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Life Cycle Analysis for the Feasibility of Photovoltaic System Application in Indonesia

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Abstract. Electricity has become the basic need for everyone, from industry to domestic. Today electricity source still depends heavily on fossil fuels that soon will be diminished from the earth in around 50 years. This condition demands us to find the renewable energy to support our everyday life. One of the famous renewable energy sources is from solar, harnessed by energy conversion device named solar cells. Countries like Indonesia are gifted with an abundance of sunlight all the yearlong. The application of solar cells with its photovoltaic (PV) technology harnesses the sunlight and converts it into electricity. Although this technology is emerging very fast, it still has some limitation due to the current PV technology, economic feasibility, and its environmental impacts. Life cycle assessment is the method to analyze and evaluate the sustainability of PV system and its environmental impact. This paper presents literature study of PV system from the cradle to grave, it begins with the material choices (from the first generation and the possibility of the fourth generation), manufacturing process, implementation, and ends it with the after-life effect of PV modules. The result of this study will be the insights look of the PV system application in Indonesia, from the best option of material choice, the best method of application, the energy payback time, and finally the possible after life recycle of PV materials.

Keywords: Life cycle analysis, photovoltaics, renewable energy

1. Introduction

Modern life creates the improvement of life quality and has made electricity as the basic need for everyone although not everyone in a developing country or third world country can have electricity connection in their homes. Today's electricity depends heavily on fossil fuels that contribute a lot to greenhouse gas emission, therefore promotes more on global warming. Another fact is that the source of fossil cell will diminish in around 50 years [1]. This unfortunate condition has driven scientists to search for new and renewable sources of power. Renewable energy is a type of energy generated from a continuous and recurring source in nature/environment. The generation of renewable energy can be at the same rate of their usage. The renewable energy can come from the air, water, earth, and sun. One of this renewable energy is provided by the unlimited source of sunlight from the sun.

The utilization of sun-ray for heating had been done by the Romans in around first to fourth century [2]. Edmond Becquerel in 1839 found the effect of photovoltaic (PV), however 1954 was considered as the time when the photovoltaic technology was born, since on that day, Daryl Chapin, Gerald Pearson, and Calvin Fuller created a photovoltaic cell made of silicon and recorded as the first solar cell having ability to convert sun ray into electricity that could power an electrical equipment in Bell Labs, and since this innovation, PV system application had been increased tremendously [2][3]. Every day, the sun dispatches enormous energy for all the living being on earth, and in one-hour energy provided by the sun can supply enough power for a year. The photovoltaic effect is a conversion of energy harvested from the sun to electricity directly. This type of renewable energy is an attractive alternative to substitute fossil fuel since it is considered safer, no-pollution, reliable, maintenance free and long life-time about 20-30 years. PV system can be installed anywhere where the sunlight can reach it, and for a country with an abundance of sunlight, this is a perfect energy source. However, PV system also has a drawback, the sun only shines during daylight, therefore batteries are needed to support it, and batteries have short life-time compare to PV's life time, and they contribute to landfills and toxic waste. The fact is that not all of the sunbeam can be converted to electricity, only those with energy higher than bandgap energy can be converted. The material used to make PV module is also one of the factors affecting the efficiency of PV system [4].

Life cycle analysis (LCA) is an analysis to assess the environmental aspects and potential impacts related to a product by examining the inventory of inputs and outputs of the whole system, the environmental impacts related to those inputs and outputs and finally determine the sustainability of that product. LCA is taking the ISO 14040 as the standard for environmental analysis. This environmental analysis is taken for a life cycle time of a product or also known as cradle to grave, from material choice until disposal [5]-[28].

PV system as a new emerging renewable energy has to through an LCA analysis to get the whole idea of it, including its impacts to environmental, feasibility and sustainability. This paper discusses the LCA analysis of PV system from material choices, manufacturing process, implementation, and disposal or the afterlife. A cradle to gate and cradle to grave analysis will be conducted through a literature study. The result of this study will be an insight look of PV system application in Indonesia, from the best option of material choice, the method of application, energy payback time and the best method to dispose the module.

2. PV System Technology

PV system converts the incident from the sun into electricity to light up any loads. Solar cells are having the concepts of ideal diodes when exposed to light the current flow as forward bias. Figure 1.a shows the schematic diagram of a PV system. As the incident from the sun falls on a solar cell, photons coming from this incident bombard the n-type part of solar cells. The photons carry energies to p-type and give up those energies to electrons. Electrons having the new energies jump across the barrier into n-type. The movement of these electrons create charges of current and DC electricity is generated.

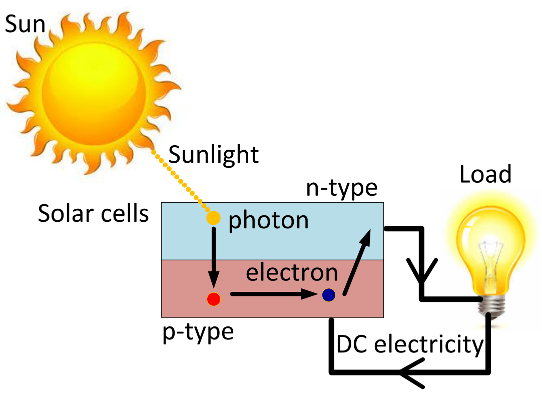

Figure 1.a. Schematic diagram of electrical conversion from sunlight

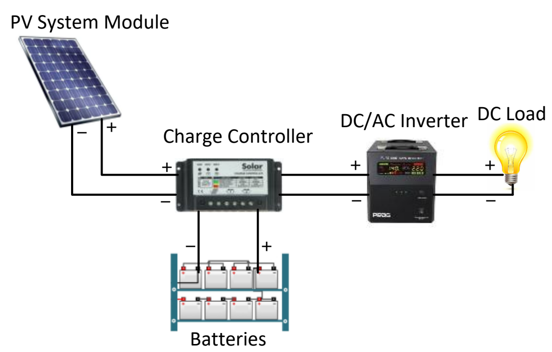

Figure 1.b. Schematic diagram of a PV system.

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PV system produces DC electricity therefore in order to power up any devices requiring AC electricity, the system needs an inverter to convert from DC to AC electricity. One of the problems with electricity generation using PV system is the dependence on sunlight availability, and during the night or cloudy days, the supply of sunlight will not be enough to power up the load, therefore for standalone system, batteries are a necessary, and a charge controller is needed to ensure the system stops charging batteries once they are full. This basic requirement of standalone PV system is shown in Figure 1.b.

There are three types of PV system standalone system (off grid), grid-connected and hybrid. A standalone system is the type of PV system that does not depend on government electrical source, grid-connected is where the PV system is connected to government electrical source, and hybrid is where the system not only depends on PV system but also with other type electricity generator such as wind turbines.

3. LCA Methodology

LCA or life cycle analysis is a thorough assessment of a product evaluating its environmental impact based on ISO 14040 and sustainability prospects. LCA is a field of study, a technique, and also a specific study of a product. To assess a product, a preparation of data, model, and formula to use are a must, and also it is necessary to find out who to involve, to report and how to use the available data.

By conducting LCA, some benefits are gained such as to structure a large complex data, to compare the product with other alternative products, and at the same time to ease the process of benchmarking. LCA analysis is including cradle to grave, cradle to gate, and cradle to cradle in which considering the best of options for the product from the raw material up to after the life-time is over and disposed of.

Figure 2 shows the block diagram of LCA analysis of a PV system. The cradle to grave assessment is starting from the choice of raw material (cradle to gate), the process of producing the PV modules, transporting PV module to location, building, and installation, during the application of PV modules and finally dismantling and disposal. When PV modules' life-time is over, a choice will be made which of those components/materials that can be recycled or simply to be disposed of. LCA analysis is also including inventory analysis aim to evaluate how much materials used or produced that can affect environment. LCA analysis calculates energy used during all the process, as shown in Figure 2. where E_{mtl} is energy consumed during preparing the raw material, E_{dstr} is energy used in distribution, E_{istl} is energy used during installation, E_{use} is energy gained in a PV module life-time application, E_{mnc} is energy needed for maintenance of the system, E_{dsp} is energy used in dismantling and disposing, and E_{rcly} is energy used if recycling is possible.

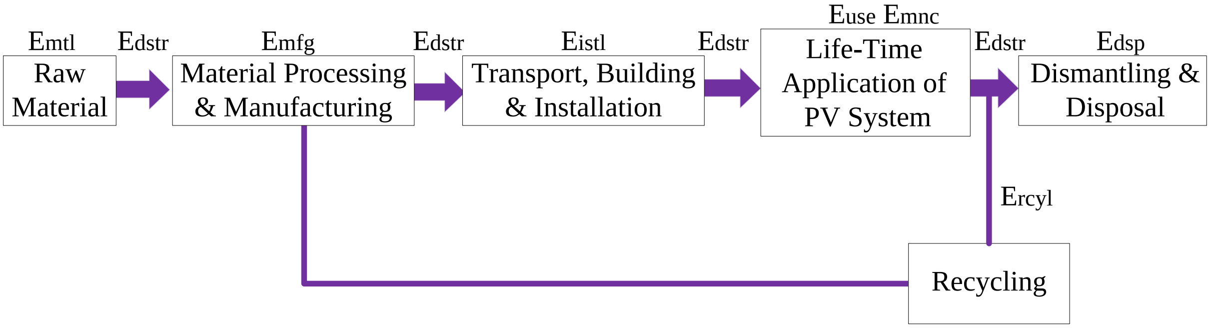

Figure 2. PV System LCA Scheme.

Impact assessment of all the process in Figure 2 is divided into classification, characterization, and weighting. All materials that are the influences to the environment are categorized in classification. In characterization, the amounts of output material are calculated by characterizing them to decide the indicator categories of the product impact. Weighting is to show the evaluation of damages caused and the estimation of environmental category [15]

The LCA assessment of PV system shown in Figure 2 will be explained in detail including the energy used and resulted and finally the recommendation of the best-applied PV module for Indonesia.

4. Comparison of PV Module Materials

PV technology for PV module materials now is up to the fourth generation. The first generation is the traditional technology involving a thick crystalline film made of mainly silicon, the monocrystalline or polycrystalline, and in another form is nanocrystalline silicon (nc-Si) [4][18].

The second generation is trying to improve the electricity generated by using thin film technology. This thin film technology not only is utilizing silicon but another type of semiconductor with better performance such as indium, gallium and phosphide. The common thin film technology material are cadmium telluride (CdTe), amorphous silicon (a-Si), and copper indium gallium diselenide ($Cu(In,Ga)Se_2$, CIGS). By stacking more than one type of material, it is expected more photo energy from the sunlight can be used to generate electricity. Stacking material type means creating different bandgap possibilities, as the only photon with energy larger than PV material energy bandgap can create electron movement that leads to charge movement and electricity generation.

The third generation is trying to overcome all the weakness in first and second generation called the Shockley-Quisser single bandgap limit and producing lower cost thin material for PV module. The third generation refers to PV technology using organic material, dye-synthesized, and quantum solar cell. The fourth generation is the technology to generate more energy by improving optoelectronic properties of the low-cost thin film PV. The third and fourth generation is still laboratory scale and not commercially produced in large scale.

Although silicon still is the most expensive type of solar cell material, however, it has the highest efficiency up to now for PV module in the market. Not only most expensive one, during the process of manufacturing, monocrystalline and polycrystalline require the highest energy compare to the second and third generation. The third and fourth generation are still in laboratory success yet.

From [4], the comparison output of different PV modules technology is given in Table 1

Table 1. Comparison of different PV modules technology

PV Module Technology		Material			
		c-Si	CIS	a-Si/Nc-Si	CdTe
Rated power	(W_P)	345	140	114	92.5
Rated current	(A)	6.02	2.98	2.18	1.94
Rated voltage	(V)	57.3	47	55	47.7
Short circuit current	(A)	6.39	3.31	2.6	2.11
Open circuit voltage	(V)	68.2	61.5	71	60.5
Dimensions	(m×m)	1.56×1.05	1.6×0.67	1.2×1.00	1.2×0.60
Expected life-time	(years)	25	25	25	25

5. Transport, Building, and Installation

Inventory analysis for transport means to calculate the energy needed to take PV modules from the factory to installation site. The distance from factory to installation site can be retrieved from Google Maps^{TM}.

Building and installation are including assembling balance of system (BOS), given it is a roof-top or a ground-mounted, and installing the modules to the system

As shown in Figure 1, PV system is not only PV modules but with other necessary devices such as inverter and battery. The transport, building, and installation of those devices should also be calculated.

The total energy required for the preparation of transport, building, and installation of a PV system is 84% for PV modules, 11% for Transportation, 3% for BOS, 2% for installation and 1% for inverter [25].

6. Maintenance

The good thing about PV system is that it requires minimum maintenance. PV system can last up to 25-30 years. Maintenance is including cleaning the surface of modules and checking the system performance periodically, other than that there is no special treatment.

Although PV modules can last up to 30 years, the battery is only up to 5 years, and other electronic devices have their own life-time. Therefore, maintenance is also including checking those devices and replacing them as required. The dependence to a battery can be cut by installing grid-connected PV system. In this type of PV system, temporary storage is not needed, if the produced electricity is not enough to power up the load, the system will connect automatically on grid and resume using PV system when the supply is back to normal.

7. Energy Payback Time

Energy payback time (in years) is the period needed for PV system to generate the same amount of energy with the energy used to produce the system and consumed throughout PV life-cycle [15]. From Figure 2, Energy payback time is given by

$$EPBT = \frac{Total\ Energy\ Consumed\ (kWH)}{Annual\ Power\ Generation\ \left(\frac{kWH}{Year}\right)} = \left(\frac{E_{mtl} + E_{mfg} + E_{istl} + E_{dsp} + Total\ E_{dstr}}{E_{use} - E_{mnc}}\right) \tag{1}$$

where E_{mtl} is energy consumed during the preparation of raw material, E_{mfg} is energy consumed during manufacturing process, E_{istl} is energy used during installation, E_{dsp} is energy used in dismantling and disposing, TotalE_{dstr} is total energy used in distribution, E_{use} is energy gained in a PV module life-time application, and E_{mnc} is energy needed for maintenance of the system.

The CO_2 emission rate (g CO_2/kWh) is defined as an index to determine the effectiveness of a PV system related to environmental impact or global warming. CO_2 payback can be calculated by

$$CO_2 Emission\ Rate = \frac{Total\ Emission\ in\ a\ Life\ Cycle\ (g\ CO_2)}{Annual\ Power\ Generation\ \left(\frac{kWH}{Year}\right) \times Lifetime(year)} \tag{2}$$

The air pollutants and greenhouse gas emission emitted by PV system are nitrogen oxides, sulfur okside(SO_2), carbon monoxide (CO), PM_{10}, lead (Pb), and hydrocarbon (HC) for the air pollutant and green house emission are carbon dioxide (CO_2) and methane (CH_4).

According to [12], the EPBT of monocrystalline panels given by Table 2.

Table 2. EPBT of PV modules technologies [12]

References	Technology	Installation	EPBT (years)	Efficiency (%)	Performance Ratio
Alsema (2000)	Multicrystalline	Rooftop	2.50	13	0.75
	Monocrystalline	Rooftop	3.10	14	0.75

Fthenakis and Alsema (2006)	Multicrystalline	Rooftop	2.70	13.2	0.75
	Monocrystalline	Rooftop	3.10	14	0.75
Meijer et al (2003)	Multicrystalline	Not reported	3.50	14.5	0.75
Jungbluth (2005)	Multicrystalline	Rooftop	3.0-6.0	14.8	0.75
Fthenakis et al. (2011)	Multicrystalline	Rooftop	1.70	13.2	0.75
Fthenakis et al. (2009)	Monocrystalline	Rooftop	1.70	14	0.75
Fthenakis and Alsema (2006)	CdTe	Ground-mounted	0.80	9	0.80
Jungbluth et al (2008)	CdTe	Rooftop	2.70	7.1	0.75

8. PV Modules Disposal

The first large installation of PV system was in the beginning of 1990s, therefore a significant number of PV system ends its life time is starting on 2015. The end of life of PV modules leads to two choices to recycle or to let them all be land-filled wastes. The choice should consider how much energy achieved and consumed during the process. Recycling PV panels are not easy since they are assembled from multiple materials including glass (on the front cover of PV panels), aluminium (frame), synthetic materials to encapsulate and seal the silicon cells such as ethylene-vinyl acetate (EVA), polyvinyl butyral (PVB) and/or polyvinyl fluoride), silicon or other material, and metals such as lead, gallium, copper, and cadmium.

German and Belgian are among the first that started to recycle their end-life PV modules. The main recycled are modules made of monocrystalline, polycrystalline and amorphous silicon.

The recycle process started from dismantling the BOS by thermal step, the plastic, glass and framed parts are removed, dissembled, and sorted accordingly. The second step is to separate wafer from PV modules structure using etching process. The broken PV modules are cleaned to get the pure Si back. The Si obtained from used PV modules is re-melted into a polycrystalline ingot and produce new wafers.

One of the recycling processes is called Chevetogne from the Belgian system; this process is considered as the manual separation. In the US, PV Company uses an automatic recycle system where all the modules are broken down by the shredder, and by using a hammer mill those shredded materials are formed in 4–5 mm size. By using acid, all the semiconductor layers are removed, and other larger parts such as glass are separated. This process will end in a resulted filtered cake, and cut into new wafers [29][30].

Table 3. Life-time PV component as shown in Figure 2

No	Device	Life-time
1	PV modules	25 – 30 years
2.	Charge Controller	5 years
3.	Battery	5 years (average all types of batteries)
4.	Inverter	15 year
5.	Structure / Balance of System	25-30 years

From Table 3, the devices for PV system have a long life-time accept for battery and its charge controller. The battery contains a number of toxic chemical and heavy metals and without proper treatment, it can be a soil contamination if it is disposed of as a land-filled. Battery can be recycled, however, the application of battery can be avoided by applying grid-connected PV system.

9. The Feasibility of PV System Application in Indonesia

Indonesia is an archipelago country situated in equator (0.7893^{O} S, 113.9213^{O} N). As a tropical country, it is blessed with an abundance of sunlight all years long with the average of radiation intensity per day is 4.5kWh/m2, as shown in Figure 3 [31]. This blessing gives 112.000 GWp of solar energy potential, however up to now, it is only around 10 MWp utilized for powering electricity in Indonesia. Most of the Indonesian populations are distributed in remote and separate islands, about 60%, and grid supply electricity still cannot reach most of them.

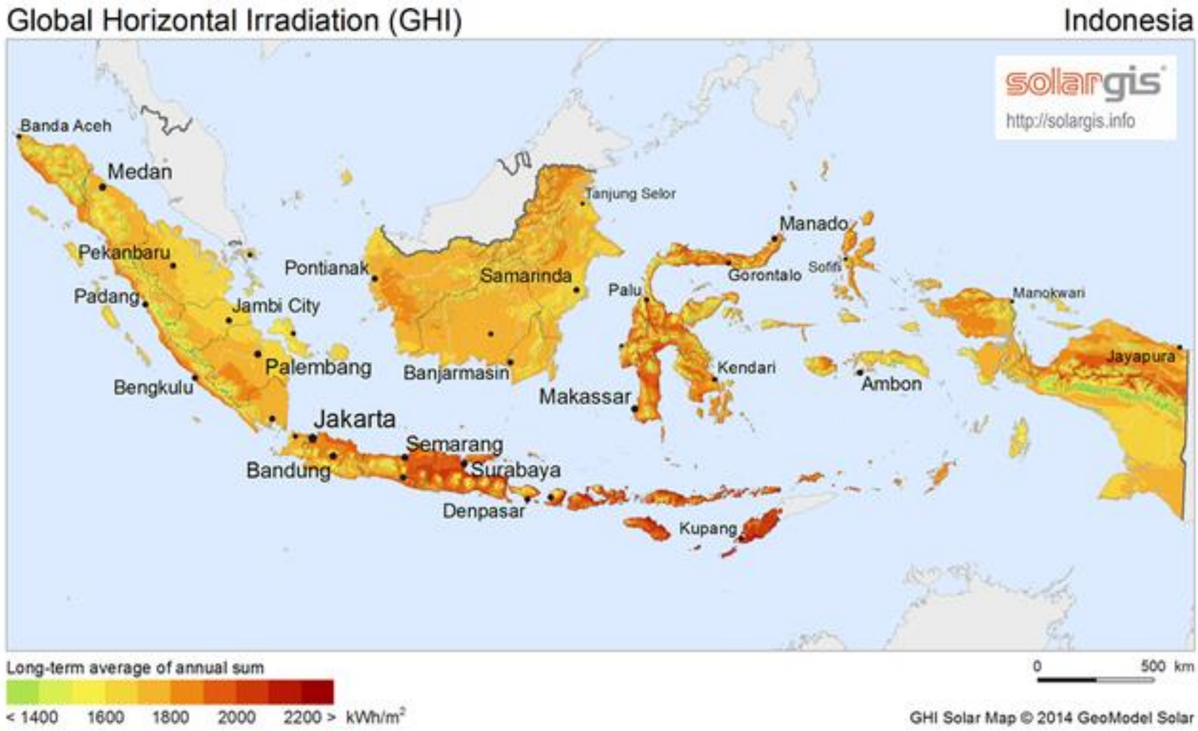

Figure 3. Sunlight incidents mapping in Indonesia [31].

PV system is one of the best options for electricity in Indonesia, not only in the cities but also up to remote areas (islands). Indonesian governments had come with several projects in proving PV system for the people living far from grid-connection. Altari Energi Surya, Mambruk Energy Internationa, and Guna Electro are private companies from Indonesia helping the government in installing 2239, 240 and 80 SHS (solar home systems) for the projects. SHS system consists of a PV panel with the capacity of 50 Wp. However, these projects, SHS was not working optimally, mainly due to most of the people were not ready for the new technology, and in the end went back to the old conventional way for energy (lighting) such as kerosene lamps [32].

However, with all those limitations in implementing PV system, Indonesian government and people have to start to find the alternatives to substitute fossil fuel that will soon diminish.

Based on LCA of PV system above, the most eligible material for PV system is monocrystalline due to having the highest efficiency, the fastest energy payback time and its availability in the market. For installation, the rooftop is the best method for cities in Indonesia to minimize shading, and also not requires additional space, however, this method only works for the new building, for more than 5 years building, ground mounted is better.

For remote area, the off-grid system is a must, however people have to be informed of battery management, and the solution has to be presented to ensure the battery replacement in every 5 years. For the cities application, grid-connected will be better, since the application of battery can be removed and PV system price can be reduced. Figure 4 shows grid-connected PV system in Indonesia.

The current applications of PV system in the rural area in Indonesia are including PV refrigerator system for vaccine storage in a rural clinic, and lighthouse navigation aid [33]. While in the cities, most application of PV system is off-grid and hybrid, tandem with a diesel generator.

The disposal of PV modules in Indonesia up to know is to be a land-filled waste since most of the PV modules are still imported, therefore the technology to re-process the used PV modules is not available yet. However, the long-life of PV modules is up to 30 years, therefore by that time the PV modules can be recycled into the new water and reused as mentioned in section 8.

Figure 4. Ground-mounted PV panels in Indonesia.

Despite the limitations above, PV system application in Indonesia keeps growing up, and more houses/companies install it. Indonesian government along with State-Owned enterprises promote the application of PV system on their buildings/company location, one of them is shown in Figure 4.

10. Conclusion

PV system is one of the choices for renewable energy, the substitute for diminishing fossil fuel. One of the main issues of renewable energy is its sustainability. LCA is a method to analyze the system thoroughly, starting from materials choice up to disposal, or called cradle to grave analysis. This method let us know how beneficial the system, comparing from the energy produced and energy consumed for the whole life-time. After looking closely the LCA of PV system (literature review), we can compare those conditions to the condition in Indonesia, the feasibility of PV system application in Indonesia is confirmed. PV system is one of the solutions for island country where the populations are spread among islands. Although, the current application is not so beneficial since the rural people are not well informed to understand the system, and see the long-term benefit of PV system. Fortunately, PV panels prices are getting lower, people are more aware of the need of clean renewable energy. In long-term, PV system will be installed more in Indonesia, as it has been a successful energy alternative in developing countries. The current most suitable material choice for PV system is monocrystalline for its highest efficiency among others, and shortest energy payback time. In 20 years, it is expected that Indonesia is able to recycle the used PV modules into a new wafer and can be re-used.

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