$
- Ratio of PV array capacity to the daily load demand, $C_A = E_{PV} / E_L$

- Ratio of battery capacity to daily load demand, $C_B = E_B / E_L$

Photovoltaic system sizing balance the energy demand and the energy production of the PV system, as well as optimizing the economic benefits of the system. The cost of the system must be compared to the annual yield. This optimization site dependent, whether the panel is perfectly place for maximum irradiation extraction, array inclination and can it either be tilted referring to the azimuthal angles, wire connections and battery efficiency effects on load estimation.

3.2.1 Stand Alone System (SAPV)

Stand-alone PV system is a system that is not connected to the electricity grid. Stand-alone systems are typically small and supported by one array of balance of system. It is usually preferred to be installed in the rural area to satisfy the energy demand only without generating profit. At which point, if the demand is high, there are cases where it is converted into a stand-alone solar farm, with the availability of land space and initial investment. Stand-alone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft. If the load is to be supplied independently of solar insolation, the generated power is stored and buffered with a battery.

The balance of system for a stand-alone PV system is as shown in Figure 11 below. The whole system is usually connected to one string (one string usually holds 20 PV modules) due to its small generation. The generated DC current pass through the charge controller, which plays the important role in preventing battery from being overcharged and to dissipate excess power from load resistance. The fuse and isolation switch protect PV from accidental shorting of wires and automate switching off when it is not required. The fuse and isolation switch are optional to the complete system but implementing it can save energy and improve battery life.

Battery bank are typical for a stand-alone system since it stores excess energy generated and allow flexible time of usage during nighttime. The stored electricity is directed to the DC load demand before going to the inverter and convert into AC current for the AC load.

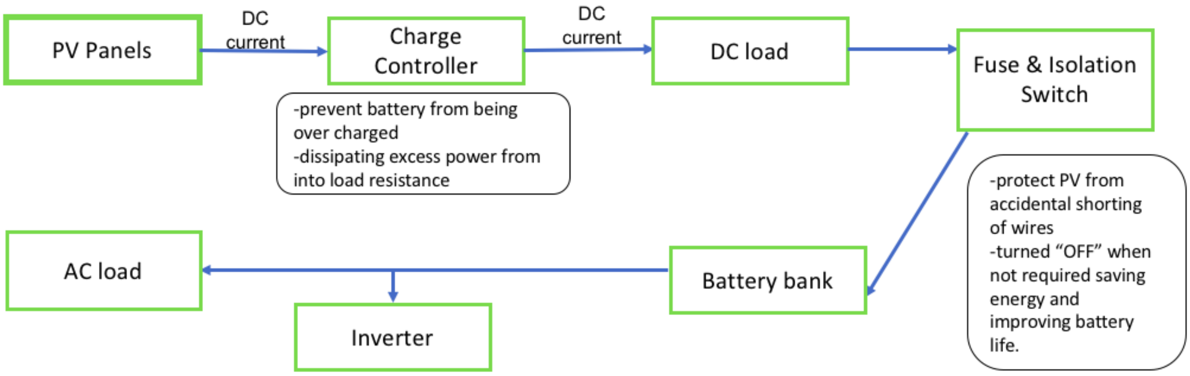


Figure 11 : Standalone PV System BOS

a) Case Study 1: Malaysia (SAPV 1)

Solar energy is regarded as a clean renewable energy source, with great potential for environment-friendly electricity generation. Properly harvested, it can optimally benefit. The current fuel mix in Malaysia for electricity generation is: natural gas 46.3% Gas + 41.0% Coal + 10.7% Hydro [30]. This heavy dependence of electricity generation on natural gas and coal, has provided cause for concerns to the industry.

In addition to that, Malaysia has been cited amongst the highest globally in growth of greenhouse gases (GHG) emissions with a 7.9% compounded average growth rate (CAGR) from 1990 to 2006 [31]. Absolute GHG emissions in Malaysia are expected to increase by 74% from 189 million tonnes of CO2e in 2005 to 328 million tonnes of CO2e in 2020 [31]. The power industry in Malaysia contributed 60 million tonnes CO2e, about 32% of the total emission in 2005, and will increase its contribution to 153 million tonnes, about 47% in 2020 due to the shift from gas to coal for power generation, [32].

However, Malaysia has a particularly abundant source of renewable energies, for solar, as evidenced by a 4.21 kWh/m^2 to 5.56 kWh/m^2 average daily radiation with a high of 6.8 kWh/m^2 [33]. Malaysia has expand the potential of photovoltaic technology throughout the economy and currently installed capacity totaling 20,493 MW, is estimated to reach 23,099 MW maximum-demand capacity in 2020, by when 190 MWp of cumulative solar energy would have been installed [34].

Throughout the years, the government of Malaysia has formulated numerous energy-related policies to combat the climate change and ensure the energy security. Pragmatic energy policies since last three decades have facilitated a clean energy development path. The fuel policy was introduced in 8th Malaysian Plan which was extension of four fuel diversification policy in which renewables was included. Contribution of 5% of the economy energy mix with RE by year 2005 was targeted with mitigation of 70 million tons of CO2 over a time period of 20 years [35].

Parallel to this, Small Renewable Energy Program (SREP) was launched in May 2001 under the initiative of the Special Committee on Renewable Energy (SCORE) to support the government's strategy to intensify the development and utilization of RE as the sustainable resource in power generation, as stipulated in the objectives of the Third Outline Perspective Plan (OPP) for 2001,2010 and the 8th Malaysia Plan (2002, 2005) (8MP) [35]. Facilitation of the expeditious implementation of grid- connected RE resources-based small power plants is the primary focus of SREP [36]. Further, in the 9th Malaysia plan the utilization of RE resources and efficient use of energy were emphasized.

In this study, the selected SAPV is located in a plantation rural area without electricity grid in Lenggeng, Negeri Sembilan, Malaysia as illustrated as a map in Photo 3 below. The system is personally owned by the family since 2015. PV system is installed over a slanted-roof with a common BOS, completely utilized by the single vacation house for less than 24 hours a day. The electricity supply from the PV system satisfy the demand and even have excess stored in the battery bank.

Photo 3 : Lenggeng, Seremban, Malaysia

The system is completely for personal use due to the unavailability of the electricity grid on the area and thus called as the smart house as shown in Photo 4. Other than that, problem also occurs throughout the operation, on which the energy stored in the battery is loss due to degradation and malfunctioning of the battery itself. Battery storage barely last for few months with every 3 month of maintenance and service. This highlight the poor quality of electrical component used in the balance of system.


Photo 4 : Smart House at Lenggeng, Malaysia

The following parameters were collected according to the SAPV 1.

1) Location : Lenggeng, Seremban (2.43'N, 101.57'E)
2) Effective area : 19.44 m^2
3) Irradiation : 1573.15 kWh/m2/year [27]
4) Number of PV panel : 12 unit
5) Type of PV panel : Monocrystalline PV
6) Module-rate efficiency : 15%
7) System's performance : 0.75
8) System timeframe : 2015 – 2040
9) Expected lifetime of BOS
   a) PV module warranties : 25 years with every 3 month of maintenance.
   b) Degradation ratio for PV : 0.59% per year
   c) Inverters : 1 unit (25 years with one replacement)
   d) Battery : 12 unit (3 years)
   e) Electric installation : 30 years
   f) Mounting Structure : 30 years
10) Average grid electricity mix {MY} : 46.3% Gas + 41.0% Coal + 10.7% Hydro

Based on the ground energy production since 2016 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 12.

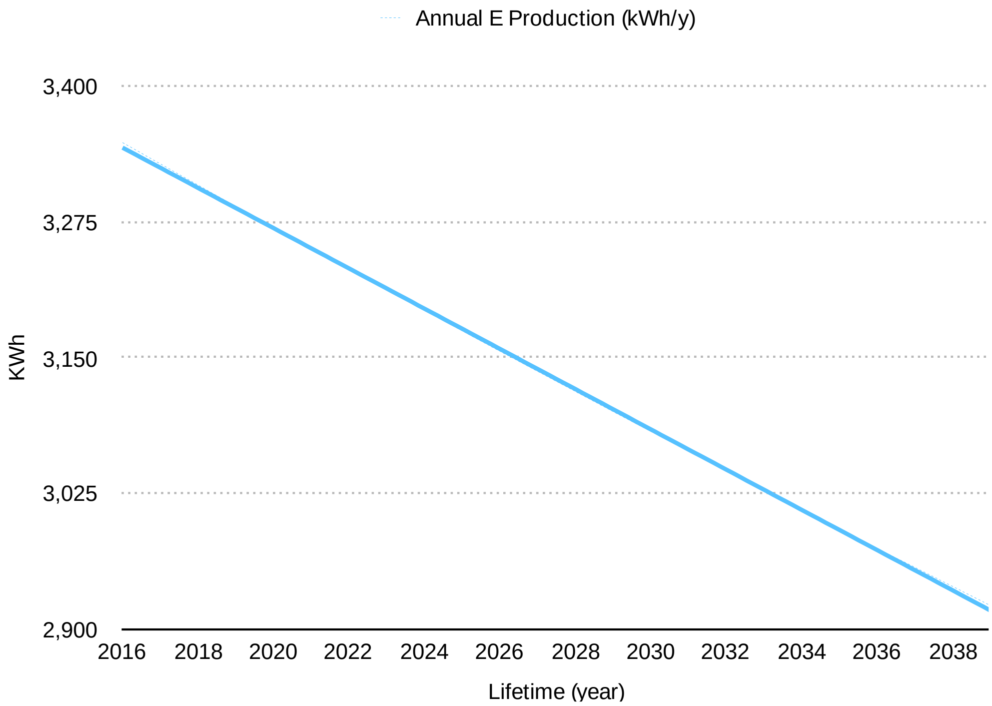


Figure 12 : Annual Energy Production Case Study 1, Malaysia

According to the obtained data of electricity generated for 2016 and 2017, it is known that the power production has reduced to a factor of 0.59%. This value can be the PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel are expected to degrade overtime according to its production. Hence, the annual production are forecasted to be reduce by this amount in the following years.

b) Case Study 2: Thailand (SAPV 2)

As Thailand's economy grows together with the GDP increment, this will give a hike in the energy demand, indicating significant improvements in energy intensity of the economy's economy [13]. Energy intensity will decrease by more than 20% from 134 tonnes of oil equivalent (toe) per USD 1 million at purchasing power parity (PPP) in 2015 to 106 toe per USD 1 million PPP by 2036 [37].

Thailand has long been promoting and supporting energy development, especially in the field of alternative energy21 and energy conservation, driven primarily by the pursuit of enhanced energy security, stabilized economic prosperity and improved well-being. With the steadily increased use of alternative energy sources and improved energy efficiency, imports of fossil fuels would be expected to decline, and so would the long-term risks of energy expenditure on energy importation. In addition, indigenous clean energy development could bring multiple co-benefits such as environmental, social and economic advantages, including job creation, in comparison to imported fossil fuels [9].

Thailand has set the goal to reduce carbon emissions by 20-25% over business- as-usual in 2030 [38]. Thailand will need to invest significantly in its energy system over the coming two decades. To achieve the levels of renewable energy capacity is seen possible by RE map. Thailand is endowed with abundant solar energy resource across the economy, with high irradiance in the northeast and central parts of the economy covering one-quarter of the total land area [38]. The peak density of solar radiation in those areas is in the range of 1,200-1,400 kilowatt hours (kWh) per square meter per year, with seasonal peak in April and low point in December [39].

Thailand's solar PV capacity installed has increase drastically over the recent 5 years, with a cumulative installed capacity of 2,761 MW by the third-quarter of 2016. The installed capacity made up of 95% solar farm and 5% solar rooftop system [9]. This attribution are from the economy's Adder programme, the dramatic global decline in the cost of PV modules and utility-scale PV projects, and growing acceptance of solar PV projects especially in the financial sector, and most importantly the consistent political support for renewable energy development [40].

The selected SAPV 2 is a standalone solar farm system which is located in Asian Development Institute for Community Economy and Technology (AdiCET), World Green City of Rajabaht University in Chiang Mai, Thailand as shown in the Photo 5. The system was originally planned to manifest the idea of smart grid technology which satisfy the need of power generation within the university compound and support the grid without having to store excess energy in a battery.

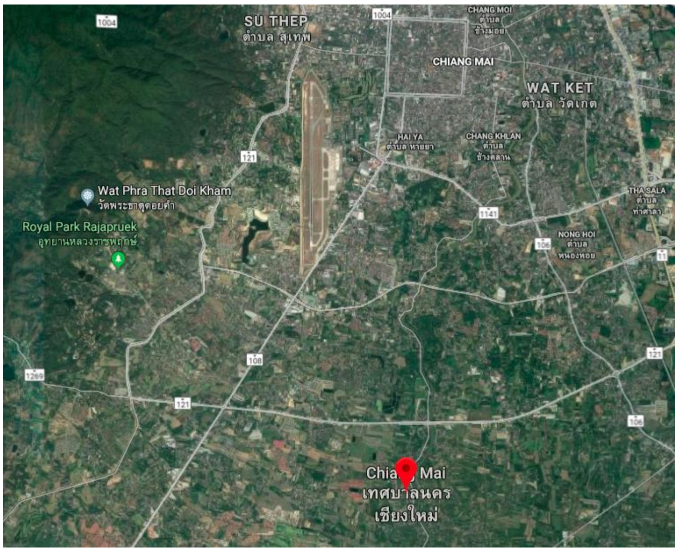


Photo 5 : World Green City, Chiang Mai, Thailand

The balance of the system includes a combiner box to fit 170 string, a monitoring system and a fuse box to support the whole 720kW farm. Other than dust and minor system failure repair, the system are easily maintain due to the isolated location that are far from human activities.

Photo 6 : Standalone Solar Farm, World Green City, Thailand

The following parameters were collected according to the SAPV 2.

1) Location : World Green City, Rajabaht University, Chiang Mai (18.7'N 98.9'E)
2) Effective area : 4548.96 m^2
3) Irradiation : 1772 kWh/m2/year
4) Number of PV panel : 2808 unit
5) Type of PV panel : Polycrystalline PV
6) Module-rate efficiency : 15%
7) System's performance : 0.70
8) System timeframe : 2011 - 2036
9) Expected lifetime of BOS
    a) PV module warranties : 25 years with every 3 month of maintenance.
    b) Degradation ratio for PV : 0.30% per year
    c) Electric installation : 30 years
    d) Mounting Structure : 30 years

10) Average grid electricity mix {TH} : 39.3% Oil + 28.2% Gas + 18.4% Bioenergy + 12.9% Coal + 0.4% Hydro.

Based on the ground energy production since 2011 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 13.

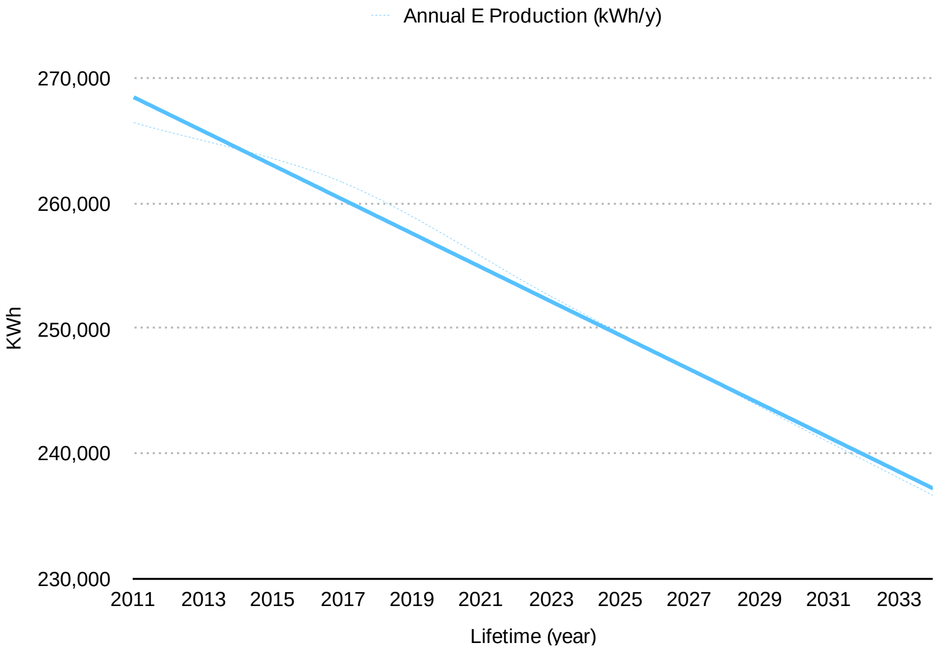


Figure 13 : Annual Energy Production Case Study 2, Thailand

According to the obtained data of electricity generated for 2011 and 2017, it is known that the power production has reduced to a factor of 0.30%. This value can be due to PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel are expected to degrade overtime according to its production. Hence, the annual production are forecast to be reduce by this amount in the following years.

3.2.2 Solar Rooftop System (SRPV)

Solar rooftop system is a common preferable system since it occupies unused space on a building's roof. It can be mounted on a flat-roof and slanted-roof, this versatility satisfy the purpose of building green upgrade. This system is often mixed up with building integrated photovoltaic (BIPV), there are differences in the balance of system between the two. Solar rooftop BOS is similar to that of a typical stand-alone system, added to an existing building. While, BIPV BOS is a panel system that are built into the building's façade, windows and roof during its construction.

The typical balance of system for a solar rooftop PV system is as shown in Figure 14 below. The system also varies in term of scale size and design to fit the available rooftop position that maximize the solar irradiation per day. Variation of rooftop system has been commercialized, some are connected to battery banks, others are grid-connected in order to maximize the power production over lower cost, depending on the demand and suitability.

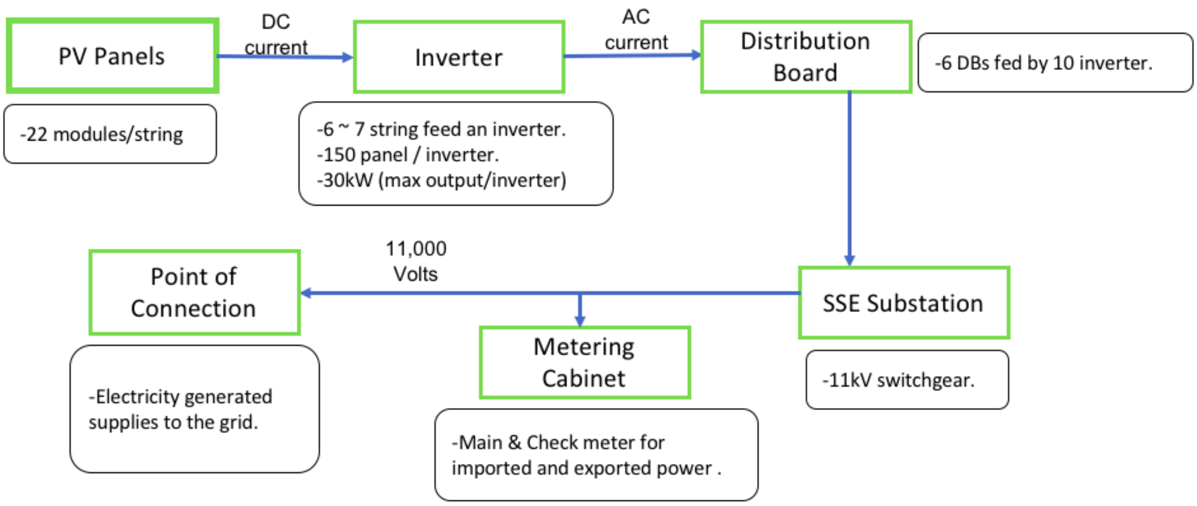


Figure 14 : Rooftop PV System BOS

The balance of system for a rooftop PV system can be one string or more, in accordance to the market, one string can fit up to 20 PV modules. The generated DC current is convert into AC through the inverter which can uphold about 6 to 7 string. If the system production is big enough, distribution board is needed for load power distribution that can be fed by 10 inverter. If the power production does not reach up to 10 inverter, distribution board are not necessary and are connected via Stand-alone system. SSE substation is required as 11kV switchgear to manage the voltage of the system before being exported to the grid. If necessary, transformer can be include into the loop before exporting the electricity.

Battery bank are typical for a stand-alone system since it store excess energy generated and allow flexible time of usage during nighttime. Then, the electricity is directed to the DC load demand before going to the inverter and convert into AC current for the AC load.

a) Case Study 1: Malaysia (SRPV 1)

The rooftop system is mounted on a slightly tilted rooftop of SK South Asia Sdn Bhd factory in Seberang Perai, Penang, Malaysia. The system is a collaboration between the factory to provide space and Pensolar to which supply the energy generator. It is the only factory installing this green technology in the industrial area.

Although the area of the rooftop is large and perfect to accommodate this system to its maximum solar harvesting, the industrial area itself contribute a lot of dust and soot which affect the system greatly in term of condition maintenance. Frequent cleaning maintenance is required to keep the system at its full efficiency capacity.

Photo 7 : Large Scale Factory Rooftop PV System, Malaysia

The following parameters were collected according to the SRPV 1:

1) Location : SK South Asia Sdn Bhd, Seberang Perai, Penang (5.22’N 100.24’E)
2) Effective area : 2138.4 m^2
3) Irradiation : 1685.39 kWh/m2/year
4) Number of PV panel : 1320 unit
5) Type of PV panel : Polycrystalline PV
6) Module-rate efficiency : 15%
7) System’s performance : 0.75
8) System timeframe : 2017 - 2042
9) Expected lifetime of BOS
   a) PV module warranties : 25 years with every 3 month of maintenance.
   b) Degradation ratio for PV : 0.23% per year
   c) Inverters (500kW) : 8 unit (25 years with one replacement)
   d) Electric installation : 30 years
   e) Mounting Structure : 30 years
10) Average grid electricity mix {MY} : 46.3% Gas + 41.0% Coal + 10.7% Hydro

Based on the ground energy production since 2017 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 15.

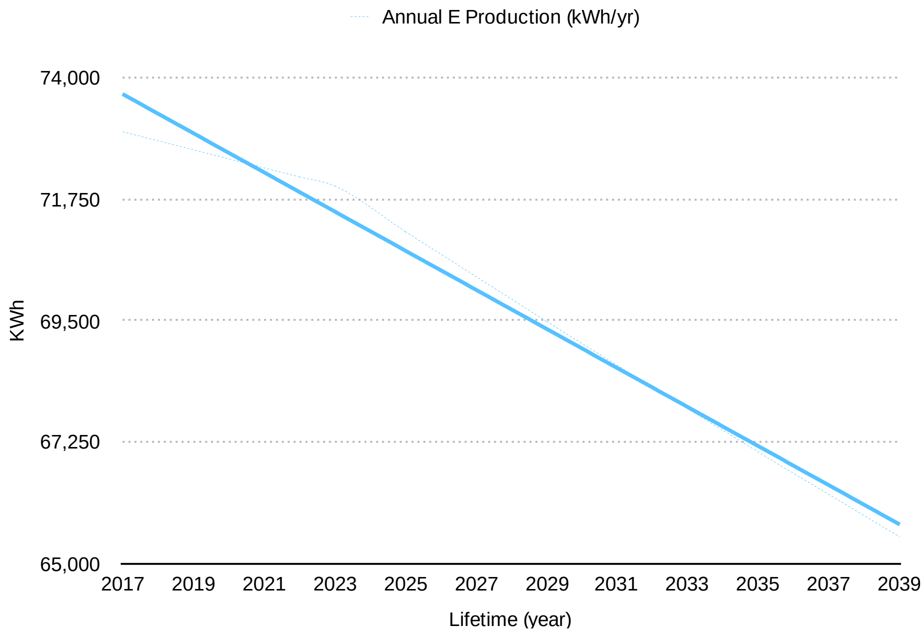


Figure 15 : Annual Energy Production Case Study 1, Malaysia

According to the obtained data of electricity generated for 2017 and 2018, it is known that the power production has reduced to a factor of 0.23%. This value can be due to PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel are expected to degrade overtime according to its production. Hence, the annual production are forecasted to be reduce by this amount in the following years.

b) Case Study 2: Thailand (SRPV 2)

The SRPV 2 is mounted on a 30' tilted roof of a conference building called as the 'bird house'. The system is located in in the World Green City, Chiang Mai, Thailand as illustrated in Photo 8 [41]. The system is a part of the community smart grid, community power is defined as decentralized hybrid renewable energy based system from natural resources and agricultural wastes. This system aims to support sustainable livelihood of the Asian Development College for Community Economy and Technology (AdiCET) from within the area.

Photo 8 : World Green City Community Smart Grid, Chiang Mai, Thailand

Source : https://www.aptep.net/ongoing-projects/technology/chiang-mai-world-green-city/

Decentralized hybrid smart grid require sufficient amount of energy to support the whole green city community, hence, many kind of PV has been implemented for research purposes to maximize the power production. Some parts of the balance of system use for this rooftop PV system are as shown in Photo 9.

The building is occupied with conference equipment for seasonal conference purposes as shown in Photo 10 below. Shape of the building itself is considered as a green architecture since its maximize air flow and natural daylight, it is even complete with four air-conditioners. Area of the rooftop which accommodate sufficient amount of panels to supply to the building as well as the grid for excess energy generated. The tilted position of the panel compromise with the maintenance requirement since it is easy to clean and does not accumulate much dust. Panels are facing south to fully utilize the sunlight.

Photo 9 : Component of the smart grid PV system, Thailand

Photo 10 : Bird House Rooftop PV, Thailand

The following parameters were collected according to the SRPV 2:

1) Location : World Green City, Rajabaht University, Chiang Mai (18.7’N 98.9’E)
2) Effective area : 51.84 m^2
3) Irradiation : 1772 kWh/m2/year
4) Number of PV panel : 32 unit
5) Type of PV panel : Polycrystalline PV
6) Module-rate efficiency : 15%
7) System’s performance : 0.70
8) System timeframe : 2011 – 2036
9) Expected lifetime of BOS
   a) PV module warranties : 25 years with every 3 month of maintenance.
   b) Degradation ratio for PV : 0.46% per year
   c) Inverters (2.5kW) : 1 unit (25 years with one replacement)
   d) Electric installation : 30 years
   e) Mounting Structure : 30 years
10) Average grid electricity mix {TH} : 39.3% Oil + 28.2% Gas + 18.4% Bioenergy + 12.9% Coal + 0.4% Hydro.

Based on the ground energy production since 2015 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 16 below.

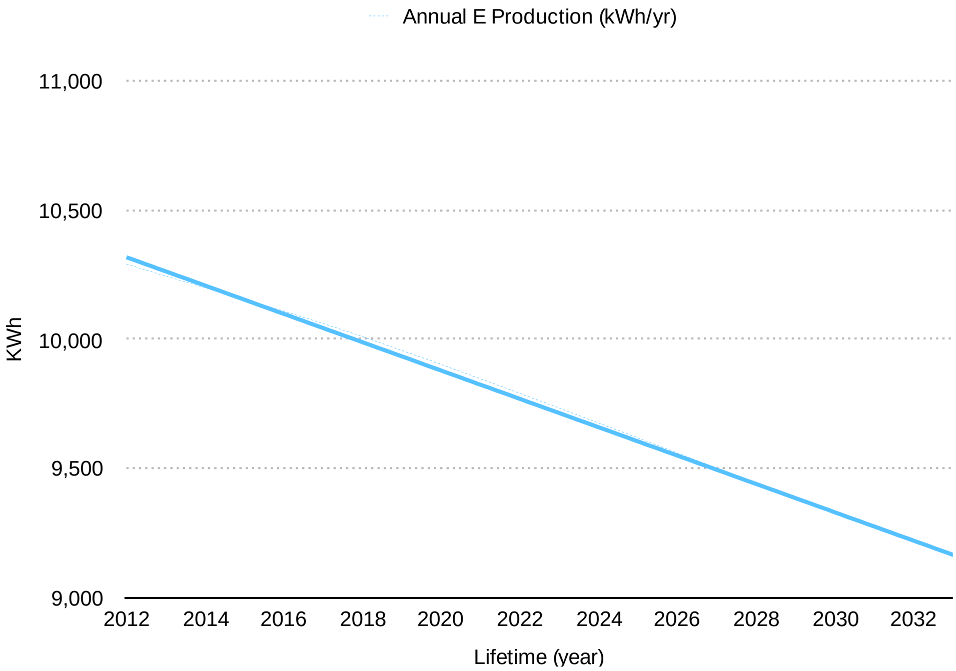


Figure 16 : Annual Energy Production Case Study, 2 Thailand

According to the obtained data of electricity generated for 2011 to 2017, it is known that the power production has reduced to a factor of 0.46%. This value can be the PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel are expected to degrade overtime according to its production. Hence, the annual production are forecast to be reduce by this amount in the following years.

3.2.3 Solar Farm System (SFPV)

Solar Farm system is an energy harvesting plant, where the main purpose of building a solar farm is to harvest energy from the inexpensive sun by using a large-scale number of solar panels and sell it to the electricity grid for profit. Solar farm system has attracted many investors into the renewable energy industry through business approach. This shift can enhance the growth of green technology all together.

This large-scale solar plant requires a massive land transformation for the solar array harvesting process. Numerous studies have explored in developing technological system design to optimize the power production with small land requirement such as solar tracker, solar concentrator, floating solar and many others but none yet to be commercialized. These technologies have their pros and cons which are applicable to fulfil certain supply and demand needs.

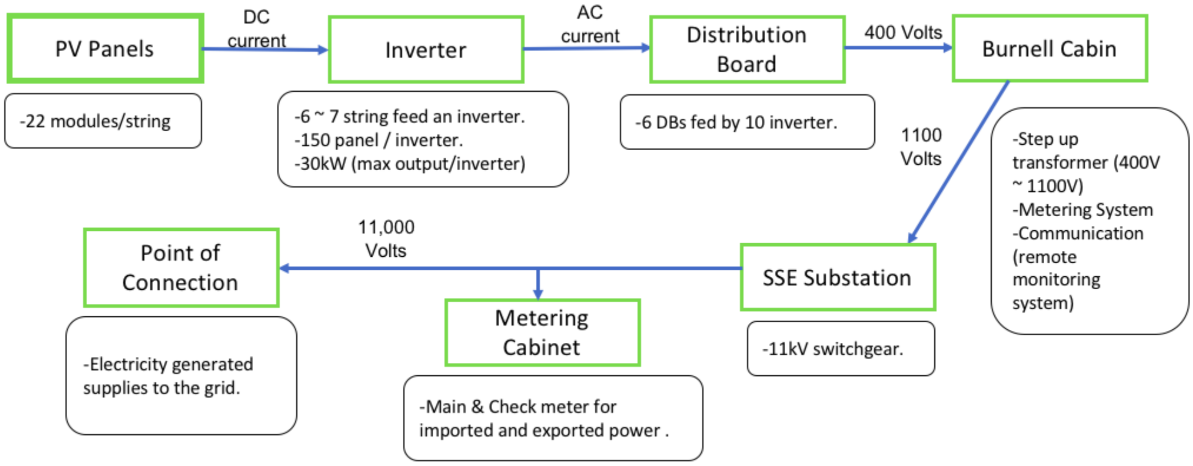


Figure 17 : Solar Farm PV System BOS

The BOS for solar farm are as shown in Figure 9 above are based on general system installation. The DC current generated shall be transform into AC current through the inverter. One 30kW inverter can handle 150 panels power production at a time which is equal to 6 to 7 strings. In a solar farm, the amount of panels is overwhelming compared to that of rooftop PV system since its purpose is to sell power to the grid for profit. This system prefer distribution board and a Burnell Cabin bundle, that includes a step-up transformer, a metering system and a communication system or so called remote monitoring system). These bundles handles large voltage efficiently.

SSE substation is required as a switchgear to manage the voltage of the system before being exported to the grid. Open-grounded system normally has large sum of electricity generation to be exported because it is the sole purpose of solar farm. Hence, Metering cabinet is needed for power imported and exported record. The power finally reaches the point of connection to the main national grid.

a) Case Study 1: Malaysia (SFPV)

Kompleks Hijau Solar owned by Gading Kencana Sdn Bhd is a large-scale solar farm system located in Ayer Keroh, Malacca, Malaysia as shown in Photo 11. The system is mounted on an open-ground 71629.36 meter square of land. This project received commencement approval three years after the initial application and proceed with the construction in the same year of 2013. The system started operation on 11 December 2014 with feed-in-tariff (FIT) commencement within the same month. It had successfully received its first FIT income on February 2015.

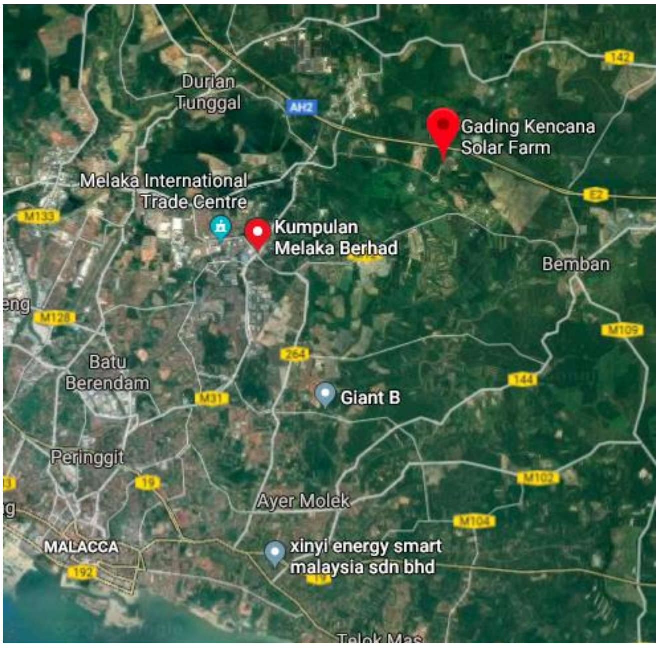


Photo 11 : Kompleks Hijau Solar, Malacca, Malaysia

The counter of this, the landscaped has 30 different orientations to obtain the right tilts for the panels and had created six slopes in different directions which explained the photovoltaic positioning in such angles compared all other solar farm. It also, installed two rows of panels at an angle to each other, resembling a pitched roof. This A-shaped mounting enables maximum tapping of sunlight as illustrated in Photo 12 below.

Photo 12 : Kompleks Hijau Solar Farm System

The following parameters were collected according to the SFPV 1:

1) Location : Ayer Keroh, Melaka (2.3 N, 102.3 E)
2) Effective area : 47,129 m^2
3) Irradiation : 1371 kWh/m2/year
4) Number of PV panel : 29,092 unit
5) Type of PV panel : Monocrystalline PV
6) Module-rate efficiency : 15%
7) System's performance : 0.75
8) System timeframe : 2014 - 2039
9) Expected lifetime of BOS
    a) PV module warranties : 25 years with every 3 month of maintenance.
    b) Degradation ratio for PV : 0.59% per year
    c) Inverters (500kW) : 10 unit (10 years with one replacement)
    d) Electric installation : 30 years
    e) Mounting Structure : 30 years
10) Average grid electricity mix {MY} : 46.3% Gas + 41.0% Coal + 10.7% Hydro

Based on the ground energy production since 2015 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 18 below.

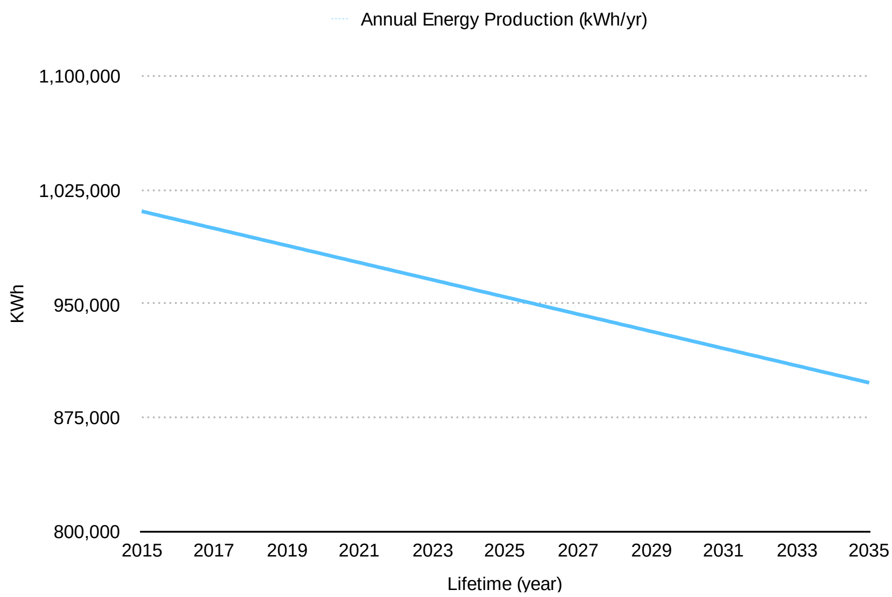


Figure 18 : Annual Energy Production Case Study 1, Malaysia

According to the obtained data of electricity generated for 2015 and 2017, it is known that the power production has reduced to a factor of 0.59%. This value can be the PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel is expected to degrade overtime according to its production. Hence, the annual production is forecast to be reduced by this amount in the following years.

c) Case Study 2: Indonesia (SFPV 2)

SFPV 2, PLTS 2MWp Gorontalo is a solar farm located far into the rural area in Gorontalo, Sulawesi, Indonesia as shown in Photo 13. The solar farm system is mounted on an open-ground 71629.36 meter square of land. This project received commencement approval three years after the initial application and proceed with the construction in the same year of 2013.

Photo 13 : PLTS Sumalata, Gorontalo, Indonesia

SFPV 2 started operation on 11 December 2014 with feed-in-tariff (FIT) commencement within the same month and its first FIT income on February 2015. Rural area is a great place for solar farm where it is far from the transportation and industrial work emission which could pollute and disturb the panel efficiency. The clean air and less busy environment reduce the need of maintenance frequency. This solar farm system uses two step-up transformers before selling the harvested energy to the electricity grid.

The photovoltaic panels as well as its components for balance of systems are all product of Indonesia itself, which is from Adya Surya. This company manages and replaces the failure in the system from time to time as maintenance. The panel as illustrated in Photo, can be seen to align facing to the south for the maximum solar irradiation over time. Although, we can see in Case Study 1, the panel is arrange in an A-shape position to take in both sunrise and sunset time.

Photo 14 : PLTS Gorontalo Solar Farm, Indonesia

The following parameters were collected according to the SFPV 2:

1) Location	: Sumalata Timur, Gorontalo utara (1.3 N, 116.3 E)
2) Irradiation	: 1888 kWh/m2/year
3) Effective area	: 13,880.16 m^2
4) Number of PV panel	: 8,568 unit
5) Type of PV panel	: Monocrystalline PV
6) Module-rate efficiency	: 15%
7) System's performance	: 0.75
8) System timeframe	: 2014 – 2039
9) Expected lifetime of BOS	
a) PV module warranties	: 20 years with low frequency of maintenance.
b) Degradation ratio for PV	: 0.20% per year
c) Inverters (2.5kW)	: 68 unit (10 years with one replacement)
d) Electric installation	: 30 years
e) Mounting Structure	: 30 years
f) Transformer	: 30 years
10) Average grid electricity mix {INA}	: 55.6% Coal + 25.8% Gas + 6.7% Oil + 6.4% Hydro + 4.7% Geothermal

Based on the ground energy production since 2015 of system installation, energy generated per year (kWh/year) stretches for 25 years of expected lifetime are as exemplified in Figure 19 below.

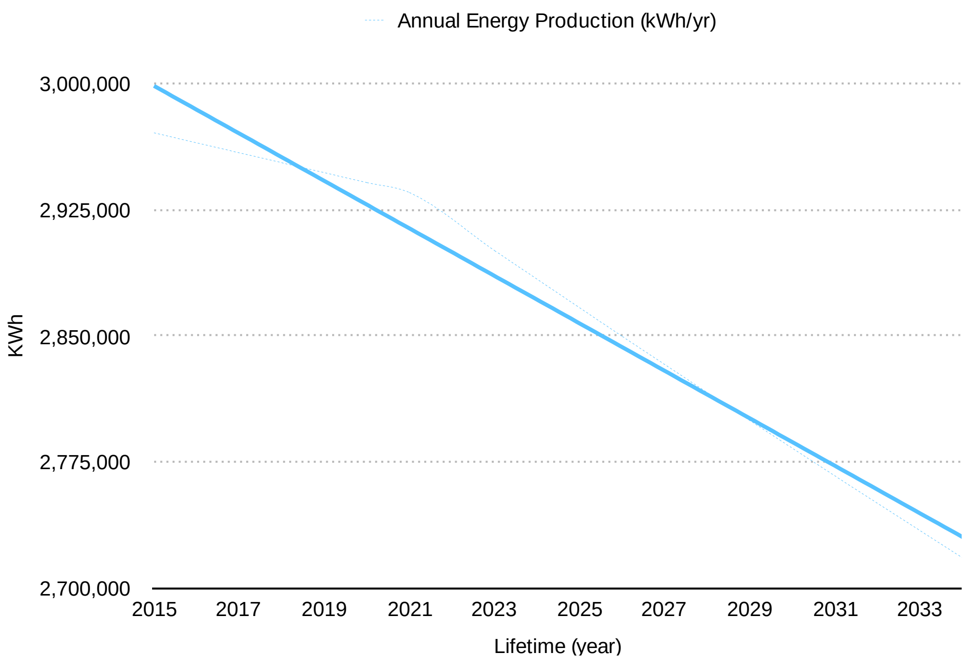


Figure 19 : Annual Energy Production Case Study 2, Indonesia

According to the obtained data of electricity generated for 2014 to 2017, it is known that the power production has reduced to a factor of 0.20%. This value can be the PV panel degradation ratio per year and also influenced by the average solar irradiance. The PV panel is expected to degrade overtime according to its production. Hence, the annual production is forecast to be reduce by this amount in the following years.

3.3 Transportation and Packaging

The road vehicles are considered one of the main sources of urban air pollution and the consumer of fossil fuel energy in a large number of cities, particularly in the developing economies of Asia. The Kathmandu valley, the home of 2.5 million people, is one of the fastest growing metropolitan cities in South Asia according to The World bank, 2014 [12].

If the transport service consists of several sections, it is necessary to identify the operation system of the vehicle (Vehicle Operation System - VOS) for individual sections, namely a number of categories, including working hours of the vehicle. The calculation is based on the identification of a vehicle's consumption of a particular vehicle operation system (VOS). Conversion from total fuel consumption for the VOS into quantities of energy consumption and GHG emissions shall be made using following formulas [42]:

- Well-to-wheels energy consumption of the VOS:
  $Ew\ (VOS) = F(VOS) \times Ew$ (1)
- Well-to-wheels GHG emissions of the VOS:
  $Gw\ (VOS) = F(VOS) \times Gw$ (2)
- Tank-to-wheels energy consumption of the VOS:
  $Et\ (VOS) = F(VOS) \times Et$ (3)
- Tank-to-wheels GHG emissions of the VOS:
  $Gt\ (VOS) = F(VOS) \times Gt$ (4)

Where:
F(VOS), is the total fuel consumption used for the VOS (litres of diesel; or kilowatt hours);
Ew, is the well-to-wheels energy factor for the fuel used (MJ/l);
Gw, is the well-to-wheels GHG emission factor for the fuel used (kgCO2e/l);
Et, is the tank-to-wheels energy factor for the fuel used (MJ/l);
Gt, is the tank-to-wheels GHG emission factor for the fuel used (kgCO2e/l).

Values for energy and GHG emission factors shall be selected in accordance with EN 16258:2012 Methodology for calculation and declaration of energy consumption and GHG emissions of transport services (freight and passengers) [43].

The standard recommended for freight and passenger traffic to use transport capacity. That means multiplying the number of passengers and the actual transport distance in terms of passenger kilometers in passenger transport, freight transport multiplying the quantity of transported goods and the actual transport distance in terms of tonne-kilometers.

Packaging is a complementary product, typically not included in the description and mass of the packed products. The product package each with their specific weights, production and disposal activities. Therefore, packaging is in general kept separate and added as a complementary input and output from the receiving activity where the packed product is used or re-packaged. Packaging discarded before re-packaging is included as input to the wholesale or retail activity, while consumer packaging is reported as a separate input to the receiving activity where the packed product is used [44].

When the type and weight of consumer packaging is unknown, the default values from Danish packaging statistics for 2004, are applied. These values are the best that are currently available to us, but since their basis is rather specific according to the Danish packaging statistics for 2004, they should only be used as indicative [44].

Table 2: Product Group/ Packaging Details

Product Group/ Packaging	Plastic (kg)	Paper (kg)
Packaging product of plastics	0.002	0.008
Other plastic products	0.003	0.007
Flat glass	0.003	0.005
Al, copper, lead, zinc, tin	0.001	
Tools	0.021	0.041
Wire product		0.001
Pumps and compressors	0.007	0.007
Furnace and Machinery	0.003	0.005
Electric domestic appliances	0.014	0.021
Insulated wires and cables		0.023
Accumulators and batteries		0.016
Electronic component	0.014	0.038
Other electrical equipment	0.001	0.006
Other manufactured goods	0.014	0.023
Other fabricated metal products	0.004	0.007
Other chemical products	0.030	0.006

Source: ICE2.0V

3.4 Operation and Maintenance

Photovoltaic module are well known for their emission free operation over 25 to 30 years of lifespan. The modules are enclosed and sealed within two glass modules, and therefore there are no expected emissions while the modules are in use [45].

In 2012, NREL reported long term reliability studies of photovoltaic modules which showed steadily improving degradation rates, with manufacturers offering over 25 years guarantee on their panels. However, very few PV plants have been in existence for such a long period of time, for verification of the guarantee. It is important for the PV industry to know the long term reliability, since it impacts the life of the PV system, and hence changes the cost considerations [46].

The test run have concluded that the degradation and the losses in maximum power are almost entirely due to losses in short circuit current, and that these losses are almost identical for single and polycrystalline panels and are highly dependent on the process used in manufacturing. The drop in short circuit current by the modules can be attributed in part to the visually observable physical defects including EVA browning, delamination at the Si-cell/EVA interface and the occurrence of localized hot spots [26].

Panels care throughout its lifetime is just making sure that the surface are clean from dirt and overshadow [47]. A thick layer of dust accumulated on the panels can cause a drop in power output. Other than that, shadow which covers the panel from receiving similar distribution of solar irradiation over the same module can cause internal overheating. Different distribution of solar irradiation may result current imbalance within the single module string and affect the module power generation. This occurrence usually known as hotspot, a certain burned spot that appears on the overheated spot on the module. Hotspot can affect the whole PV array power generation and it is damaging the module which calls for replacement [48].

Moreover, solar panels gradually become damaged by ultraviolet radiation, rain, dirt, temperature fluctuations, hail, and wind. The most recent distribution for long term stability of performance has a mean value of 0.8% per year and a median of 0.5% per year where a decrease in performance is defined as a positive degradation rate [49]. The majority of these reported rates, 78% of all data, are below a rate of 1% per year. The data from long term tests showed that module degradation for 10 years can be in the range of 4 to 7%, lower than the 10% degradation currently guaranteed by most manufacturers [50].

This information is extremely relevant during power plant design for getting an accurate estimate of the amount of power and therefore revenue to be expected each year after installation. The NREL study suggests that a more reasonable rule of thumb of degradation is less than 0.5% per year [46].

The methodology guidelines on life cycle assessment published by the IEA PVPS Task 12 recommend life expectancy used in life cycle assessment studies of photovoltaic components and systems as follows [11]:

- Modules: 25 years for mature (Monocrystalline/Polycrystalline) module technologies;
- Inverters: 15 years for small size PV system, 30 years with 10% of part replacement every 10 years (parts need to be specified) for large size plants (utility PV), [18];
- Structure: 30 years for rooftop and façades and between 30 to 60 years for ground mounted installations on metal supports. Sensitivity analyses should be carried out by varying the service life of ground mount supporting structures within the time span indicated;
- Cabling: 30 years with periodic maintenance;
- Battery: 5 years with replacement and maintenance on battery cycle.

The performance of a PV system is clearly related to not one single but a variety of factors. Some of these factors are controllable, but some are not in the realm of human control. It is worthwhile to note that achieving optimal performance is next to impossible without monitoring of the efficiency or Performance Ratio (PR) of the system. Only when monitoring exists, it is possible to ascertain that all systems are working as expected. When the PR drops, the operator must search for the reason for the drop, as to allow for improved performance.

Uncertainties of Energy Yield Predictions, several modelling steps add to the total uncertainty of a PV system's yield estimation. These steps and their related uncertainties may be grouped into five categories [51]:

- Energy Rating comprises the prediction of module behaviour dependent on STC power, low light response, angular effects and spectral response under given meteorological conditions. The accuracy of ER calculations depends on the suitability of the numerical models as well as on the uncertainty of input component parameters. Typical uncertainties range from 0.5% to 2.5%.

- Performance Ratio prediction adds the influence of system design and BOS components to the ER results. So, besides shading losses, also inverter efficiencies and limitations and cable and transformer losses need to be considered. Again, typical uncertainties may range from 0.5% to 2.5%.

- Deviations from specifications (mainly with module STC power and low light response) also affect the uncertainty of actual system PR. STC power deviations may reach up to a few percent and are assumed to be nearly constant over all irradiance conditions.

- Module and system degradation affects the long term actual PR, as degradation rates considerably vary from system to system there are relatively high uncertainties for single systems. Furthermore the influence of the degradation rate on the simulated PR is increasing with the lifetime of the system.

- Finally, the solar resource determines the long term actual yield of a PV system, and the uncertainties of solar resource figures add directly to the uncertainty of predicted energy output.

While typical yield estimations mention some 5% as overall uncertainty, this value might even be greater than 10% under certain conditions [52]. However, in this contribution, we concentrate on design decisions; so, mainly uncertainties in PR prediction are of concern. When comparing prediction results to observed yields, there are additional measurement uncertainties. Pyranometer measurements are expected to be in an uncertainty range of ±2% while energy meters show uncertainties of ±0.1% to ±0.5%. However this overall uncertainty in PR verification should not influence the simulation results strongly for single simulation steps [53].

3.5 Decommissioning and Waste Disposal Scenario

A complete life cycle assessment starts with extraction of raw material for primary product to its end-of-life disposal, where applicable, recycling. The overall environmental impact originates from the decommissioning and disposal phase of the product life cycle [54].

The growth of the solar power sector may have its own environmental consequences. For example, the increase in PV module manufacturing, and the eventual need for decommissioning and disposal, may create a wave of electronic waste (e-waste). Decommissioning waste for PV is expected to result in the largest environmental impact when PV is evaluated on a full life cycle basis. That said, recycling of spent PV modules has now begun and has shown potential to improve the environmental profile of PV technologies [55].

However, PV system has their long lifespan to about 25 to 30 years of operation, most commercialized PV modules have not reached the disposal stage yet. Hence, there has not been any real case where PV module being manages as a waste or recycles. Recycling presents a number of challenges because of the lamination of the layers of the module [56].

PV Modules that are disposed of in municipal landfills pose the risk of heavy metals leaching out into the surrounding soil. As with other laminated, layered and mixed-material items, it can be difficult to separate the various components safely and efficiently. The leachability of metals in landfill is characterized by two elution tests: (1) the US EPA Toxicity Characterization Leachate Profile (TCLP) and (2) the German DEV S4.

The BOS components (circuitry, inverters, etc.) make up a large proportion of the environmental impact of PV systems, as well as the large amount of glass used in the modules [57]. Heavy metals and organic substances found in the capsule material may leach from modules and may exceed environmental limits [53].

Hence, should these modules inadvertently end up in municipal waste incinerators, the heavy metals would gasify and a fraction would be released into the atmosphere [16]. Electrostatic precipitators can reduce this release to less than 0.5%. The remaining heavy metals would end up in the incinerator ash, which will be disposed of in a secure landfill [54].

Thus, taking into account possible scenario that would be taken by scheduled waste management industry in this case will be very helpful for the study. Case study industrial visit has been done at Cenviro Sdn Bhd, a waste management center with a designated scheduled waste management center located at Kualiti Alam, Seremban as shown in Photo 15 below.

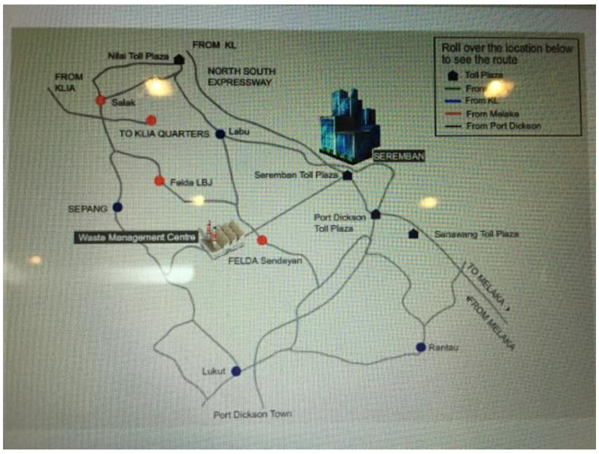


Photo 15: Kualiti Alam, Seremban, Malaysia.

Kualiti Alam has 5 integrated waste management operation which are incineration plant; physical and chemical treatment; solidification plant; secure landfill, and clinical waste treatment center. These waste management operation are executed in the waste management center as shown in Photo 16 below.

All waste management operation and treatment as listed above are done according to the specific content of a certain waste product. whether it is suitable to undergo incineration or needed to be solidified, etc., before going to the secure landfill. They also provide a vast range of recycling and recovery facilities for scheduled waste management solutions.

Cenviro has more than 20 field experts (chemist) for the waste separation and categorizing process. This is to ensure that the scheduled waste under certain condition guidelines is properly managed. Guidelines used for the waste management are Environmental Quality (scheduled wastes) Regulations 2005, Environment Quality Act 1974 (EQA), Occupational Safety & Health 1994 Act (OSHA), and Machinery Act 1967 (FMA).

Specifically for used photovoltaic module, is estimated to be incinerate and sent to landfill. For worse case of non-inert material, it shall undergo solidification treatment plant before going into the secure landfill. In the other hand, BOS components will be separated under municipal waste process, either recycled or sent to landfill.

Photo 16 : Kualiti Alam Waste Management Centre, Cenviro,

Scheduled waste incineration plant uses co-generation heat from the fuel combustion chamber to reach a stable temperature of 10,000’C at one time and continue to run for 24 hours operation over 330 days per year. While, the solidification treatment plant operates for 8 hours, 5 days per week. The energy use for these operations are recycled within the common ground, hence there is no external emission and energy loss.

The stunning innovation of Geo Grid wall build to utilize the full secure landfill ground. These Geo Grid wall creates a vertical landfill on top a fully closed landfill and estimated to hold waste capacity of a minimum 1.5 million tonne over an area of approximately 45 acres. Moreover, leachate treatment ground is also available to manage the final disposal of residues and other solid hazardous waste from the secure landfill.

4.0 Life Cycle Inventory (LCI)

The life-cycle inventory (LCI) component of LCA quantifies the material and energy inputs and outputs related to a product life-cycle [11]. Detailed and quantitative methodology that involves an inventory of the inputs and outputs of a system, measured at the boundaries of the system, as well as an assessment of the potential impacts associated with these inputs and outputs. Each stage of a product's life cycle consumes energy and non-renewable resources, as well as generating emissions associated with certain environmental impacts [58].

Inventory analysis of extractions and emissions: the primary energy and raw materials used, and emissions to the atmosphere, water, soil and land, are quantified for each process, then combined in the process flow chart and related to the functional unit basis; The outflows pollutants, materials, resources are recorded in inventory analysis. These elementary flows emissions, resources and energy consumptions are characterize and aggregated for different environmental problems in impact assessment [44].

4.1 Life Cycle Input Energy (LCIE)

Life cycle input energy are the energy use for the manufacturing or production phase, the transportation phase, the assembly and construction phase and also the decommissioning and disposal phase. Energy input can be quantified into two types which are (i) the cumulative energy demand (CED) and (ii) embedded energy of the product, i.e the photovoltaic panels. The difference of these energy shall be further discussed in this section, and usage in the impact assessment calculation [59].

4.1.1 Cumulative Energy Demand (CED)

The CED represents the total energy requirements valued as primary energy, during the life cycle of the solar PV system. Basically, it includes the direct and indirect energy requirements. The direct aspect indicates the direct energy use, while the indirect aspect represents the grey utilization of energy due to the use of raw materials and consumables.

The primary energy in this case signifies both the renewable and non-renewable energy requirements along the system's life cycle. The cumulative energy demand of the PV system is estimated by [60];

$$CED = E_m + E_T + E_I + E_O + E_D \quad (5)$$

- $CED = (PE + Inv)/ Out_{el}$ = Cumulative primary energy demand per unit of electricity output

- nr-CED = non-renewable cumulative primary energy demand per unit of electricity output (corresponding to the non-renewable share of the CED).

The method to calculate CED is based on the method published by Ecoinvent version 1.01 and expanded by PRé for energy resources available in the SimaPro database. Extra substances, according to the Ecoinvent database version 2.0, are implemented and expanded by Pre consultants for raw materials [61]. Each impact category is given the weighting factor 1. The factor for methane was changed to 55.53 MJ/kg.

Characterization factors are given for the energy resources divided in 5 impact categories:

1. Non-renewable, fossil
2. Non-renewable, nuclear
3. Renewable, biomass
4. Renewable, wind, solar, geothermal
5. Renewable, water

Total CED for each case studies of the 3 type of PV system are made up of the 5 phases system boundaries, manufacturing; transportation and packaging; BOS construction; operation and maintenance; and decommissioning and disposal as shown in Figure 20 below, It can be seen that, Photovoltaic manufacturing dominate the chart with 91% of the total energy consumption; 405,827.82 MJ compared to the rest of the life cycle phases.

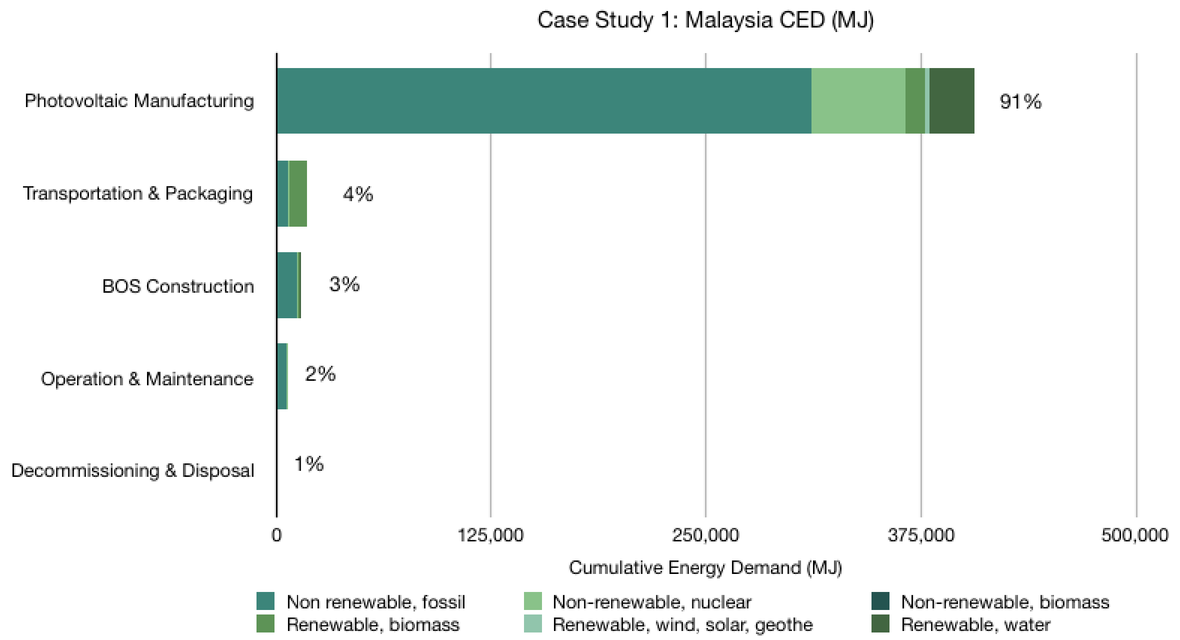


Figure 20 : Solar Standalone PV System Case Study 1, Malaysia CED (MJ)

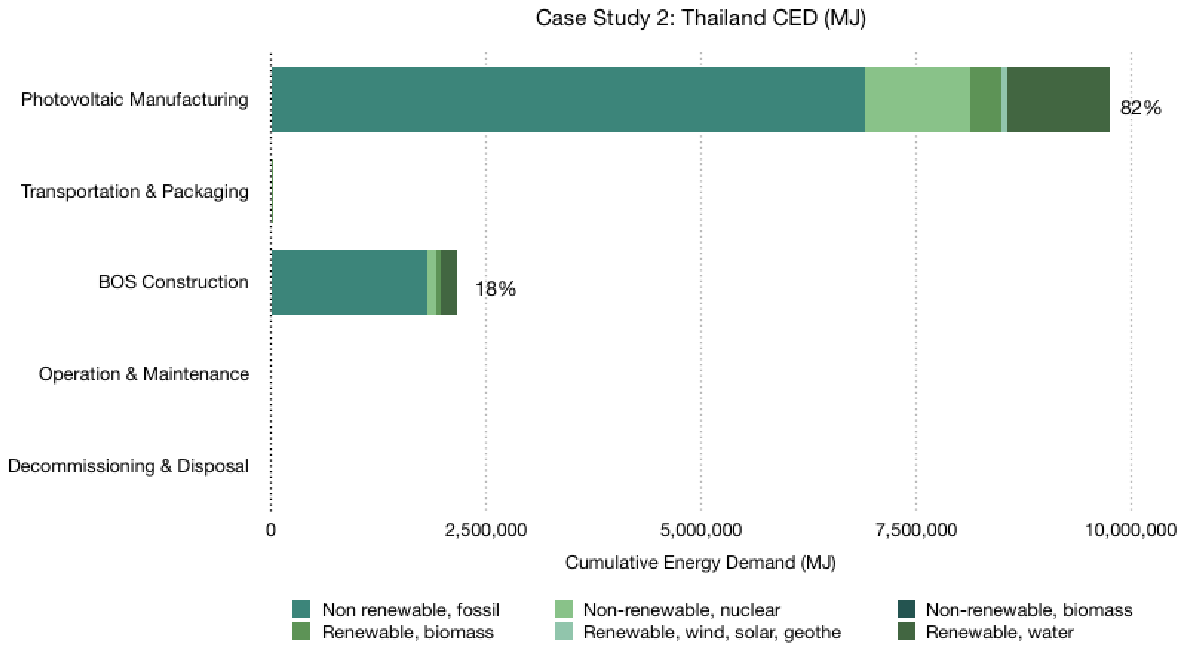


Figure 21 : Solar Standalone PV System Case Study 2, Thailand CED (MJ)

Both graphs has display quite similar pattern of photovoltaic manufacturing high CED with 91% and 82% for SAPV 1 and SAPV 2 respectively. SAPV 2 has more energy consumption in the BOS construction since the system uses a great amount of metal mounting installation due to its large-scale size. The energy consumption account to produce a large of mounting system is greater.

Large scale SAPV requires a massive BOS typical of solar farm except it is not grid-connected and only supports a certain designated area and are not for sale. Thus, its energy consumption is second to that of photovoltaic manufacturing from solar farm case studies. This is different from the small-scale standalone system in SAPV 1 in Malaysia, where the decommissioning and disposal phase is more than the BOS. This can be due to the need for disposal management dominates since it is a small system.

Moreover, SRPV system which is installed separately (non-integrated) shows a different pattern in its energy demand but obviously photovoltaic manufacturing still tops due to the large amount of panel. Again, SAPV 1 has a larger size compare to the second case study, it can be seen that large scale system consume more energy on BOS construction phase compare to the small ones which put more into decommissioning and disposal phase.

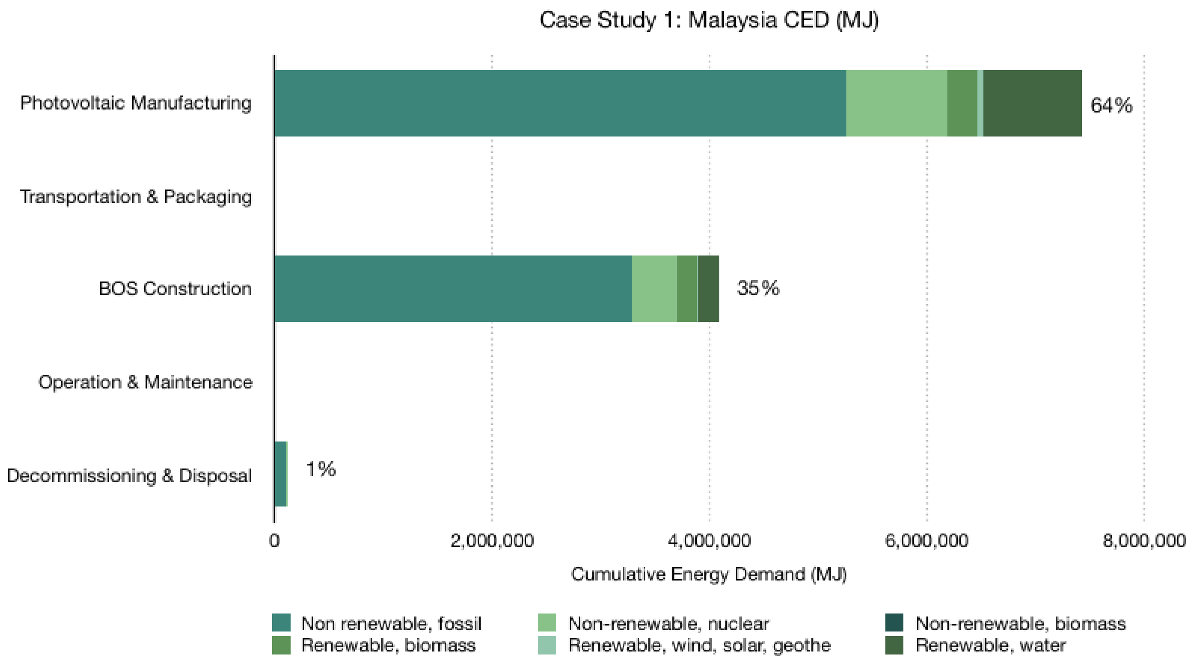


Figure 22 : Solar Rooftop PV System Case Study 1, Malaysia CED (MJ)

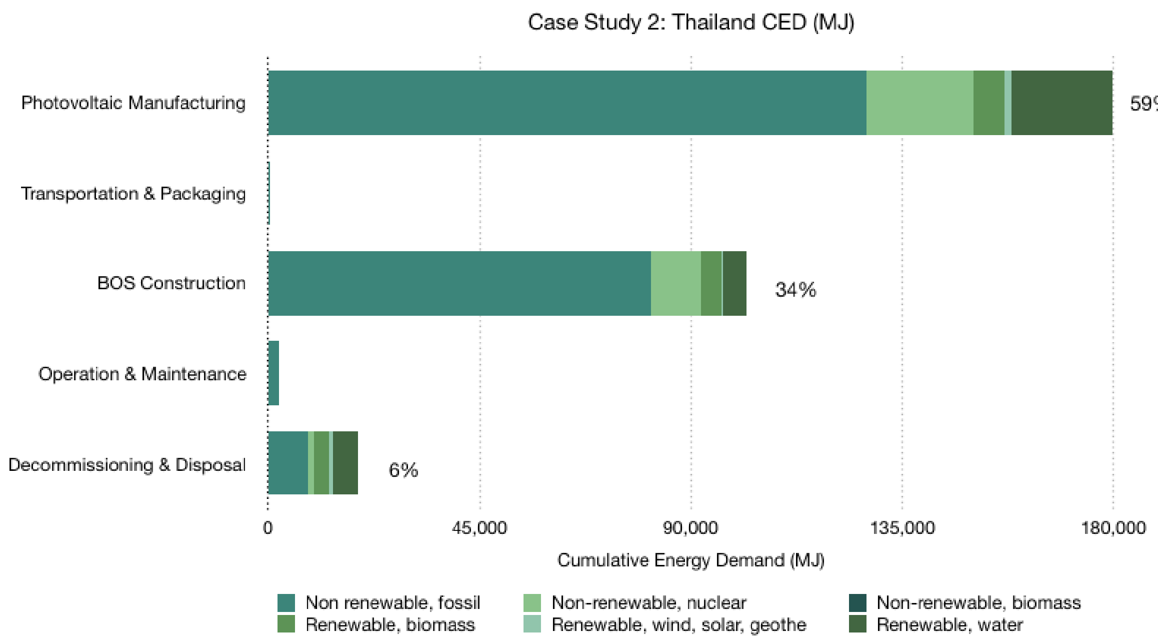


Figure 23 : Solar Rooftop PV System Case Study 2, Thailand CED (MJ)

Based on the SRPV 1 and SRPV 2 for graphs above (Figure 22 and Figure 23), photovoltaic manufacturing still takes the lead in energy consumption with 64% and 59% respectively. Moreover, the BOS construction also consumes almost half to that of PV manufacturing, 35% and 34% respectively.

In SRPV 1, its relevant because the amount of photovoltaic panels use in this system is higher compare to SRPV 2. In the other hand, mounting system which are included in the BOS construction for SRPV system itself are considered energy consuming due to the metal works especially in titled roof. In this SRPV 1, has a flat rooftop installation which is favorable to reduce mounting system complexity while SRPV 2, has a tilted roof that require a stronger metal mounting component to hold it in place.

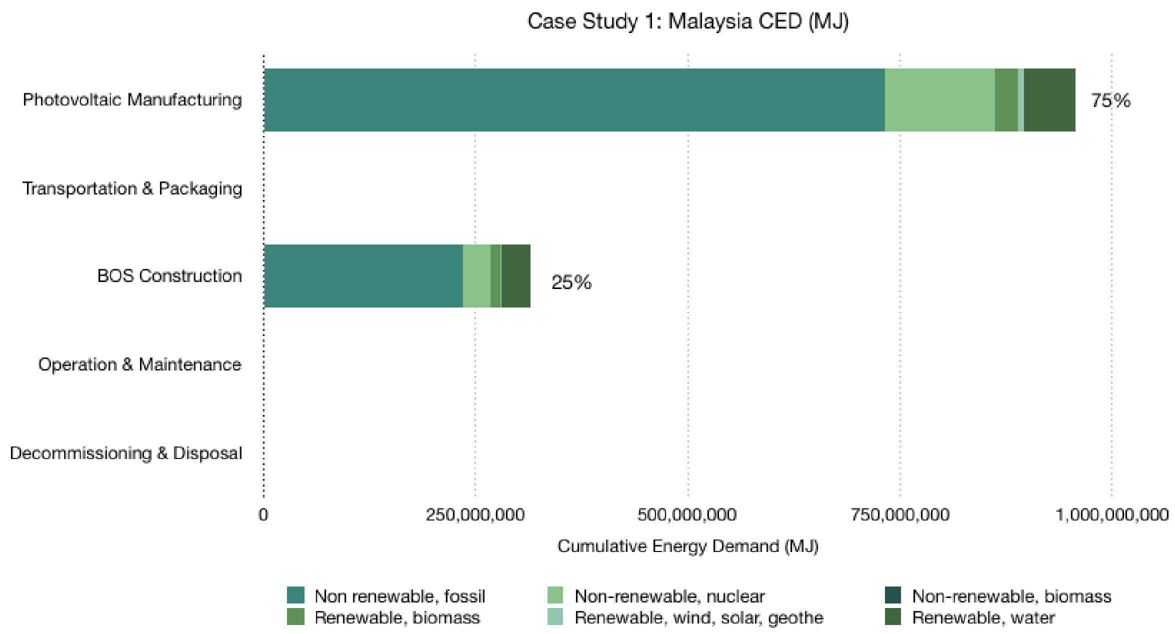


Figure 24 : Solar Farm PV System Case Study 1, Malaysia CED (MJ)

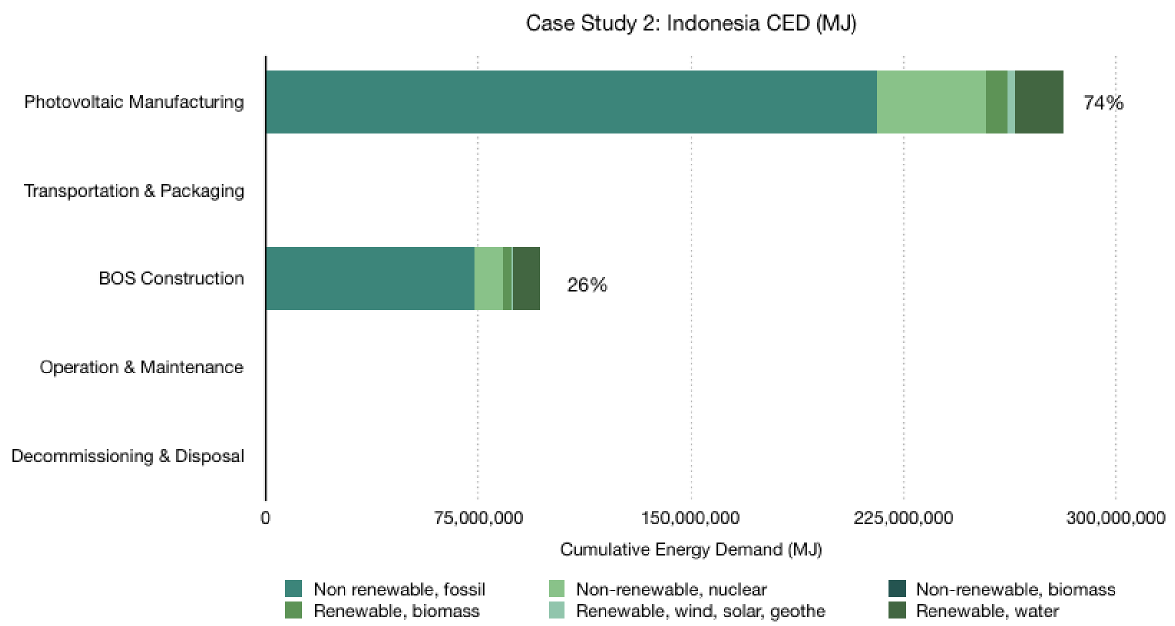
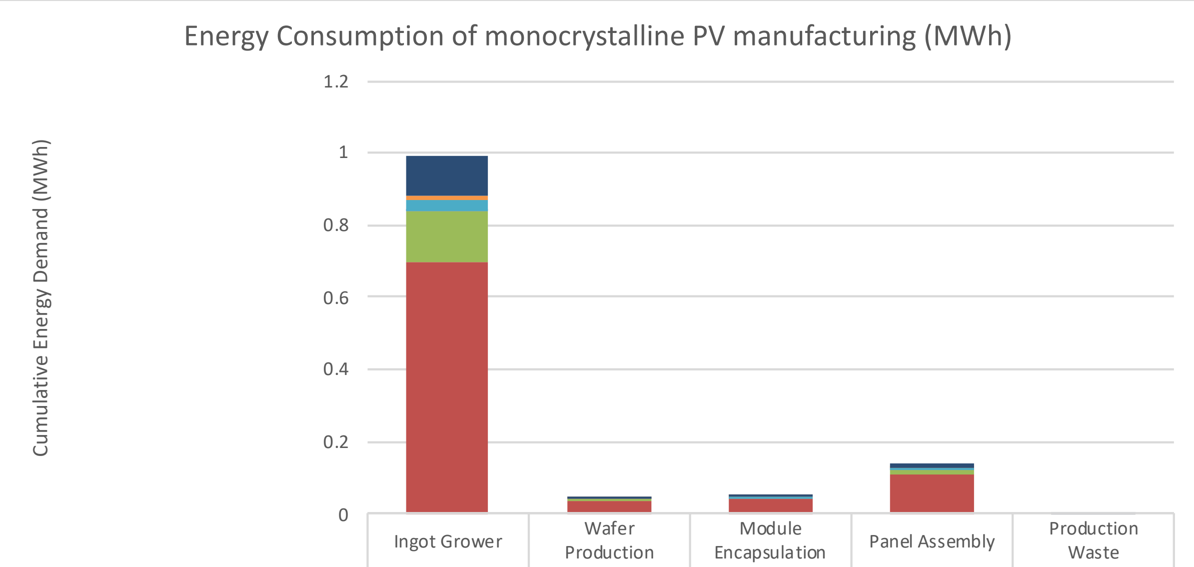


Figure 25 : Solar Farm PV System Case Study 2, Indonesia CED (MJ)

SFPV system CED both has high BOS construction due to the large-scale size of the system. This is proven by both SFPV 1 and SFPV 2 in Figure 24 and 25 above. The energy consume by BOS construction is great compare to the ones in SAPV system but almost equal to that of the SRPV system of 25% and 26% respectively.

Based on the CED analytical result, it can be seen that photovoltaic manufacturing dominates the energy demand in all the case studies in all three economies surveyed. This is because the energy consumption for photovoltaic manufacturing is high compared to the other life cycle phases since it depend on the number of PV panels use in the system.

Energy input is an important factor that will now give the CED for the three module types, expressed in MJ of primary energy (MJp) per m^2 of module area. The energy consumption (MJ) to produce one panel of polycrystalline PV according to Silicon Lab UKM case study is as shown in Figure 26 below.



	Ingot Grower	Wafer Production	Module Encapsulation	Panel Assembly	Production Waste
Renewable, water MWh	0.113872942	0.000734985	0.000619531	0.008126267	3.80231E-06
Renewable, wind, solar, geothe MWh	0.009239816	0.000140552	9.07959E-05	0.000324418	5.14601E-07
Renewable, biomass MWh	0.031078302	0.000842358	0.001022589	0.008150494	2.45731E-06
Non-renewable, biomass MWh	5.11639E-05	5.62781E-07	8.69051E-07	4.78618E-05	3.5239E-09
Non-renewable, nuclear MWh	0.141759995	0.003033318	0.001591148	0.012805845	8.7612E-06
Non renewable, fossil MWh	0.698971648	0.037184074	0.043011918	0.108731596	0.000130151

Figure 26 : Energy Consumption of Monocrystalline PV Manufacturing

Monocrystalline PV Manufacturing process is divided into 5 stages which are Ingot Grower, Wafer Production, Module Encapsulation, Panel Assembly and Production Waste. Energy consumption from the manufacturing is considered over commercialized value of which 60 wafer string on one panel module.

The energy demand for each case study differs depending on their number of panel. According to the energy consumption breakdown, predominantly energy consumption is from the Ingot growing process with 1.0 MWh and is followed by the panel assembly process with 0.14 MWh. These made up a total of 1.22 MWh of CED for the manufacturing process only.

If we scope down the manufacturing domination, it can be seen that SRPV and SFPV system have a higher energy consumption from the BOS construction compare to the SAPV, followed by the operation and maintenance of the system throughout its predicted lifetime of 25 years. Large scale system consume much more but this extraction are replaced quick through energy payback which will be discuss further in this report.

4.1.2 Embedded Energy

Embedded energy is the quantity of energy associated with manufacturing the materials and products that are needed for the replacement, maintenance and repair of the PV system materials and components throughout a the photovoltaic service life and is directly affected by the service life of the PV system [62].

The embodied energy of a material refers to the energy used to extract, process and refine it before use in product manufacture. Therefore, a correlation exists between the number and type of processing steps and the embodied energy of materials. For example, the fewer and simpler the extraction, processing and refining steps involved in a material's production, the lower its embodied energy. The embodied energy of a material is often reflected in its price.

In some cases, the most technically appropriate material will lower energy costs over the life cycle of a product. For example, composite materials involving carbon fiber or ceramic compounds may have a relatively high embodied energy, but when they are used appropriately, they can save energy in a product's use-phase due to their advanced physical properties, e.g., strength, stiffness, heat or wear resistance [60].

The desired purpose of the described method of embodied energy calculations carried out on residential developments is to establish improvements in the design and compare design options prior to construction [63]. The results are not designed for comparison with other studies due to the huge variations of calculation boundaries. The model developed in conjunction with this paper establishes key components in embodied energy contribution as follows [50]:

- Cradle to gate embodied energy estimates from a range of databases
- Transport energy freighting the finished product to the construction site
- Major components of assembly energy (particularly when these differ between construction options)
- Recurring Embedded Energy (based on a ‘churn rate’ during the buildings lifetime)

The detailed approach for a full study for embedded energy requires a massive amount of data. Thus, in this study as defined in the system boundary follows the general approach which **exclude the following**:

- Transport or assembly energy
- Recurring energy (and associated transport / assembly energy)
- Embodied energy of services installation
- Fittings and finishes
- Landscaping and earthworks

Subjective consideration of the ability to recycle and reuse products at the end of the building life can have an enormous effect on energy consumption. This limitation is addressed with clients in consultation by making recommendations on materials that have a high recycled value and/or using materials that will last longer.

Table 3: Cradle-to-Gate Embedded Energy

Materials	Embedded Energy & Carbon Coefficient			Comments
	EE (MJ/kg)	EC (kgCO2/kg)	EC (kgCO2e/kg)	EE: embedded energy EC: embedded carbon
Aggregate (general)	0.083	0.0048	0.0052	UK industrial fuel consumptions
Aluminum (general)	155	8.24	9.16	Assumed UK ratio
Primary Glass	15.00	0.86	0.91	Includes CO2 emission from primary manufacturing
Silicon	2355	-	-	
Lithium	853	5.30	-	
Water	0.01	0.001	-	
Plastic	80.50	2.73	3.31	Includes feedstock energy (EU)
Wire	36.00	2.83	3.02	
	MJ/sqm	kgCO2/sqm		
Monocrystalline PV	4750	242		UK industrial fuel mix
Polycrystalline PV	4070	208		

Source: ICEV2.0

4.2 Energy Payback Time (EPBT)

Energy payback time is the time required to recover the total energy investment made in a photovoltaic system can be determined by calculating the energy payback time. The Energy

Payback Time of PV systems is dependent on the geographical location; PV systems in Northern Europe need around 2.5 years to balance the input energy, while PV systems in the South equal their energy input after 1.5 years and less, depending on the technology installed [64].

This definition differs from the conventional definition for energy payback time because E_{elm} is accounted for as part of the total energy investment. A portion of this energy is readily determined, while the energy requirement for maintenance of a landfill, to operate a leachate collection system for example, is indeterminate. If it were necessary to monitor and treat leachate indefinitely, this energy requirement would eventually exceed the energy generated by a module. This fact illustrates the importance of sustainable end-of-life management practices [45].

Energy payback time is given by;

$$t_{epb} = E_{in} / P_{gen} \tag{6}$$

$$E_{in} = CED + \text{Embedded Energy} \tag{7}$$

Considering the lifetime of the PV system which are fixed on this study 25 years of operation for E_{in} and then solving for t_{epb} explicitly gives;

$$t_{epb} = E_{in} / (P_{gen} - E_{o\&m}) \tag{8}$$

This calculation does not include energy loss from the operational phase which emphasize the balance of system efficiency. Restate the system boundary.

4.2.1 Solar Stand-alone PV system

a) SAPV 1, Malaysia

The total primary energy consumption is 430,985.1MJ, and the annual energy production of the standalone system, 3,348.13 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.75
- Effective area of PV : 19.44 m2
- Solar irradiation : 1573.15 kWh/m2/year
- Degradation per year : 0.59%

The energy payback time for SAPV 1, Malaysia, is **36.1 years**. This considering the maintenance of 102.1 MJ/year.

b) SAPV 2, Thailand

The total primary energy consumption is 14,352,917.2 MJ, and the annual energy production of the standalone system, 266,450 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.70
- Effective area of PV : 4548.96 m2
- Solar irradiation : 1772 kWh/m2/year
- Degradation per year : 0.30%

The energy payback time for SAPV 2, Thailand, is **15.0 years**. This considering the maintenance of 4908.9 MJ/year.

4.2.2 Solar Rooftop PV System

a) SRPV 1, Malaysia

The total primary energy consumption is 8,639,518.71 MJ, and the annual energy production of the roof mounted system, 73,000 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.75
- Effective area of PV : 2138.4 m2
- Solar irradiation : 1685.39 kWh/m2/year
- Degradation per year : 0.23%

The energy payback time for SRPV 1, Malaysia, is **32.9 years**. This considering the maintenance of 86.09 MJ/year.

b) Case Study 2, Thailand

The total primary energy consumption is 289,760.58 MJ, and the annual energy production of the rooftop system, 10290.61 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.70
- Effective area of PV : 51.84 m2
- Solar irradiation : 1772 kWh/m2/year
- Degradation per year : 0.46%

The energy payback time for SRPV 2, Thailand, is **7.84 years**. This considering the maintenance of 92.89 MJ/year.

4.2.3 Solar Farm PV System

a) SFPV 1, Malaysia

The total primary energy consumption is 967,745,012.6 MJ, and the annual energy production of the solar farm system, 10,120,000.0 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.75
- Effective area of PV : 47,129 m2
- Solar irradiation : 1573.15 kWh/m2/year
- Degradation per year : 0.59%

The energy payback time for SFPV 1, Malaysia, is **26.6 years**. This considering the maintenance of 54,813.5 MJ/year.

b) SFPV 2, Indonesia

The total primary energy consumption is 289,607,589.8 MJ, and the annual energy production of the solar farm system, 2,970,720.0 kWh/year (1 kWh = 3.6 MJ). The following parameters are taken into account for the energy payback time;

- The module efficiency : 15%
- Performance Ratio : 0.75
- Effective area of PV : 13880.16 m2
- Solar irradiation : 1826 kWh/m2/year
- Degradation per year : 0.20%

The energy payback time for SFPV 2, Indonesia, is **27.1 years**. This considering the maintenance of 109.1 MJ/year.

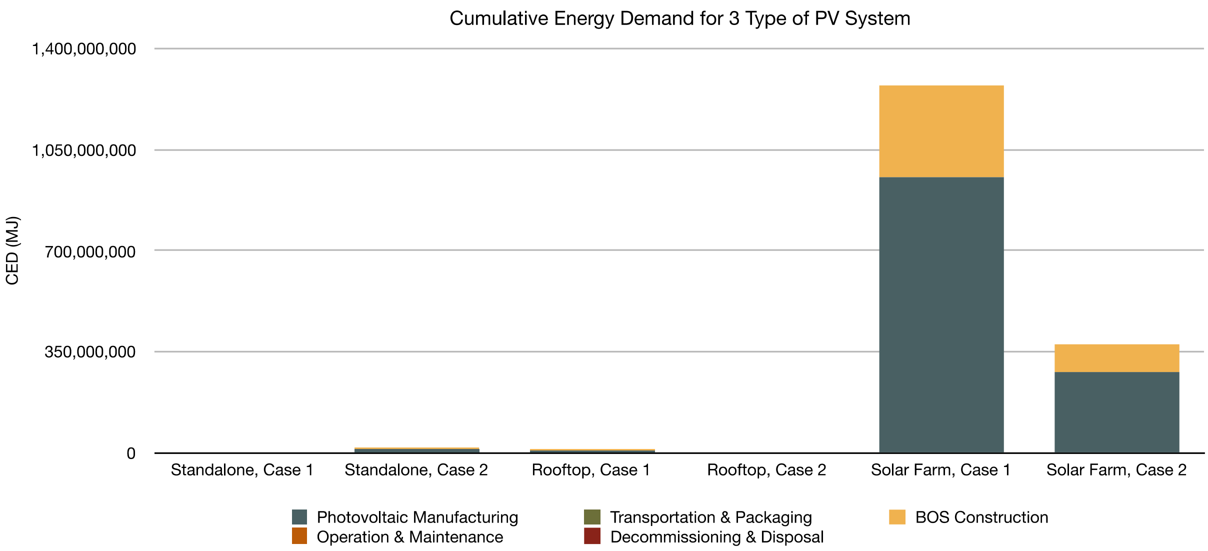


Figure 27 : Cumulative Energy Demand for 3 Type of PV Systems

Energy payback are greatly influence by many component and activities during the life cycle phases which expands for 25 years of lifetime. Large number of energy payback years by ecoinvent which include component production are relevant, this is because relying solely on photovoltaic production does not separate the fact that global warming potential takes in this into account [65].

EPBT calculations are heavily influenced by how much sunlight a PV system will receive. The more sunlight received, the more KWH the PV system will produce and the faster the PV system will offset the energy it took to manufacture it. The 2006 study reported EPBT of one to two years based on an average of 4.7 peak sun-hours received in southern Europe. If you live in a sunnier climate, then the energy payback time will be less. The current overall worldwide average EPBT of one to three years (rather than one to two years for southern Europe) accounts for cloudier locations across the globe [11].

5.0 Life Cycle Impact Assessment (LCIA)

LCIA method includes 16 midpoint impact categories [66]:

1) Climate change: GWP calculating the radiative forcing over a time horizon of 100 years | IPCC 2007.
2) Ozone depletion: Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over time horizon of 100 years | World Meteorological Organization (WMO) 1999.
3) Human Toxicity, cancer effects: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a mas of a chemical emitted (cases per kilogramme) | USEtox
4) Human Toxicity, non-cancer effects: Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a mas of a chemical emitted (cases per kilogramme) | USEtox
5) Particulate matter: Quantification of the impact of premature death or disability that particulates/ respiratory inorganics have on the population, in comparison to PM2.5. It includes the assessment of primary (PM10 and PM2.5) and secondary PM (include creation of secondary PM due to Sox, NOx and NH3 emissions) and CO. | Rabl and Spadaro 2004.
6) Ionizing radiation HH (human health): Quantification of impact of ionizing radiation on the population, in comparison to Uranium 235. | Frischknecht et al 2000.
7) Ionizing radiation E (ecosystem): Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a radianucleide emitted (PAF m3 year/kg). | Garnier-Laplace et al, 2008.
8) Photochemical ozone formation: expression of potential contribution to photochemical ozone formation | Van Zelm et al. 2008.
9) Acidification: accumulated exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit. | Seppala et al, 200 and Posch et al, 2008.
10) Terrestrial eutrophication: accumulated exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit | Seppala et al, 2006 and Posch et al, 2008.
11) Freshwater eutrophication: Expression of the degree to which the emitted nutrients reaches the freshwater end compartment | ReCiPe version 1.05.
12) Marine eutrophication: Expression of the degree to which the emitted nutrient reaches the marine end compartment | ReCiPe version 1.05.
13) Freshwater ecotoxicity: Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3 year/kg) | USEtox
14) Land use: Soil Organic Matter (SOM) based on changes in SOM, measured in (kg C/m2/a). Biodiversity impacts not covered by the data set. | Mila I Canals et al, 2007.

15) Water Resources depletion: Freshwater scarcity: Scarcity-adjusted amount of water used. | Swiss Ecoscarcity, 2006.
16) Mineral, fossil & renewable resources depletion: Scarcity of mineral resource with the scarcity calculated as 'Reserve base'. It refers to identified resources that meets specified minimum physical and chemical criteria related to current mining practice. | Van Oers et al, 2002.

5.1 Impact Assessment

There are many impact assessment method available in the ecoinvent system, according to economies such as Europe, United Kingdom, China and United States. Even so, taking consideration of the Asia the consistent category falls under rest of world {RoW} or global {GLO}. These impact assessment also covers the single issues which is more focus over a certain impact such as IPCC 2013 GWP 20a (version 1.02), IPCC 2013 GWP 100a (version 1.02), GHG Protocol (version 1.01), Ecosystem Damage Potential (version 1.00), and Cumulative Energy Demand (1.09) [67].

These impact categories will standardize the LCI result into a comparable impact indicator generally known as characterization or equivalent factors. This will allow all kind of material be under a similar basis for impact comparison such as Global Warming, for instance. These classification is usually facilitated by software, such in this study, SIMAPro that can take the component inputs and calculate allocated impacts based on either actual data gathered or standardized data tables. While there are pros and cons to each classification tool, some have been adopted more broadly than others [68].

5.1.1 Global Warming Potential (IPCC GWP 20a)

Global warming potential based on IPCC 2013 (version 1.02), which was developed by the Intergovernmental Panel on Climate Change method, Contains the climate change factors of IPCC with a timeframe of 20 years [69]. IPCC characterisation factors for the direct (except CH4) global warming potential of air emissions [70];

- Not including indirect formation of dinitrogen monoxide from nitrogen emissions.
- Not accounting for radiative forcing due to emissions of NOx, water, sulphate, etc.
- Not considering the range of indirect effects given by IPCC.
- Not including indirect effects of CO emissions.
- The factor for biogenic methane was calculated by subtracting 2.7 kg of CO2 per kg of methane from the methane factors. The correction factor of 2.75 is the molar mass of CO2 divided by the molar mass of CH4.
- The factors for fossil methane in the IPCC report were not used. The factor for methane in IPCC also apply to fossil methane.

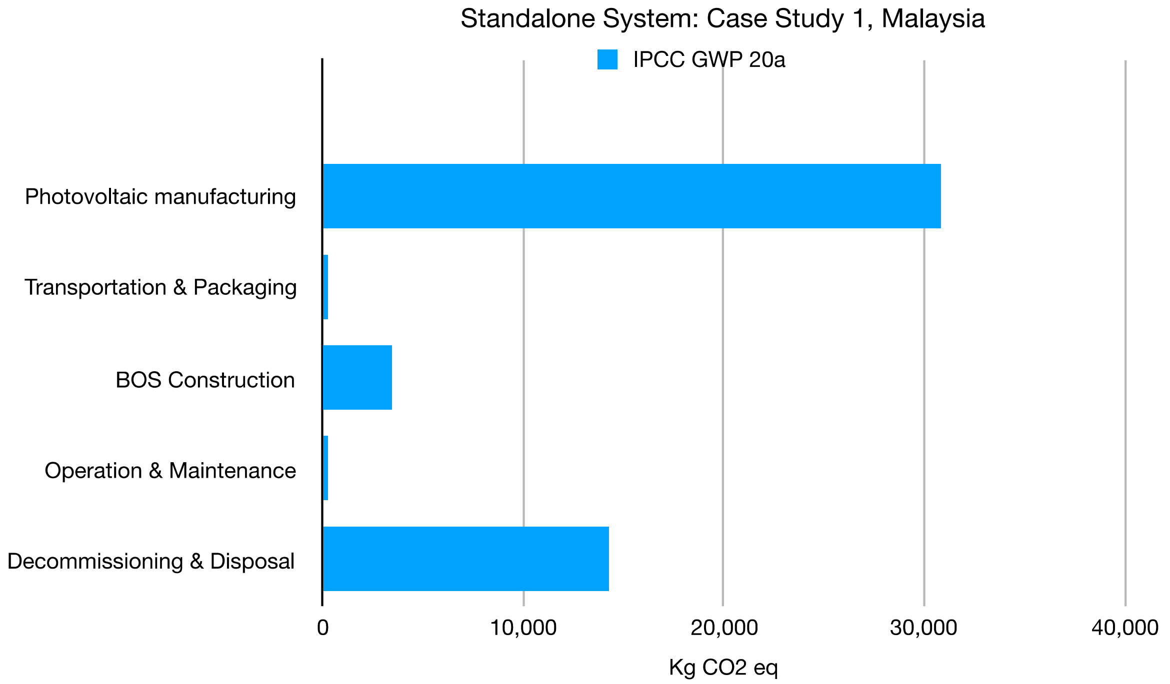


Figure 28 : Standalone System: Case Study 1, Malaysia GWP20a

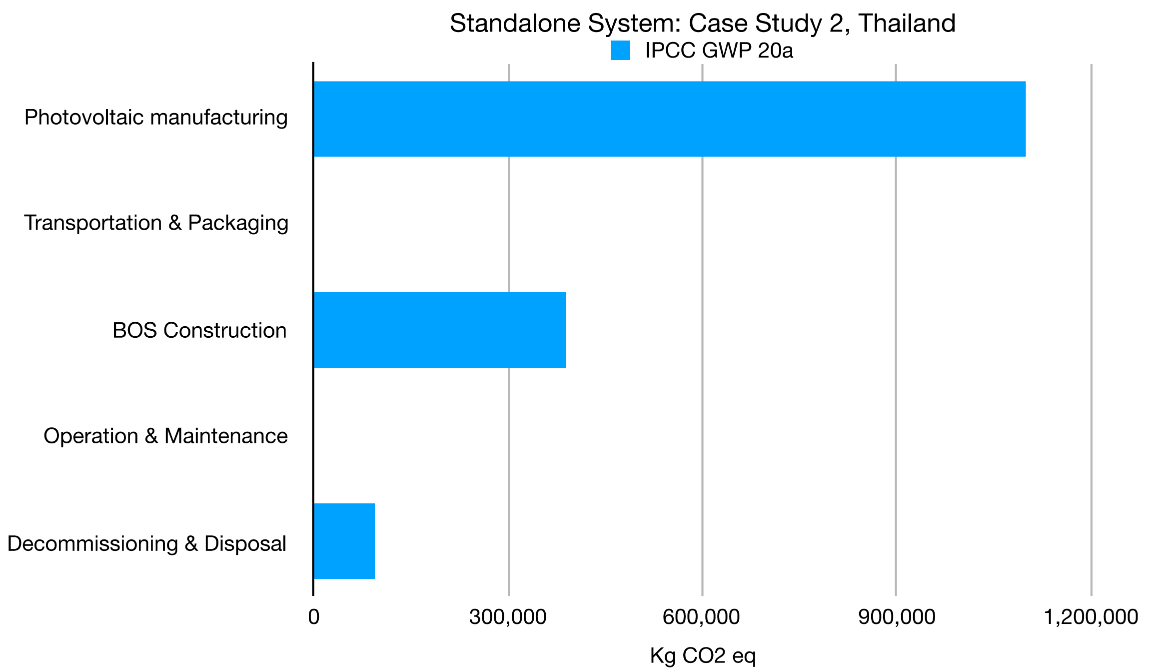


Figure 29 : Standalone System: Case Study 2, Thailand GWP20a

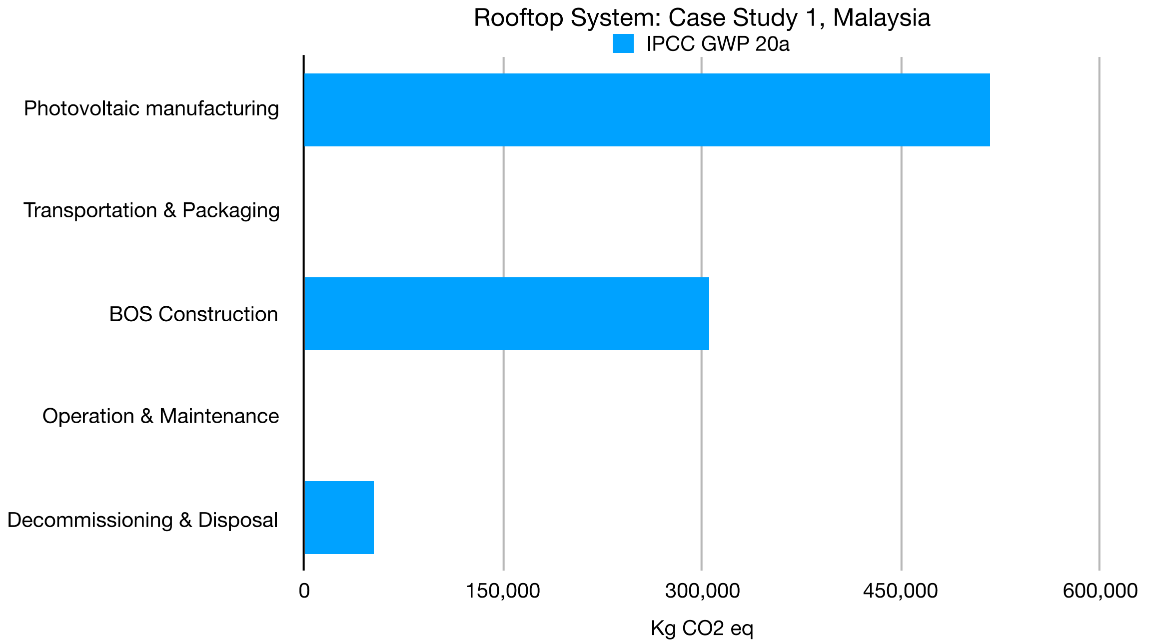


Figure 30 : Rooftop System: Case Study 1, Malaysia GWP20a

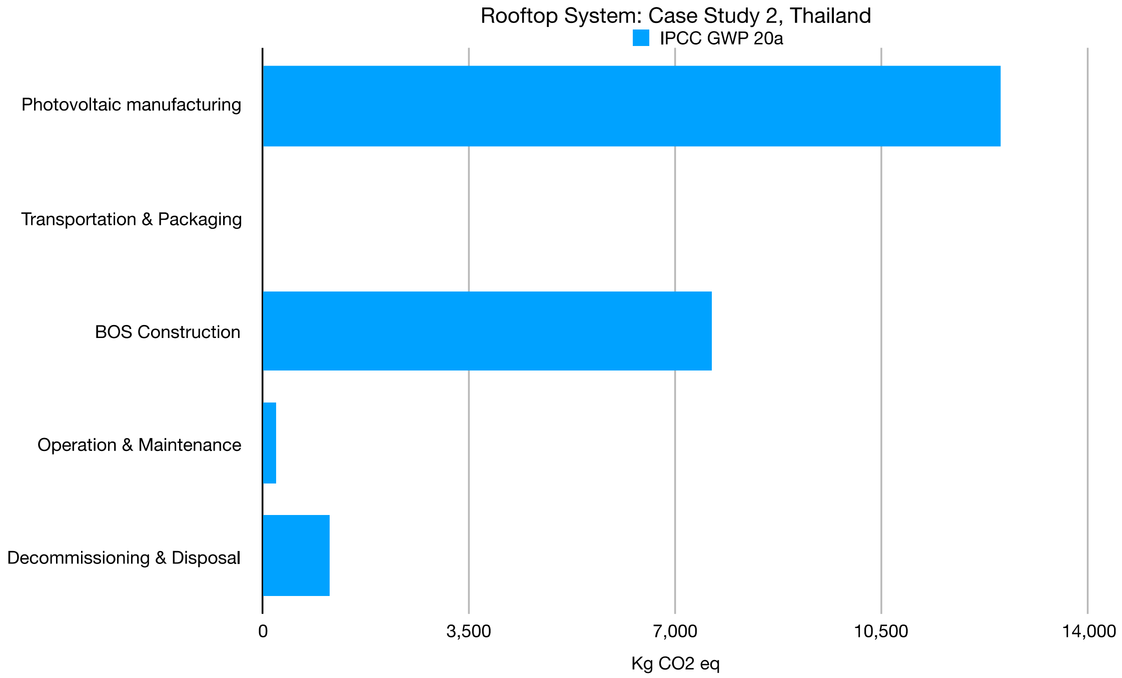


Figure 31 : Rooftop System: Case Study 2, Thailand GWP20a

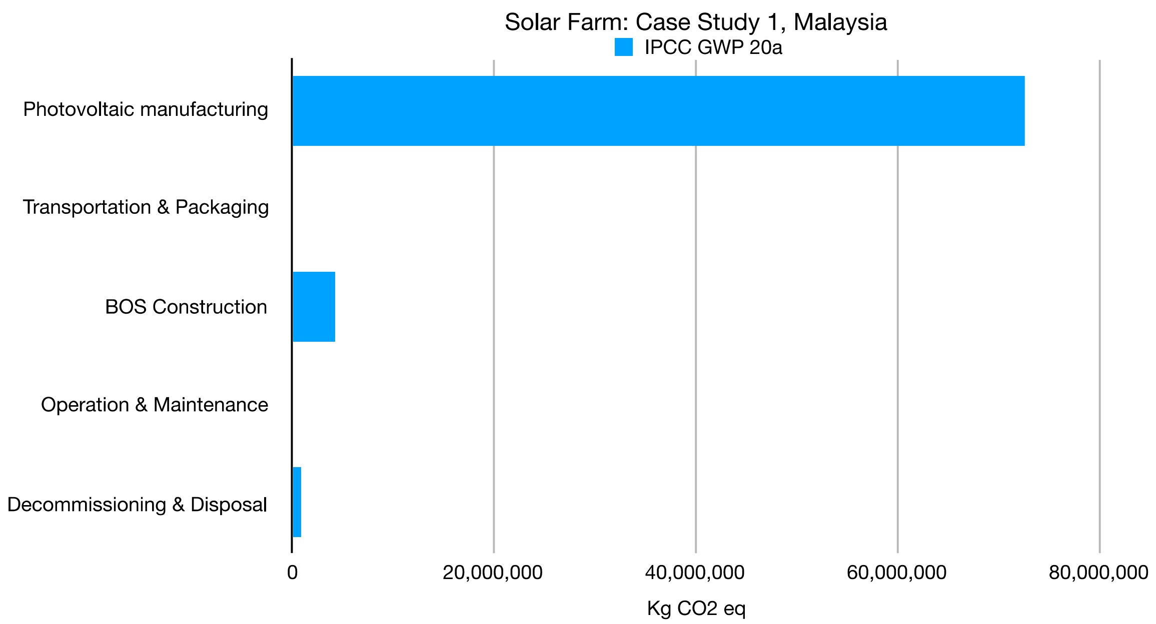


Figure 32 : Solar Farm System: Case Study 1, Malaysia GWP20a

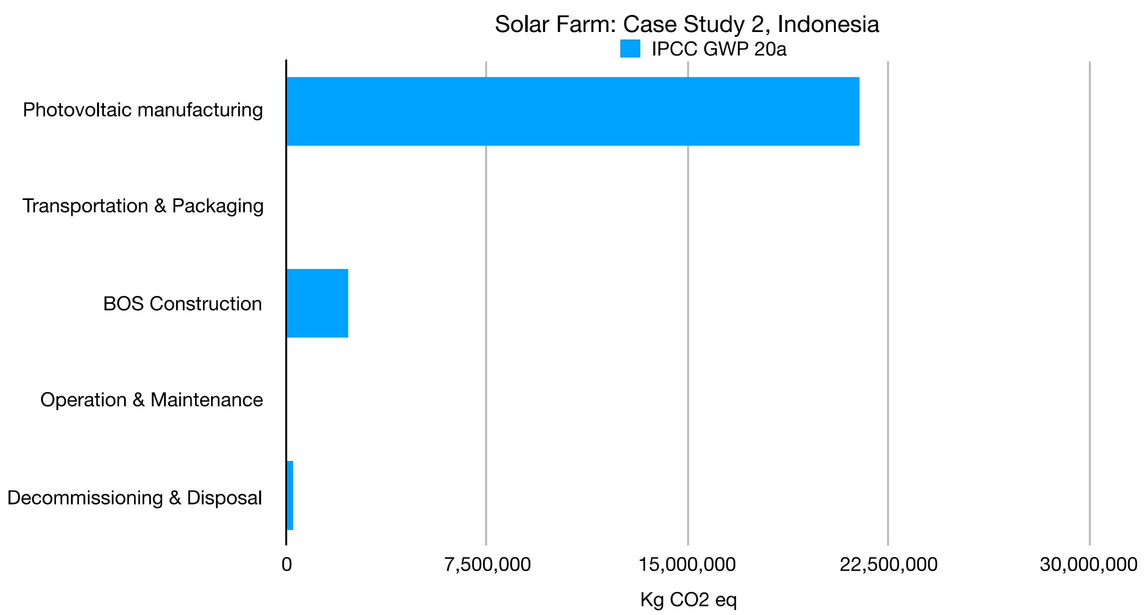


Figure 33 : Solar Farm System: Case Study 2, Indonesia GWP20a

Based on the graphs above, the global warming potential for over the period of 20 years are greatly affected by the photovoltaic manufacturing given its large energy consumption which depend on the grid electricity mix of the economies as stated. Consistently, about thousands of kg CO2 equivalent are affixed through this process.

5.1.2 Global Warming Potential (IPCC GWP 100a)

Global warming potential based on IPCC 2013 (version 1.02), which was developed by the Intergovernmental Panel on Climate Change method, Contains the climate change factors of IPCC with a timeframe of 20 years. IPCC characterisation factors for the direct (except CH4) global warming potential of air emissions [69];

- Not including indirect formation of dinitrogen monoxide from nitrogen emissions.
- Not accounting for radiative forcing due to emissions of NOx, water, sulphate, etc.
- Not considering the range of indirect effects given by IPCC.
- Not including indirect effects of CO emissions.
- The factor for biogenic methane was calculated by subtracting 2.7 kg of CO2 per kg of methane from the methane factors. The correction factor of 2.75 is the molar mass of CO2 divided by the molar mass of CH4.
- The factors for fossil methane in the IPCC report were not used. The factor for methane in IPCC also apply to fossil methane.

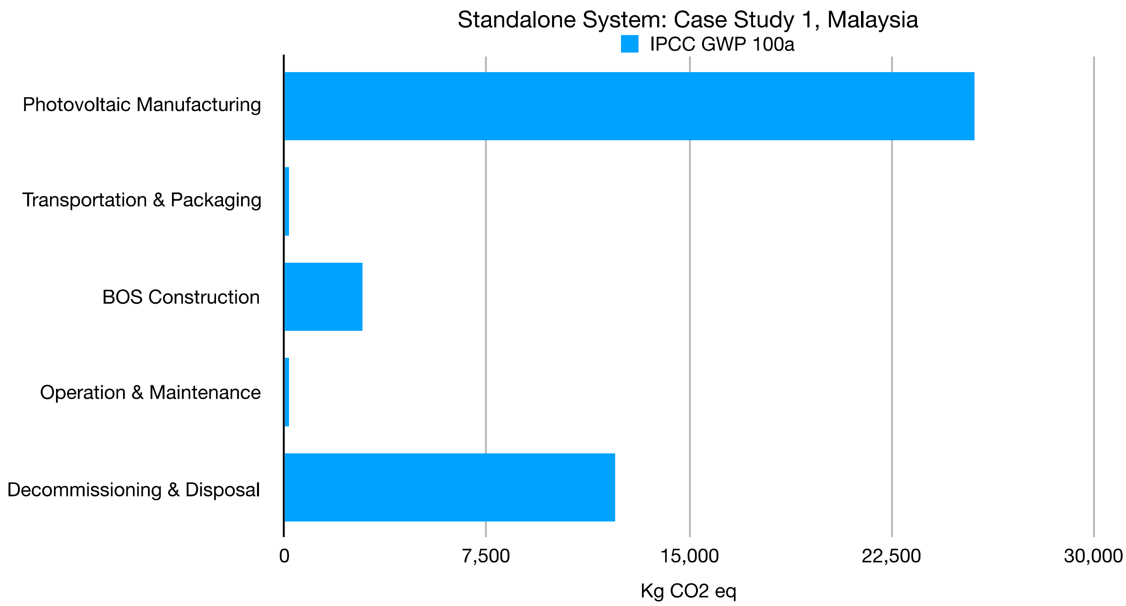


Figure 34 : Standalone System: Case Study 1, Malaysia GWP100a

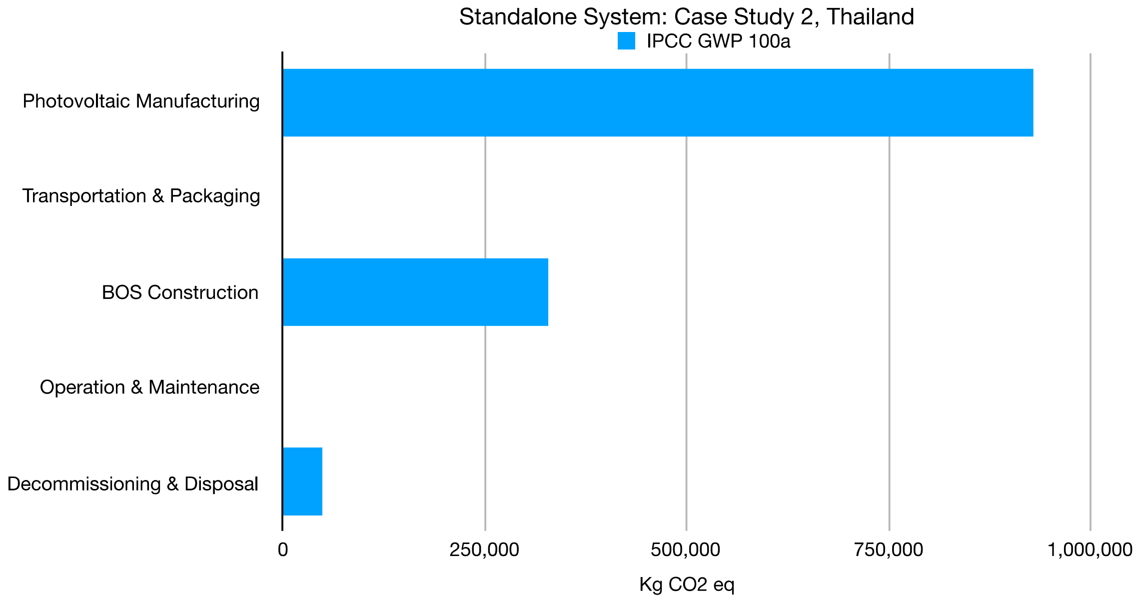


Figure 35 : Standalone System: Case Study 2, Thailand GWP100a

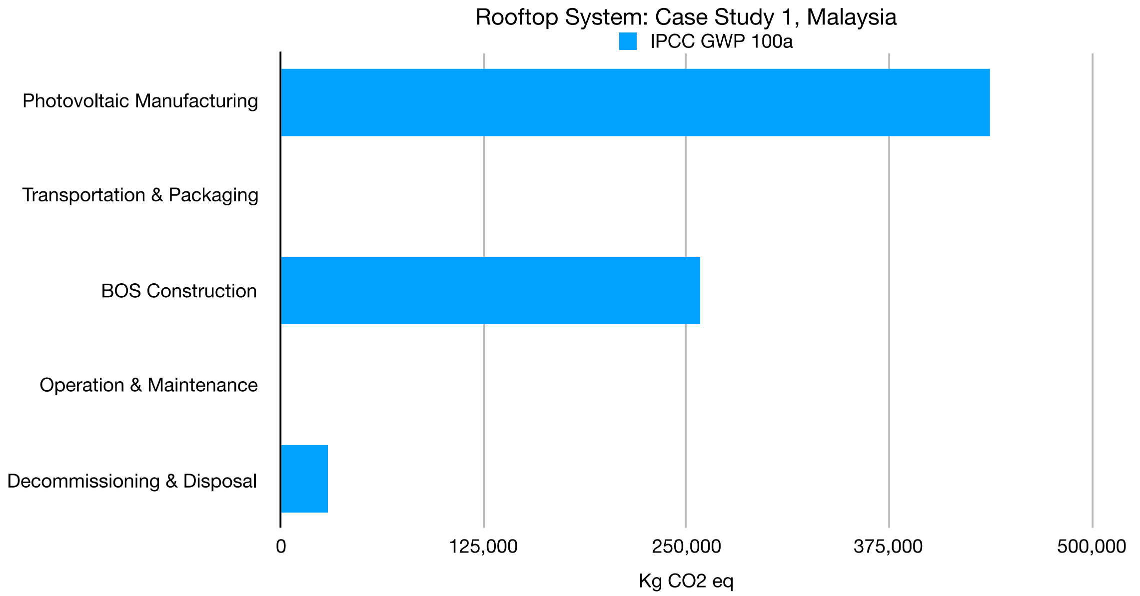


Figure 36 : Rooftop System: Case Study 1, Malaysia GWP100a

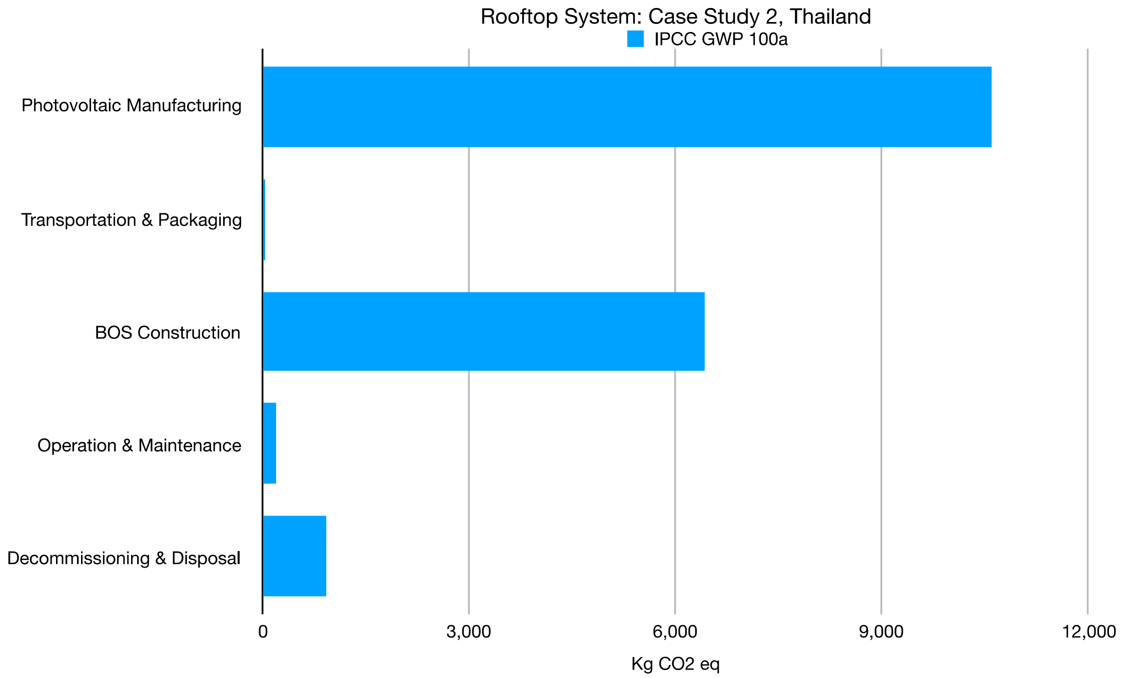


Figure 37: Rooftop System: Case Study 2, Thailand GWP100a

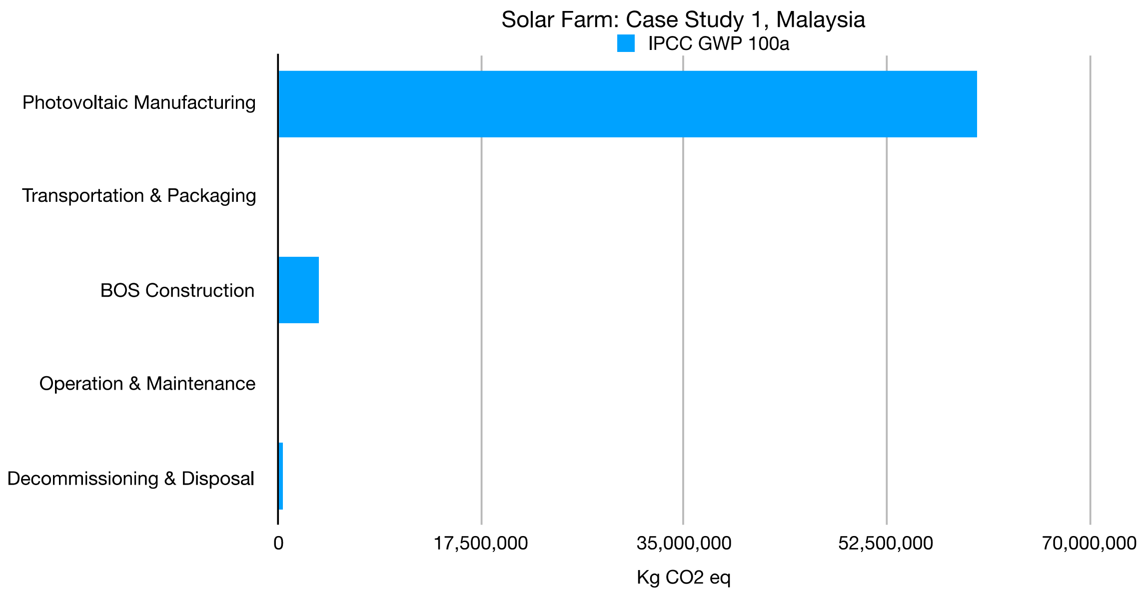


Figure 38 : Solar Farm System: Case Study 1, Malaysia GWP100a

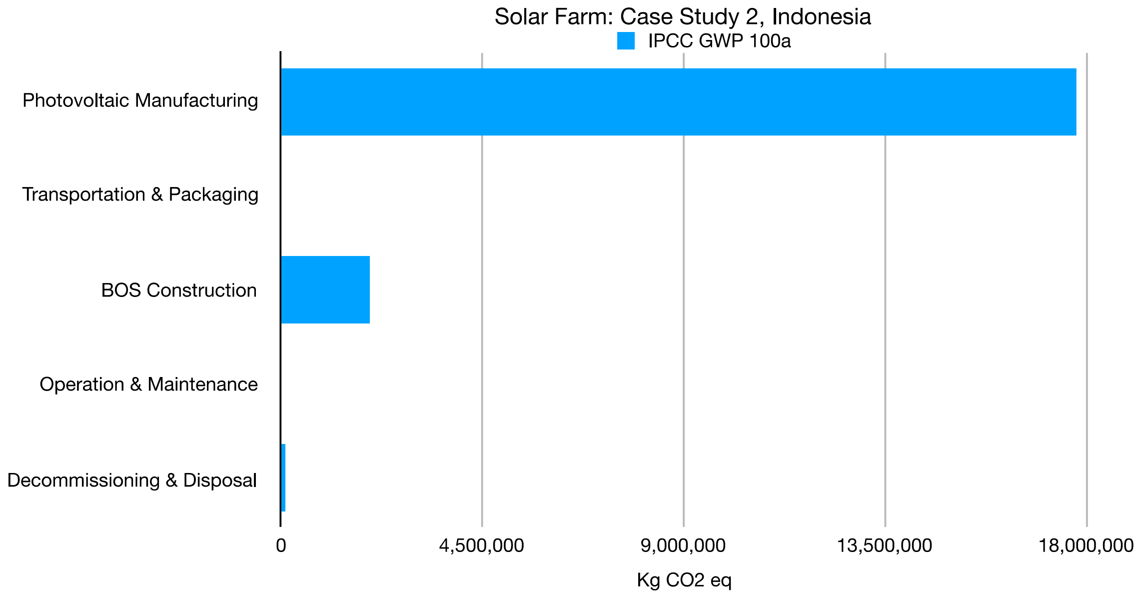


Figure 39 : Solar farm System: Case Study 2, Indonesia GWP100a

5.1.3 Greenhouse Gases Protocol (GHG Protocol)

The greenhouse gas protocol method has been developed especially for the Road Testing process of WRI/WBCSD, which aims to test the usability of the draft Greenhouse Gas Protocol carbon footprint standards [61].

The characterisation factors per substance are identical to the IPCC 2007 GWP (100a) method in SimaPro. The only difference is that carbon uptake and biogenic carbon emissions are included in this method and that a distinction is made between:

1) Fossil based carbon (carbon originating from fossil fuel)
2) Biogenic carbon (carbon originating from biogenic sources such as plants and trees)
3) Carbon from land transformation (direct impacts)
4) Carbon uptake (CO2 that is stored in plants and trees as they grow)

The draft standards require fossil and biogenic carbon to be report separately. Reporting of carbon caused by direct land use change is currently defined as optional, depending on the product category while reporting of carbon uptake is not required.

Although, there are data limitations, currently only the ecoinvent datasets specify carbon in these four sub categories. If you use other data, for instance, From the Input Output libraries, you will not get a correct specification of biogenic carbon, carbon uptake and land use related carbon. This is due to the different data collection strategies used in these libraries. In the process contribution tab in the results section you can see the relative share of the contribution of each process [66].

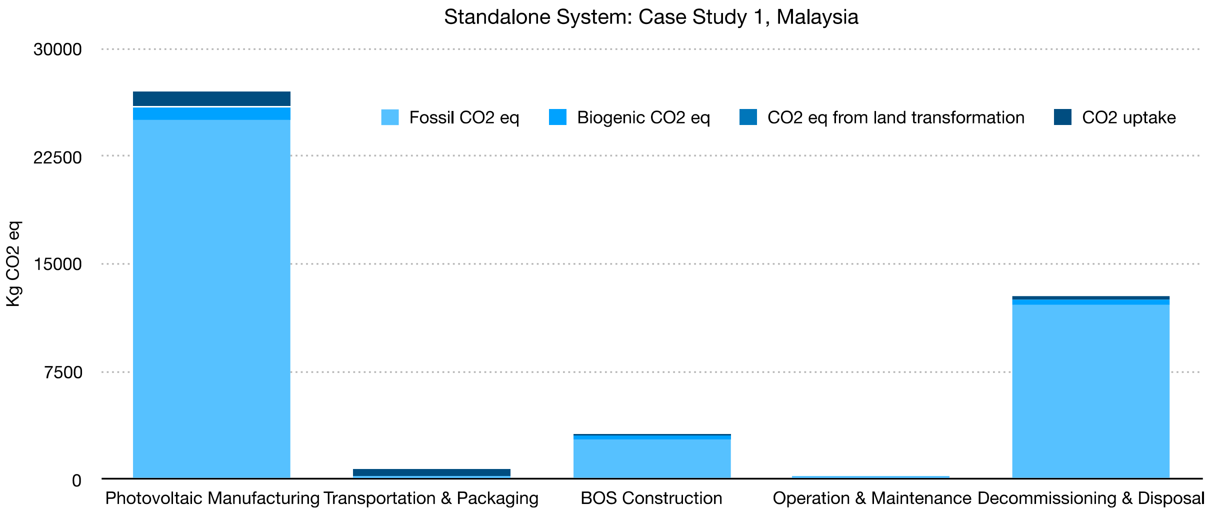


Figure 40 : Standalone System: Case Study 1, Malaysia GHG

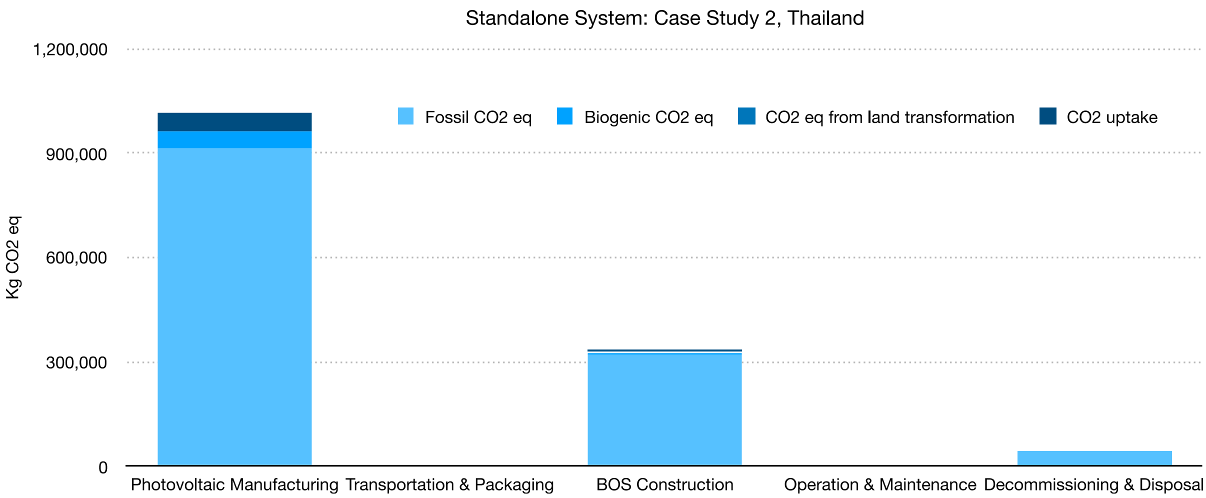


Figure 41 : Standalone System: Case Study 2, Thailand GHG

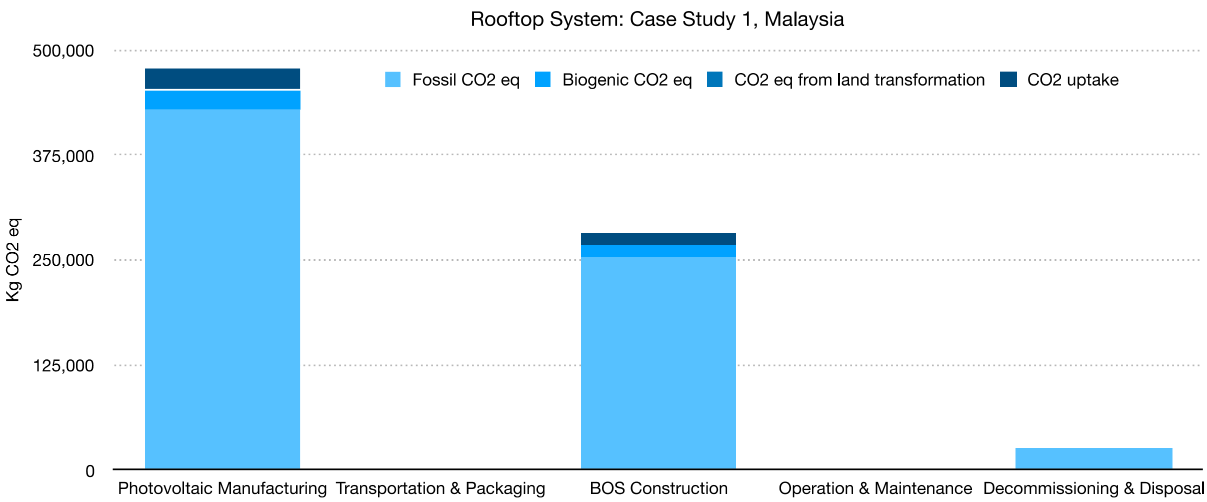


Figure 42 : Rooftop System: Case Study 1, Malaysia GHG

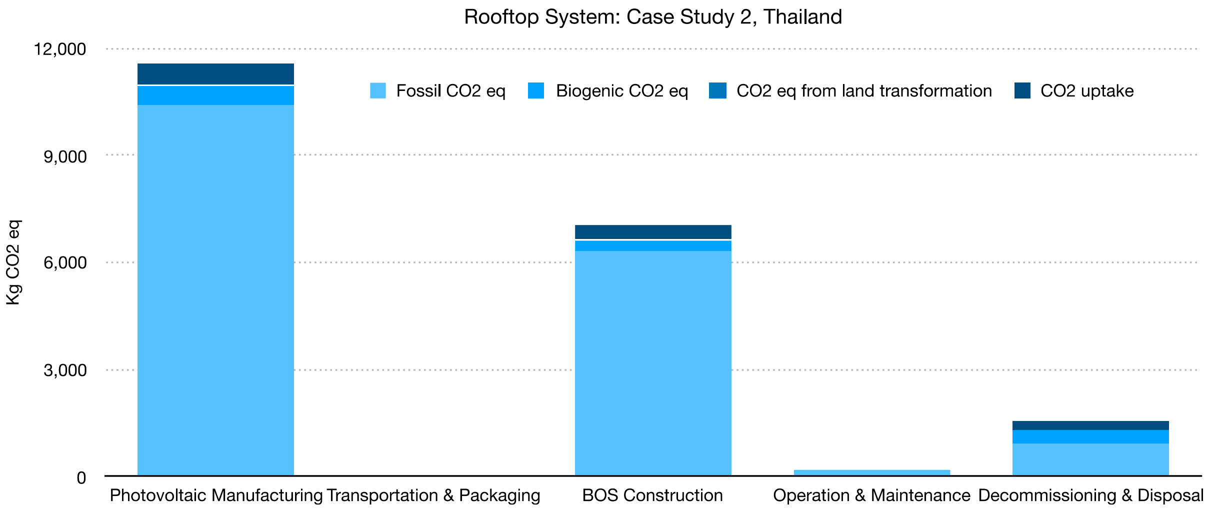


Figure 43 : Rooftop System: Case Study 2, Thailand GHG

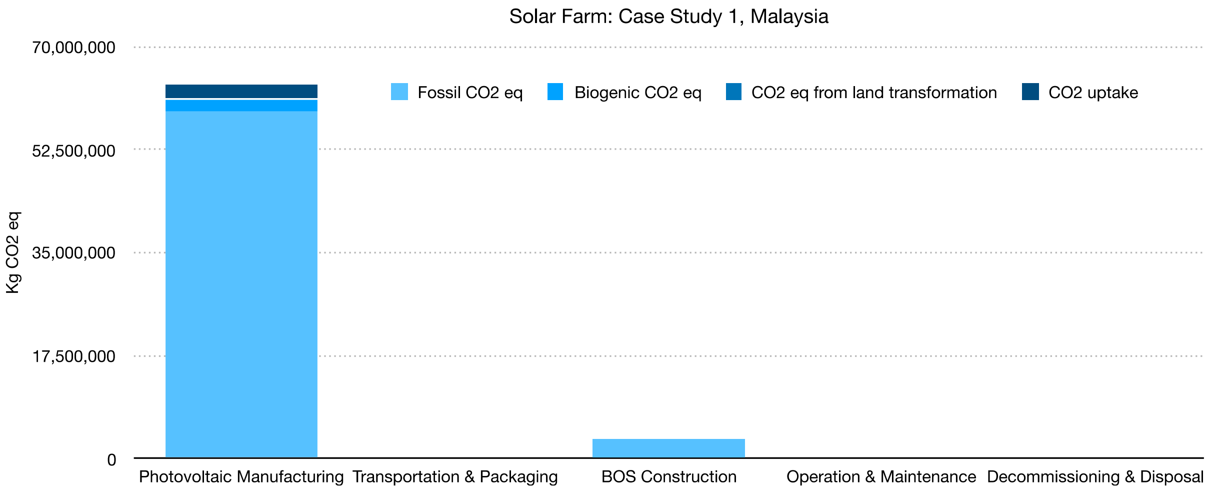


Figure 44 : Solar Farm System: Case Study 1, Malaysia GHG

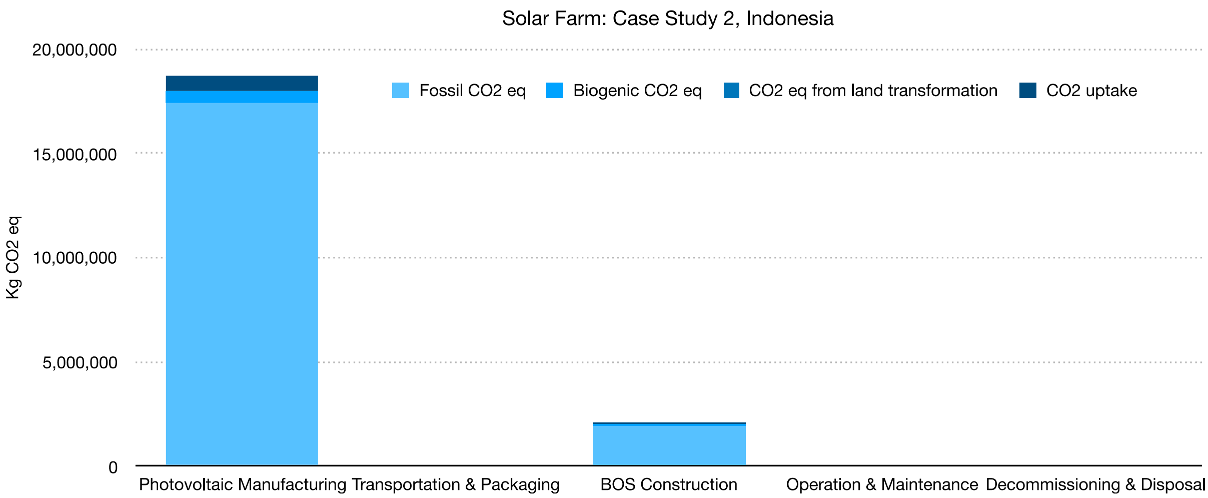


Figure 45 : Solar Farm System: Case Study 2, Indonesia GHG

The greenhouse gases release of the three case study are based on the above mentioned factors. Fossil CO2 eq (kg CO2 eq) contribute the most to the carbon uptake compare to the others, in which the amount is almost double to that of biogenic, land transformation and carbon uptake. These values are also considered to be the involvement of grid electricity mix of the economy that use for photovoltaic manufacturing.

5.2 Impact Category Indicator Result – (I) Midpoint Recipe

Impact category indicator result use in this report is the Midpoint Recipe (Individualist). Environmental relevance and scientific robustness have been specified by ten sub-criteria in order to outline the modelling of climate change in more detail [44].

- Atmospheric fate and transport is considered.
- For damages on ecosystems, all relevant effects are considered.
- For damages on Human Health, all relevant effects are considered.
- All category indicators and characterisation models linking midpoint to endpoint fulfil the science-based requirements.
- The coverage of the impacts in modelling from midpoint to endpoint is complete. The fate and transport model reflects the latest stage of knowledge.
- The human damage model is scientifically robust.
- The ecosystem damage model with loss of species is scientifically robust.
- The ecosystem damage model on primary production is scientifically robust.
- The model including the underlying data has potential for being consistently improved and further developed regarding geographic and temporal differentiation.

5.2.1 Climate Change

As energy costs increase, controlling the cost of living will require reductions in energy demand. Furthermore, managing global greenhouse gas emissions from property development is of key importance for minimising climate change. Life cycle energy analysis clearly identifies optimum strategies for reducing both energy demand and greenhouse gas emissions [1].

As concentrations are changed in the environment, we would expect to see intermediate impacts. For the case of climate change, increased concentrations of greenhouse gases are expected to lead to increased warming (actually radiative forcing). Emissions of conventional pollutant emissions lead to increased concentrations in the local atmosphere. These intermediate points of the chain are also called midpoints, which are quantifiable effects that can be linked back to the original emissions, but are not fully indicative of the eventual effects in the chain [53].

Climate change involves a number of environmental mechanisms that affect both the Human Health and Natural Environment. Climate change models are, in general, developed to assess the future impact on climate resulting from different policy scenarios. The environmental mechanisms used for this impact category have a somewhat different structure, compared to the fate, effect and damage steps applied to many of the other impact categories. Man-made climate change is caused by the emission of greenhouse gases and by other activities influencing their atmospheric concentration. Greenhouse gases are substances with the ability to absorb infrared radiation from the earth (radiative forcing).

When modelling the radiative forcing of an emission, the change in concentration and radiative forcing is determined, taking into account the residence time of the substance. A globally-recognised model (the Bern model) has been developed by the Intergovernmental Panel on Climate Change (IPCC) that calculates the radiative forcing of all greenhouse gases and branded them Global Warming Potentials (GWP) [70].

The IPCC GWPs are recommended for use at midpoint by using GWP relatives as shown in Table 4. Firstly, at midpoint the GWPs are used directly as characterisation factors. Secondly, these factors are used to express a combined fate and effect in terms of radiative forcing, which is then coupled to a modelling of a resulting temperature increase, using the residence time and the radiative forcing of the greenhouse gas. Thirdly, the temperature rise results in damage to Human Health and ecosystems, and here several effects are considered, such as an increase in malaria and malnutrition for Human Health or disappearance of a species and change in biomass for ecosystems [58].

Table 4 : Global Warming Potential Relative

GHG	Atmospheric Lifetime (year)	GWP-20	GWP-100	GWP-500
CO2	~10,000	1	1	1
CH4	12 ± 3	72	25	8
N2O	114	289	298	153
SF6	3,200	16,300	22,800	32,600

Source: IPCC 5th

The low level of solar energy utilisation so far is the result of a number of factors. historically, a major hindrance was the high cost of solar photovoltaic technologies but dramatic price reductions have meant that solar PV technology is now cheap, with cost limited by other components of the system. the low private cost of fossil fuels for instance, ignoring atmospheric pollution and climate costs which are relative to lower-carbon alternatives has led to the current dominant position of fossil fuels in the energy system. investment in and development of associated [58].

If emissions are to be significantly reduced in line with a stated intent to limit the change in global mean surface temperature to 2°c above pre-industrial levels, then there are only a few decades for the world to make a transition to a much lower-carbon energy system. it therefore seems that we need both to drive down costs and expand deployment of current solar technologies while at the same time continuing to invest in R&D on the most promising new solar technologies that have the potential to deliver a significant improvement in one or both of cost and efficiency [71].

The substances that contribute to an impact category are multiplied by a characterization factor that expresses the relative contribution of the substance. For example, the characterization factor for CO2 in the Climate change impact category can be equal to 1, while the characterization factor of methane can be 25. This means the release of 1 kg methane causes the same amount of climate change as 25 kg CO2. The total result is expressed as impact category indicators (formerly characterization results [67]).

The characterization factor of climate change is the global warming potential, based on IPCC 2013 report. For the Individualist perspective 20 year time horizon was used, for Hierarchist 100 years and for Egalitarian 1000 years. Climate- carbon feedbacks are included for non-CO2 GHGs in the Hierarchist perspective. The unit is yr/kg CO2 equivalents [72].

5.2.2 Ozone Layer Depletion

The characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). The unit is yr/kg CFC-11 equivalents [61].

The hole in the ozone layer was detected over Antarctica in 1985. Ozone is continuously formed and destroyed by sunlight and chemical reactions in the stratosphere. Ozone depletion occurs if the rate of ozone destruction is increased due to fugitive losses of anthropogenic substances which persist in the atmosphere. Stratospheric ozone, which is 90% of the total ozone in the atmosphere, is vital for life because it hinders harmful solar ultraviolet UV-B radiation from penetrating the lower levels of the atmosphere. If not absorbed, UV-B radiation below 300 nanometres will reach the troposphere and the surface of the earth, where it can increase the human risk of skin cancer and cataract when appropriate precautions are not taken. It may also cause premature aging and suppression of the immune system. In addition to the increased risk to Human Health the UV-B radiation can also damage terrestrial plant life and aquatic ecosystems [15].

The characterization factor for ozone depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances (ODS). These are persistent chemicals that contain chlorine or bromine atoms. Because of their long atmospheric lifetime Cl and Br are able to reach the stratosphere. Chlorine atoms in chlorofluorocarbons (CFC) and bromine atoms in halons are effective in degrading ozone due to heterogeneous catalysis, which leads to a slow depletion of stratospheric ozone around the globe. The chlorine and bromine atoms that are released from these reactions have the ability to destroy a large quantity of ozone molecules in the stratosphere because they act as free radical catalysts in a sequence of degradation reactions, in which they react with ozone to split it into molecular and atomic oxygen without being consumed [73].

5.2.3 Particulate Matter

The characterization factor of particulate matter formation is the intake fraction of PM2.5. The unit is yr/kg PM2.5 equivalents [72].

Ambient concentrations of particulate matter (PM) are elevated by emissions of primary and secondary particulates. The mechanism for the creation of secondary emissions involves emissions of SO2 and NOx that create sulphate and nitrate aerosols. Particulate matter is measured in a variety of ways: total suspended particulates (TSP), particulate matter less than 10 microns in diameter (PM10), particulate matter less than 2.5 microns in diameter (PM2.5) or particulate matter less than 0.1 microns in diameter (PM0.1) [72].

The characterisation factor (CF) for particulate matter/respiratory inorganics accounts for the environmental fate (F), exposure (X), dose-response (R) of a pollutant for midpoint factors, and of severity (S) for endpoint factors [72].

$$CF = S\ R\ X\ F = EF\ iF \tag{9}$$

The pollutant can be a single chemical (e.g. CO) or group of agents (e.g. PM2.5). The fate factor relates the emission flow to the mass in the air. The exposure factor determines the change in intake rate per change in mass in the environment. The dose-response slope relates the change in intake with the marginal change in morbidity and mortality cases and the severity is the change in damage per morbidity and mortality case.

The fate and exposure can be combined into an intake fraction (iF). The dose-response and the severity can be combined into the effect factor (EF, in DALY/kg inhaled). The intake fraction describes the fraction of the emission that is taken in by the overall population. Intake fractions can be calculated using fate and exposure models. For the case of particles, it is possible to characterize the fate and exposure further in the cause-effect chain by an intake factor or even an uptake factor because:

1. The exposing particle can be different from the emitted particle (e.g., secondary PM from precursors);
2. The influence of the changing particle size distribution (PSD) throughout time through phenomena like coagulation and nucleation can render the metric of the intake fraction, only a partial representation of exposure.

However, since these two metrics are not yet widespread and not used for other toxic impacts, the metric of the intake fraction is recommended to be used. Several studies suggest that no thresholds for PM10 should be assumed in the effect calculations. Thus it is recommended to derive dose- response from epidemiological studies assuming linear slopes.

6.0 Life Cycle Inventory (LCI) Interpretation

6.1 Comparison between PV System

Based on the six case studies done on 3 economies, which are Malaysia, Thailand and Indonesia, there are significant differences in term of type of PV system management since it is economy dependent. However, if it is compared between type of PV system, the typical implementation and life cycle of the system is almost similar, as shown in Figure 46.

Standalone system in both Malaysia and Thailand has the same component for balance of system but the quantity or the size of system is different. Thus, this affect the BOS construction consumption and emission. As for the short-term of global warming potential (GWP) 20 years, it can be seen that SAPV 2 in Thailand is about 20% more emission of kg CO2 equivalent compared to standalone system in Malaysia which is about 30,000 kg CO2 eq. Meanwhile, the same case applied to the rooftop study case at which SRPV 1 in Malaysia having a larger amount of solar panel and solar harvesting area that contributes to a bigger amount of emission compared to the Thailand bird house, SRPV 2. The difference is also about 20% from Thailand emission of 12,000 kg CO2 equivalent.

Moreover, the SFPV in Malaysia has a larger amount PV panels installed compared to the one in Indonesia. Even though, SFPV 2 (Indonesia) has an added component to their BOS system that is the transformer, which make the BOS construction peak but it still low compare to case study 1. This is proven by Figure 46, a massive amount of emission release by the SFPV is overwhelming. This numbers are 80% more than both the SAPV and SRPV system. Not only the photovoltaic manufacturing but both BOS construction and operation and maintenance also contribute greatly to this.

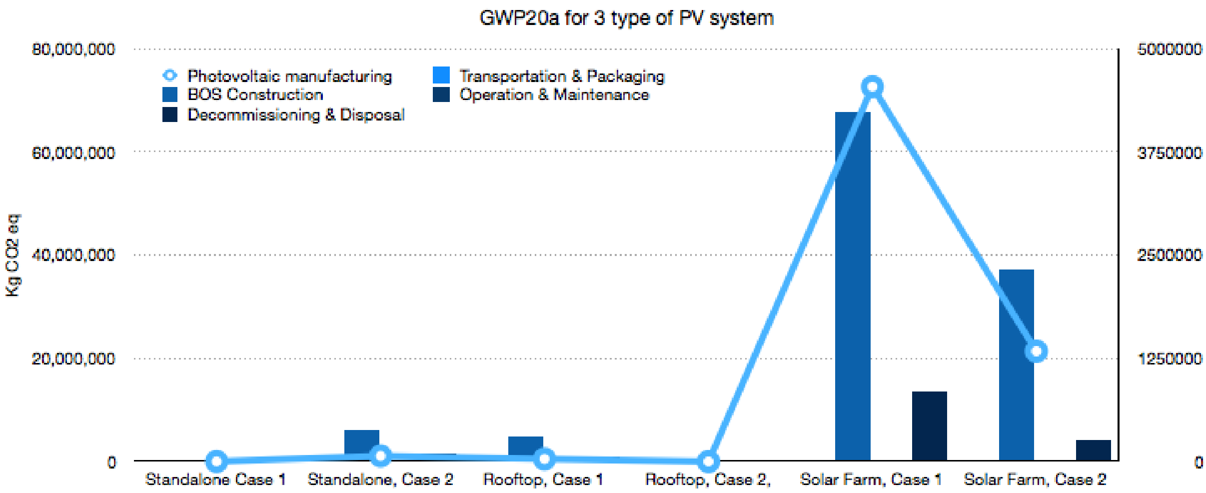


Figure 46 : GWP20a for 3 type of PV Systems

In addition to the above, if another evaluation is made of the three kind of systems under similar basis, that is, 1MJ energy consumption. Referring to Figure 47, the photovoltaic systems case studies CO2 equivalent emission over 1 MJ energy consumption, the ratio of the numbers plays a significant role in portraying the highest CO2 emission rate. It can be seen that any type of photovoltaic system are in a very small range between 0.063 to 0.067 of CO2 emission by photovoltaic manufacturing.

This is comparable to the other phases, whereas the ratio of the CO2 emission to energy consume are rather high for only the decommissioning and disposal phases. True, that the decommissioning and disposal phases does not consume much energy in term of processing but it is known to have a fair amount of CO2 release as it is waste itself. Thus, lifespan of 25 years toward disposal of all system are quite similar except for its waste termination phase.

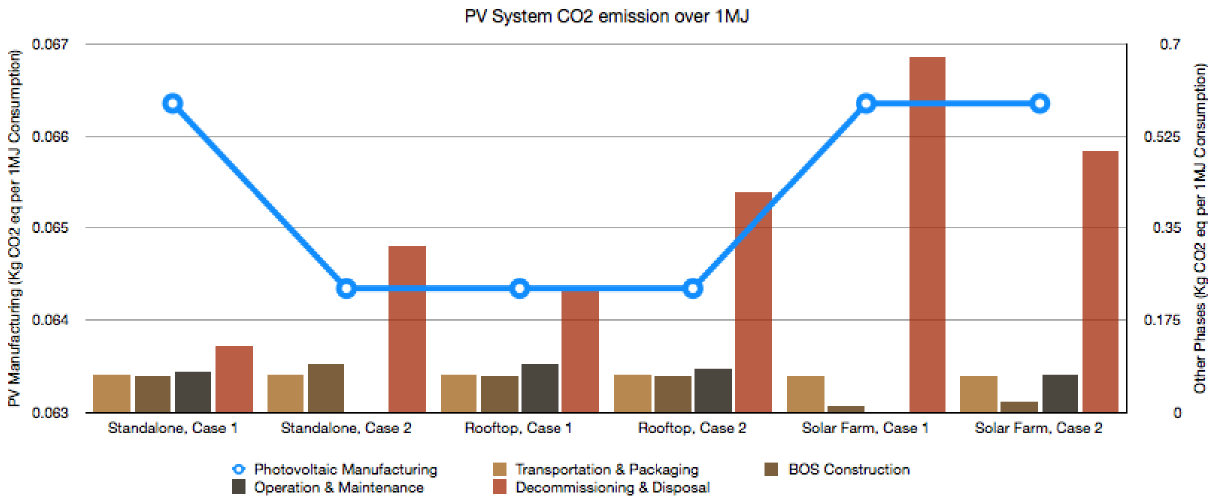


Figure 47: PV System CO2 emission over 1 MJ Consumption

Moreover, photovoltaic system CO2 equivalent per KWh of energy produce by the system itself is as shown in Figure 48 below. According to the energy payback of the systems discussed in the above section, each PV systems has large differences in their energy production per year. However, if comparison is made under similar basis of 1 KWh of energy production, it can be seen that the Kg CO2 equivalent per 1 KWh for both SFPV 1 and SFPV 2 is lower than its total Kg CO2 equivalent emission. This shows that the system is producing enough energy to cover up its CO2 emission throughout its life cycle.

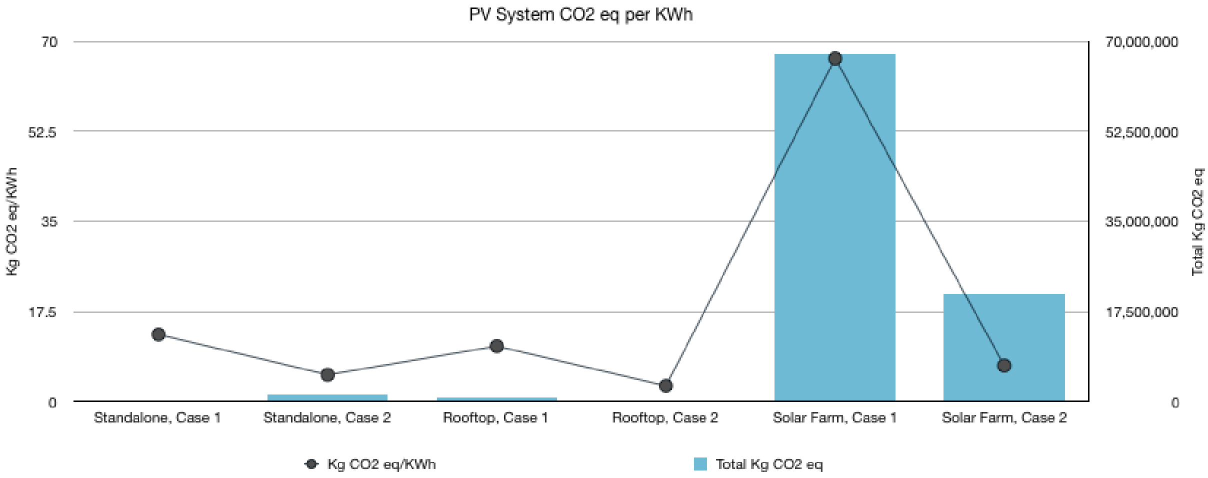


Figure 48: PV System CO2 eq per KWh energy production

6.2 Comparison between APEC Region Economies

The Indonesia-Malaysia-Thailand Growth Triangle is a sub-regional economic cooperation program composed of 14 provinces in southern Thailand, 8 states of Peninsular Malaysia, and the 10 provinces of Sumatra in Indonesia an area encompassing over 70 million people bound together by shared economic interests, geographical proximity, and close historical, cultural and linguistic ties.

The 2006 IPCC Guidelines Report26 suggests a minimum, maximum, and an average value for GHG emissions per TJ of natural gas combusted. The minimum and maximum, as percentages of the average, were used in conjunction with the average combustion emissions factor for natural gas [45]. Sources of GHG emissions from the transmission and distribution of natural gas include the combustion of pipeline fuel in these systems, and fugitive and vented CH4 and CO2.

Based on the result of analysis, the condition of the PV system depended on the economy conditions factor, whether it is, environment, geographical, gross domestic product, renewable energy policy and even accessibility to the technology itself. APEC economies in the Asia region, has similar weather condition of only one season around the years. The factors that affect a slight difference in generation is the specific solar irradiation fall onto the area. In these case study, that the environmental condition or the surrounding of the PV system will greatly affect its operation and maintenance over the long period of lifetime.

Moreover, photovoltaic manufacturing and implementation technology which align to the APEC economies awareness and initiative taken towards low carbon society is different for every economy. This can be seen throughout the case studies site visit data collection, where the photovoltaic manufacturing is different in each economy and even so between companies. These differences are influenced by considering the trilemma, affordable, stable and environmentally sensitive.

The photovoltaic panel and BOS technology used in Malaysia, for SAPV 1 and SRPV 2 is a Malaysia product, manufactured and produce in Malaysia but using an established manufacturing technology of advance economies such as Japan, China and US. Whereas, for solar farm case study 1, uses China products photovoltaic panel and BOS.

Moreover, Thailand SAPV 2 and SRPV 2 uses photovoltaic panel and BOS produced in Thailand. While, Indonesia SFPV 3, uses photovoltaic panels and BOS produced in Indonesia itself. This shows that there are significant different in the technology used and its production requirement which leads to the difference in the PV panel efficiency, energy production and maintenance of the system.

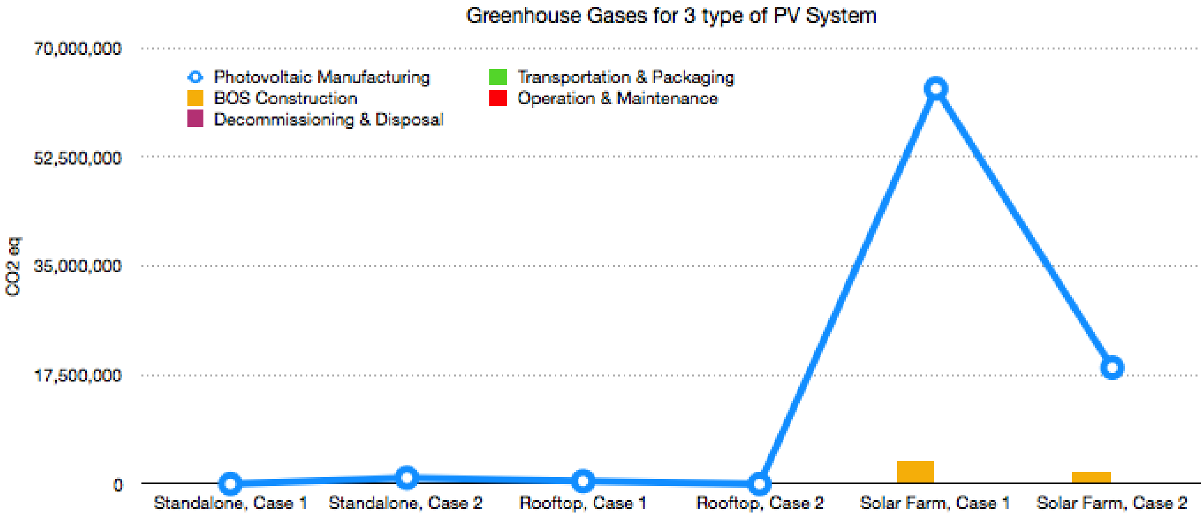


Figure 49 : GHG for 3 type of PV System

SRPV 1, Malaysia is located in an industrial area at which it affect the maintenance frequency. The dust and greenhouse gases emission from the factory itself and the other factory gave a large drawback to keep the efficiency high to a certain point as shown in Figure 47 above. In comparison to SRPV 2, Thailand which is located in a rural area, the green city, far from excessive transportation and other industrial emission.

Other than that, the standalone system as in SAPV 1, in Malaysia has an unstable BOS operation. The system often undergoes breakdown and failure. Certain technology are not efficient to be considered for a long-term implementation such that of a PV system. Meanwhile, the standalone solar farm system in SFPV 2, Thailand has a satisfying operating system that are manage to maximize the energy production to support the green city area.

In addition, both SFPV 1 and SFPV 2 in Malaysia and Indonesia shows a similar pattern but with distinct amount due to the size of the farm itself. Thus, it is assume that economies product also plays a role in the photovoltaic system life cycle not only relying on the systems operation.

7.0 Conclusion

Promoting PV technologies with lower embedded energy or lower cost give a higher chance of reducing the obvious GWP and greenhouse emission throughout its life cycle. Innovations in module manufacture can lead to significant savings in both module cost and emissions during manufacture. The EPBT can be reduced along with reductions in the wafer thickness and in the amount of silicon wasted in the manufacturing process. however, given that the majority of the cost of the photovoltaic system is already due to the balance of systems, continuing reductions in the module cost will have a small effect on the cost of electricity, unless the new technologies also enable savings in installation, electrical connection or application.

PV system implementation based on this report has tackled the main concern of cumulative consumption, global warming potential through viable type of PV systems are made known to be the photovoltaic manufacturing and followed by the BOS construction for all case study. Thus, focusing on finding alternative solution for a better production process of photovoltaic should be consider as best practice to improve the quality of the system.

The CED of both SAPV 1 and SAPV 2 are 81% and 82% for photovoltaic manufacturing respectively. In SAPV 1 the next highest contributor to CED is transportation & packaging phase at 4%. Meanwhile, for SAPV 2 BOS has the second highest CED at 18%. This is due to SAPV 2 being a large scale system standalone solar farm requiring larger BOS. Similarly, for SRPV 1, SRPV 2, SFPV 1 and SFPV 2 also showing similar pattern with photovoltaic manufacturing CED of 64%, 59%, 75% and 74% respectively. This proves that the size of system plays an important role since life cycle takes into account the production of the product itself. All of these large systems have BOS as the second highest CED of 35%, 34%, 25% and 26% respectively.

EPBT of SRPV 2 Thailand has the fastest payback period of 7 years compare to the other PV systems. The amount, size and power production a PV system really becomes a factor affecting energy payback period. According to this report data, it can be seen that a large system such as SFPV 1 and SFPV 2 has the lowest EPBT of 26 years and 27 years respectively. This shows that if the SRPV and SFPV system wants to be as competitive with this EPBT period, it should either increase its energy production as proven by SAPV 2 EPBT of 15 years in comparison to SAPV 1 EPBT of 36 years or reduce its energy consumption as shown by SRPV 2 EPBT of 7 years in comparison to SRPV 1 EPBT of 32 years.

The photovoltaic system for all six case studies has its own pros and cons depending on factors discussed. The manufacturing of PV gives out the largest effect on *EPBT* due to huge energy consumption during ingot growing process. However, EPBT of PV systems as a whole, varies according to the size of system, amount of panel installed, type of BOS used and method of operation and maintenance. Thus, such type of PV systems should take into account these outlined factors, best practices, in order to properly choose the most viable system based on the location, surrounding, land transformation, and etc. Therefore, in choosing a new PV system these factors should be taken into consideration to get the most efficient system with the least energy consumed. This in turn would improve the environmental impact of the PV system and lead to a lean and efficient system with a small carbon footprint.

Small scale SAPV is not efficient in term of CO2 equivalent emission because it has low power production and high CED from PV manufacturing. It is recommended for any SAPV system to be of a large scale since it is a self-sufficient system and thus depend only on return of energy produced. SRPV system also viable at large scale since the energy production is bigger and thus would lower the CO2 equivalent emission over 1 KWh production. The EPBT of a large scale SAPV and SRPV system is also reduced by more than half of that of a small scale system. Other than that, both of the SAPV and SRPV system are best to be installed on flat surface than on tilted surface which will reduce the BOS and maintenance requirements.

In the other hand, SFPV system is considered as the best system in its whole life cycle assessment. This is because the ratio of kg CO2 equivalent over 1 KWh production is lower than its total kg CO2 equivalent emission i.e. nett positive system. SFPV has an efficient energy payback period of around 26 to 27 years far superior than any small scale SAPV and SRPV systems. Hence, the study has met its objective that PV system contributes to the low carbon society which both give impact in satisfying the energy trilemma and green technological shift in the APEC region economies.

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9.0 APPENDIX

PROJECT CASE STUDY SURVEY COLLECTION

CASE STUDY :
Company Name :
Contact Person :
Company address :
Production Site Address :
Reference Product name :

General Details

Company :
PV Manufacturer :
No. of Panels :
Type of Panel :
Launch :
Operated :
Power Production :

Construction
This includes land clearing/ ready building. Whether the addition of PV change the infrastructure.

Land Setup	Activities	Waste	Comments

Raw Materials

Material	CAS	Source	Amount	Comment

Balance of System (BOS)

Component	Model	Qty	Power	Comment

Machine/Tools

Machine	Model	Qty	Power	Period	Comment

Transport & Installation

Raw Material & BOS Transport:

Product	Transport type	Distance (km)	Comment

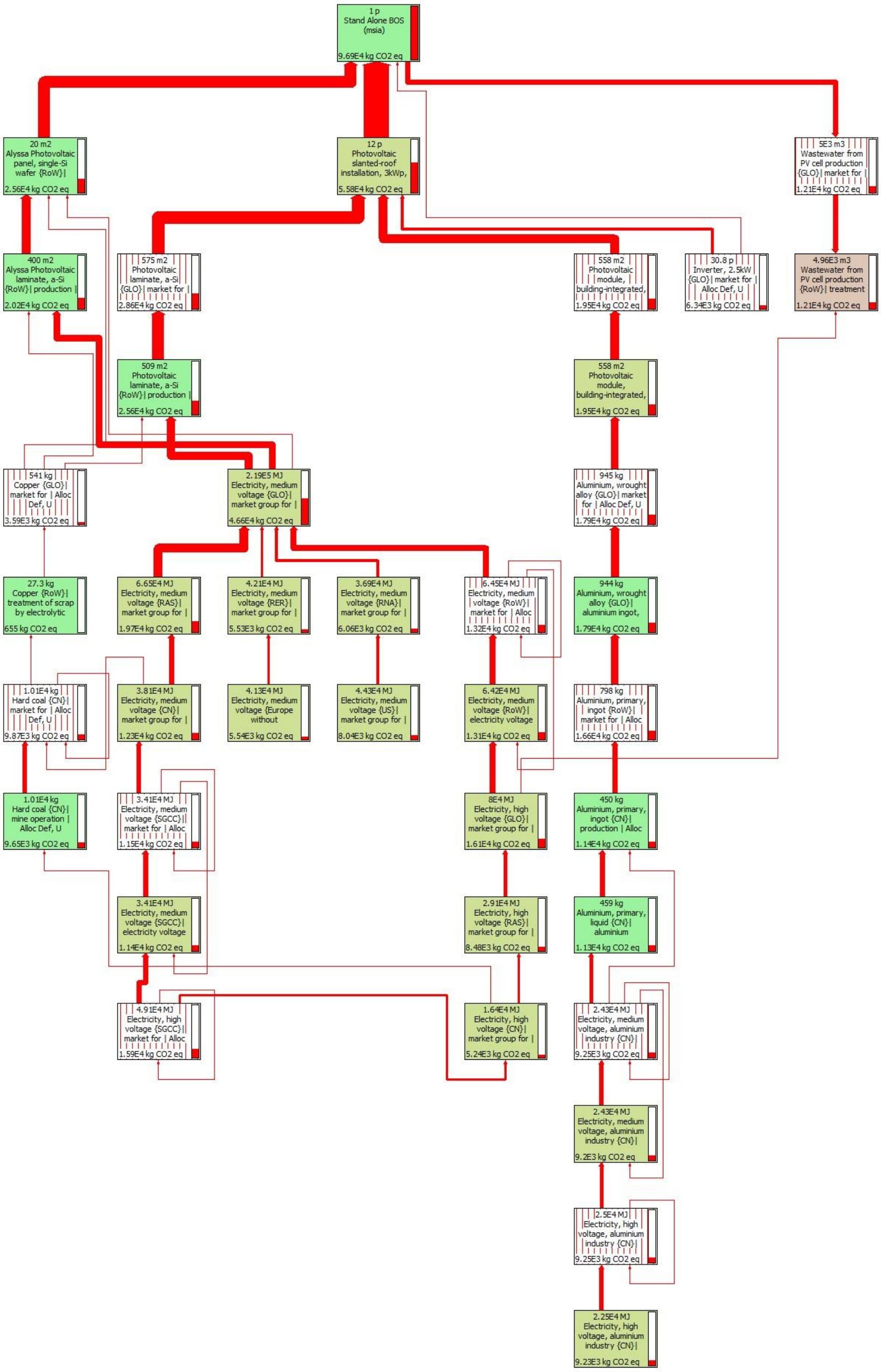
Product Packaging

Product	Source/ Model	Type of Package	Comment

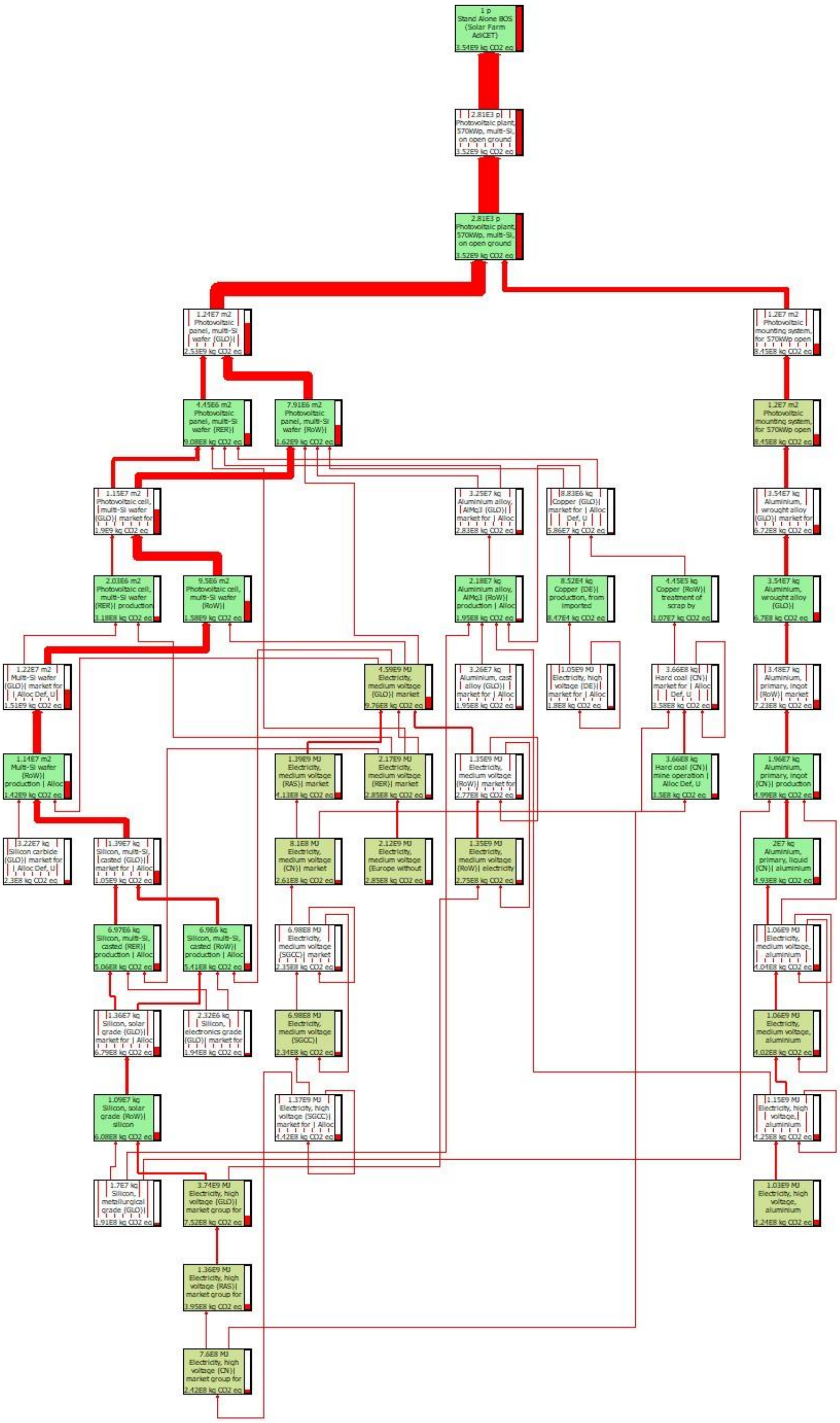
Operation & Maintenance

Activities	Qty	Frequency	Comments

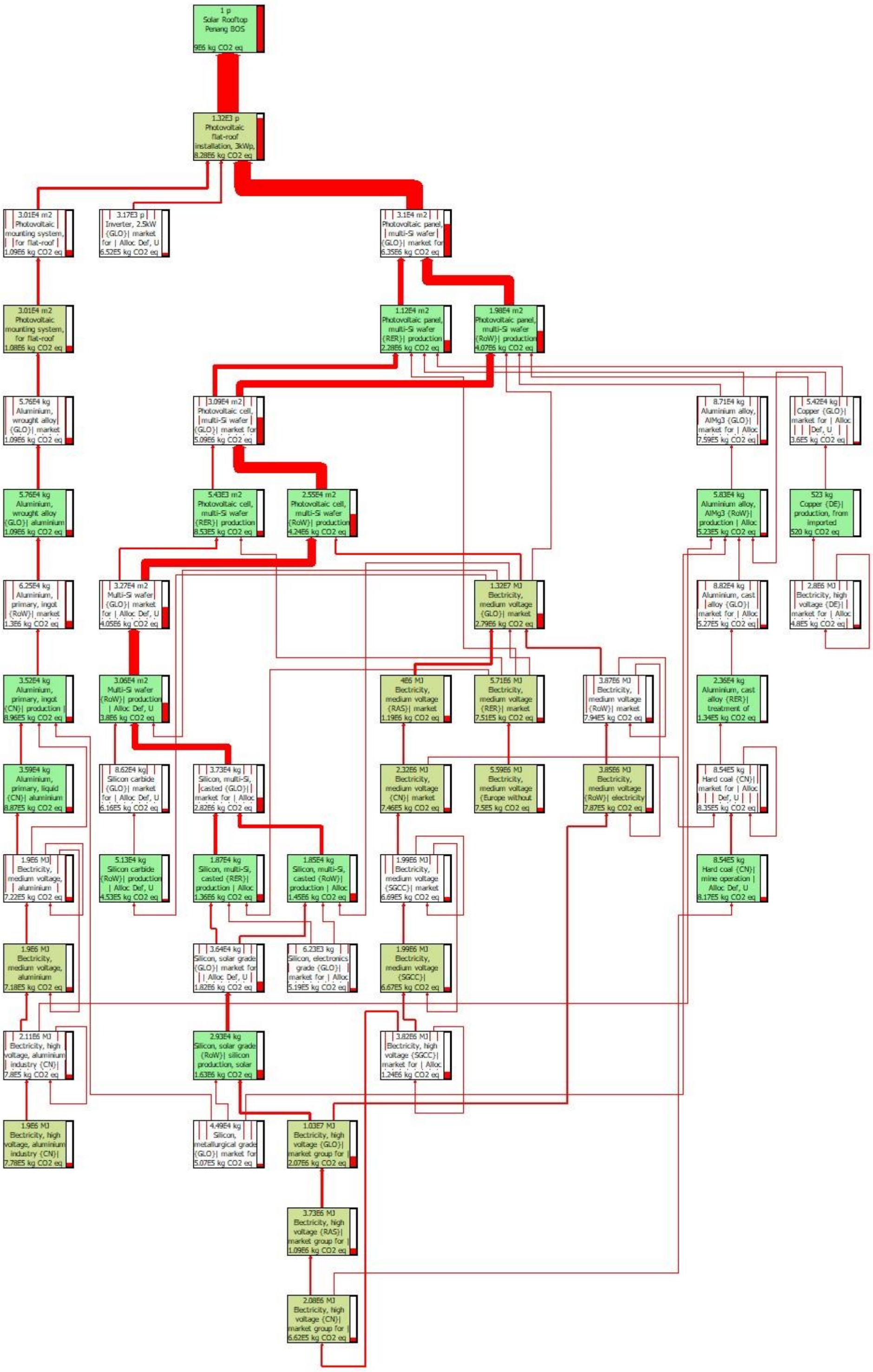
1) Standalone PV System, Case Study 1, Malaysia Process Flow



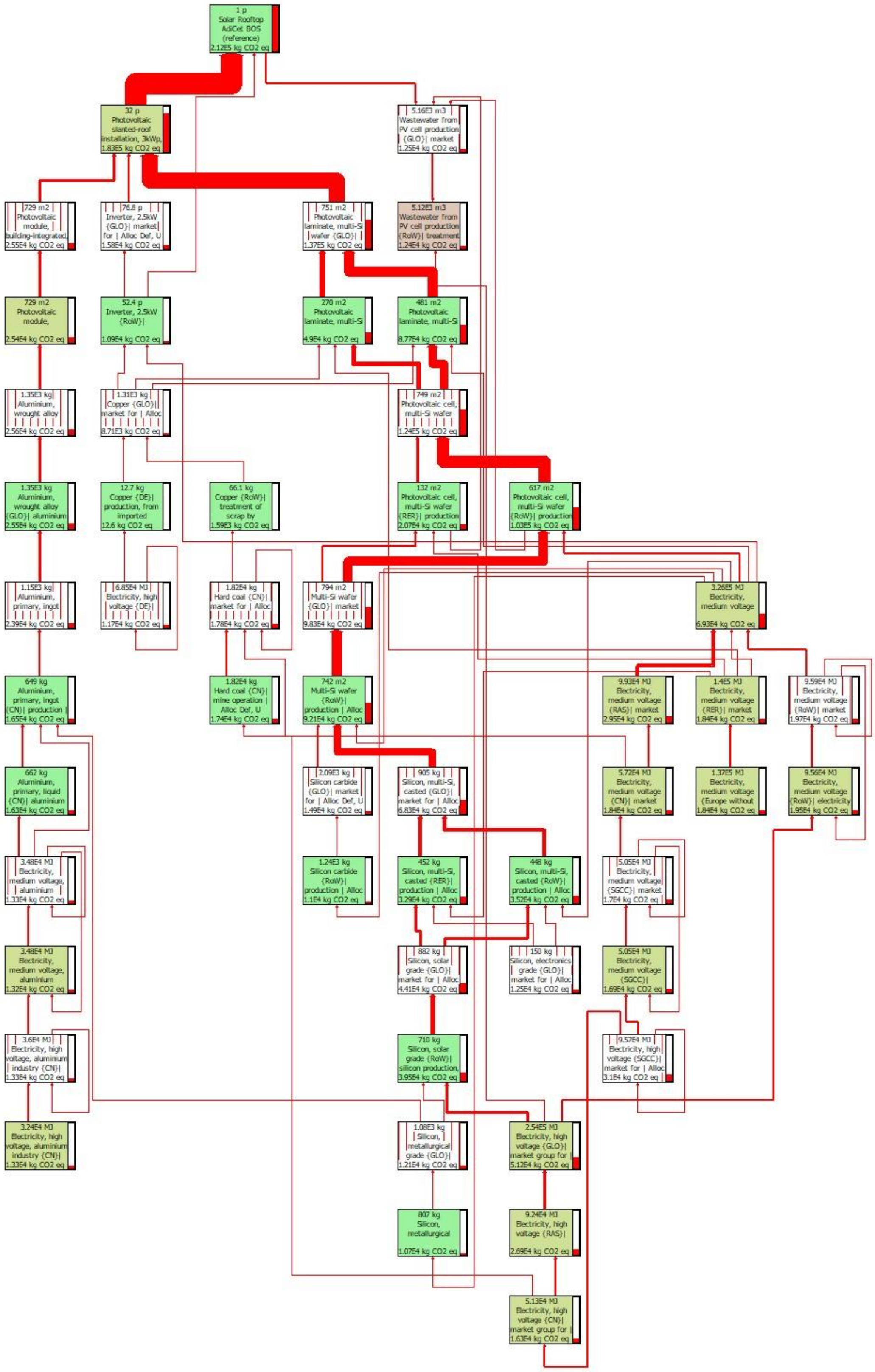
2) Standalone PV System, Case Study 2, Thailand Process Flow



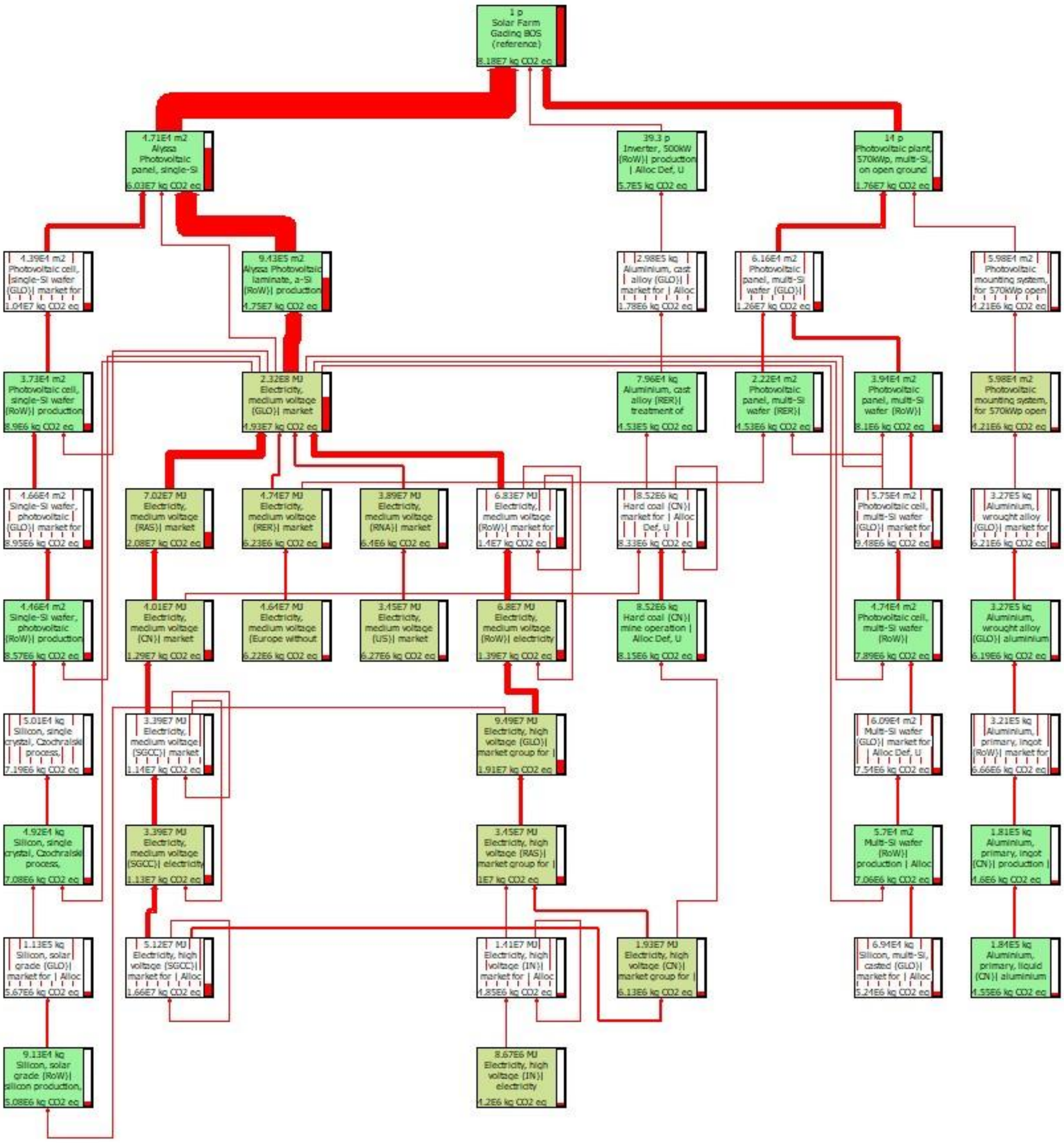
3) Rooftop PV System, Case Study 1, Malaysia Process Flow



4) Rooftop PV System, Case Study 2, Thailand Process Flow



5) Solar Farm PV System, Case Study 1, Malaysia Process Flow



6) Solar Farm PV System, Case Study 2, Indonesia Process Flow