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Life Cycle Analysis of Solar PV System: A Review

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Abstract

Electricity generation is a key source to global emissions of greenhouse gases (GHG) and their related environmental impact. Sustainable development requires methods and tools to measure the environmental impacts of human activities for various products such as goods, services, etc. Life-cycle analysis is a valuable tool for evaluating the environmental profile of a product or technology from cradle to grave. Such life-cycle analysis of energy technologies are essential, especially as material and energy flows are often intermingled, and divergent emissions into the environment may occur at different life-cycle-stages. Photovoltaic system is a technology for the production of electricity from renewable sources that is rapidly growing thanks to its potential to reduce the energy consumption from traditional sources and to decrease the air pollution. During the operational phase, there are no emissions and the only input is solar power. However, it should be noted that, considering the entire life cycle of a plant, photovoltaic systems, like any other means of electricity production, give rise to emissions that focus especially in the manufacturing stage and installation of components. In this study, the environmental load of photovoltaic power generation system (PV) during its life cycle by energy payback time (EPT) and Greenhouse Gas emissions are reviewed through LCA study to the state of art of the photovoltaic technologies.

Keywords: Life Cycle Analysis, Solar PV System, GHG emission, EPBT.

1. Introduction

In these last decades, energy related problems are becoming more and more important and involves the rational use of resources, the environmental impact due to the emission of pollutants and the consumption of non-renewable resources [1]. Therefore, there is urgent need for developing renewable energy technologies, especially photovoltaic (PV), to cope with the challenges of energy shortage and environmental pollution [2]. PV technology, directly generating electricity from solar energy, is free from fossil energy consumption and greenhouse gases (GHG) emission during its operations. Thus, it seems to be completely clean and have no environmental impacts. However, during its life cycle, it actually consumes a large amount of energy and emits some GHG during some stages such as solar cells manufacturing processes, PV module assembly, balance of system (BOS) production, material transportation, and PV system installation and retrofitting, and system disposal or recycling [5]. When sunlight hits PV materials, photons with a certain wavelength trigger electrons to flow through the materials to produce direct current (DC) electricity. Commercial PV materials include multi-crystalline silicon, mono-crystalline silicon, amorphous silicon, and thin film technologies, such as cadmium telluride (CdTe), and copper indium diselenide (CIS). A typical PV system consists of the PV module and the balance of system (BOS) structures for mounting the PV modules and converting the generated electricity to alternate current (AC) electricity of the proper magnitude for usage in the power grid. [3]. Life cycle assessment (LCA) is usually used as a technique to compare and analyze the energy using and environmental impacts associated with the development of products over their life-cycle. The framework of LCA methodology is shown in Fig. 1 [4].

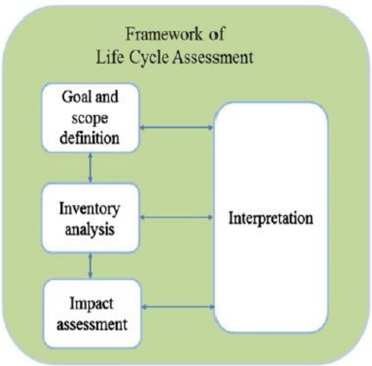

Fig. 1: Framework of Life Cycle Assessment.

LCA stage includes definition of goal and scope, inventory analysis, impact assessment and interpretation of results. The goal and scope definition describes the underlying question (objective), the system, its boundaries and the definition of a functional unit. The flows of pollutants, materials, resources are recorded in inventory analysis. These elementary flows (emissions, resource consumption, etc.) are characterize and aggregated for different environmental problems in impact assessment and finally conclusions are drawn in interpretation stage [4]. Informational publications for decision-makers in the European Community (European Commission, 2003) and Australian Coal Industry Association Research Program (ACARP), 2004 indicated that photovoltaics have relatively high environmental impacts compared with other technologies, 10 and 2.5 times higher than the GHG emissions of the nuclear-fuel cycle for each country, and 45% and 23% of those of combined cycle (CC) natural-gas power generation in the same country [3]. This paper investigates required energy and environmental impact for major Si and Thin Film type PV module technologies along with some recent technologies by means of review of their Energy payback time and GHG emission rate.

2. LCA of PV System

2.1 LCA of Mono Crystalline PV System

Kato [9] investigated the total energy requirement of a mono-Si PV module range from 4160 to 15520 MJ/m2 and the EPBT and GHG emission rate for mono-Si PV system was CO2-eq./kWh, respectively under the irradiation of 1427 kW h/m2/yr. Alsema [10] found energy requirement of crystalline silicon PV modules varying from 5300 to16,500 MJ/m2 for mono-Si modules. Kannan carried out LCA of a distributed 2.7 kWp solar PV system and found the life cycle energy use 2.2 MJ/kWh and the estimated EPBT and the GHG emissions were 4.5 years and about 165 g- CO2/kWh [11]. Kreith [12] has studied 300 kW PV plant established at Austin having Single Axis tracker. The total embodied energy (emission) was 16.5 GWh and the life cycle CO2 emissions are 280 g-CO2eq/kWh. Knapp and Jester [13] observed on PV modules production that the total process energy and embodied energy of materials of mono-Si modules were 2742 kWh/kWp and 2857 kWh/kWp, respectively and resultant EPBT is 4.1 years. Nawaz evaluated the embodied energy for production of the crystalline silicon PV modules and BOS components and estimated that embodied energy for open filed and roof-top PV systems was 1710 and 1380 kWh/m2, respectively, and the EBPT was 7–26 years as a result [14].

2.2 LCA of Multi Crystalline PV System

Multi-Si PV system has almost same conversion efficiency as the mono-Si system, but consumes less energy during its life cycle. Therefore, multi-Si may be has a shorter EPBT and lower GHG emissions rate than mono-Si system [6]. Phylipsen and Alsema [15] considered the life cycle assessment of multi-Si PV module in 1995. The embodied energy requirement was found to be 1145 kWh/m^2 and EPBT of 2.7 years with module efficiency and performance ratio of 13% and 0.75, respectively. For a grid-connected PV system, LCA is accomplished in [10]. Ito [16] studied assessment of a 100MW large-scale PV plant in Gobi Desert with module efficiency of 12.8%. The results shows that the EPBT and CO2 emission rate of the plant were less than 2 years and 12 g CO2-eq./kW h, respectively. Pacca [7] studied the LCA of multi-crystalline modules with BOS, inverter and transportation. The manufacturing of one module consumed 1000 MJ of primary embodied energy in materials and 3020 MJ as process energy. The EPBT for KC120 was 7.5 years while the life CO2 emissions were 72.4 g-CO2eq/kWh for considering US energy fuel mix whereas 54.6 g-CO2eq/kWh for European energy fuel mix.

Table I: LCA of Crystalline PV Modules.

Author	Type of Cell	Energy Required	EPBT (years)	GHG emission (g CO_2 eq./kWh)
Kato [9]	Mono	4160-15520	8.9	61
Kannan [11]	Mono	2.2 MJ/kWh	4.5	165
Phylipsen and Alsema [15]	Multi	1145 kWh/m^2	2.7	NA
Ito [16]	Multi	NA	2	12
Pacca [7]	Multi	4020 MJ/module	7.5	72.4
Jungbluth [17]	Multi	NA	3-6	39-110

2.3 LCA of a-Si PV System

Thin film PV modules have lower conversion efficiency than crystalline silicon, but require less material and energy during life cycle due to the relatively low temperature production technologies. Therefore, have less EPBT and GHG emissions. Lewis and Keoleian [18] conducted a case study on amorphous PV module production. The total process energy was about 491 MJ/m2 while embodied energy were 864 and 1990 MJ/m2 for low energy consumption and high energy consumption, respectively. The EPBT for a-Si frame modules were 8.1 and 4.5 years for high energy consumption and low energy consumption, respectively. This energy can be reduced to 386 and 640 MJ/m2 by using frameless modules. Alsema [19] reviewed the energy analysis studies of thin film PV modules from six studies on a-Si modules and three studies on CdTe module, the author presented the best approximation for the energy requirement of a-Si and CdTe thin film frameless modules was between 600 and 1500 MJ/m2 and estimated the EPBT of a grid-connected system below 2 years with 1700 kWh/m2/yr irradiation.

2.4 LCA of CdTe /CIS PV System

The first solar cell based on CdTe/CdS has been reported in 1972 with an efficiency of 6%. Since then, significant improvement has been made in the cell and the highest efficiency of 16.5% has been reported. Kato [9] estimated that the total required primary energy for producing the CdS/CdTe PV module was approximate 1803 MJ/m2 at 10 MW/yr and 1272 MJ/m2 at 100 MW/yr. The results shows that the EPBT of PV system was in the range of 1.7 (10 MW/yr scale) to 1.1 years (100 MW/yr), and the lifecycle CO2 emission rate was from 14 (10 MW/yr) to 9 g CO2-eq./kW h (100 MW/yr). Ito [16] studied the life cycle analysis for 100MW PV system at Gobi desert using CdTe and CIS solar cell modules. The life cycle CO2 emissions are 15.6 and 16.5 g-CO2eq/kWh. Hynes [20] conducted life cycle analysis on two types of CdTe thin film modules using different deposition technologies. The total energy requirements were 992.52 and 1187.7 MJ/m2, respectively and the corresponding EPBTs were 5–11 and 6–13 months, respectively with the efficiency of 10%. Raugei [21] conducted analysis for CdTe and CIS compared to crystalline modules. The results showed that the EPBT of CdTe and CIS PV modules were 0.5 and 1.9 years, and their life-cycle GHG emission rates were 17 and 70 g CO2-eq./kW h, respectively. Though, if the BOS components were taken into account, the EPBT and GHG emission would goes up to 1.5 and 2.8 years, and 48 and 95 g CO2-eq./kW h, respectively. Alsema[19] investigated required primary energy as 350-650 MJ/m^2(process energy) and 300-400 MJ/m^2 (material energy) while EPBT is 3.2 yr for CdTe Modules with 6% module efficiency and 1000 W/m^2 irradiation. Ito and Komoto 2010 evaluated EPBT is 1.8 and GHG is 46 g CO_2-eq./kWh for 11 % Efficiency at Very-large scale PV systems installed in desert [23].

Table 2: LCA of Thin Film PV Modules.

Author	**Type of Cell**	**Energy Required**	**EPBT(years)**	**GHG emission (g CO_2eq./kWh)**
Pacca [7]	Amorphous	1861 MJ/ Module	3.2	34.3
Lewis and Keoleian [18]	Amorphous	491+(864 and 1990)	4.5, 8.1	NA
Hynes [20]	CdTe	992.52 and 1187.7 MJ/m2	5-11, 6-13 month	NA
Raugei [21]	CdTe	NA	0.5	17
Raugei [21]	CIS	NA	1.9	70
Wild-Scholten[22]	CIS	1684 MJ/m^2	1.45	21
Ito and Komoto [23]	CdTe	NA	1.8	46

3. Results and Conclusions

The usually used four types of solar PV system had been reviewed with some latest PV technologies based on Life Cycle Assessment. The energy requirement, EPBT and GHG emissions have been estimated for mono-crystalline, poly-crystalline, amorphous and CdTe/CIS and other solar PV systems. For Crystalline modules have good conversion efficiency but the required primary energy is very high and corresponding EPBT and GHG emissions are also high while Thin film modules consumes less primary energy and have lower EPBT and GHG emission but the efficiency is low.

A set of parameters is responsible for the variability in the performance of different installations. Aside from the level of incoming solar radiation, Life expectancy, BOS components, conversion efficiency, Cell Type, manufacturing process are some parameters on which it depends.

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