

Research Article

Emerging Trend in Life Cycle Assessment of Various Photo-voltaic Systems

Anand Kumar^{A*}, Soumya Das^B, Pradip Kumar Sadhu^A and Nitai Pal^A

^ADepartment of Electrical Engineering, Indian School of Mines, Dhanbad, Jharkhand, India-826004.

^BDepartment of Electrical Engineering, University Institute of Technology, Burdwan University, West Bengal, India,

Accepted 01 May 2014, Available online 01 June 2014, Vol.4, No.3 (June 2014)

Abstract

This paper seeks to study the sustainability and environmental well-being of PV-based electricity generation systems by performing a thorough case study of life cycle assessment (LCA) of solar PV based electricity generation systems. Life-cycle analysis is an useful tool for examining the environmental characteristics of a product or technology from its origin to de-commissioning. Mass and energy flow over the complete production process starting from silica extraction to the final panel assembling has been observed. Life cycle assessment (LCA) studies of five common photovoltaic (PV) technologies, i.e., mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), CdTe thin film (CdTe) and CIS thin film (CIS) are presented in this work. The results depicts that, among the five common PV systems, the CdTe PV system presents the best environmental performance with reference to energy payback time (EPBT) and greenhouse gases (GHG) emission rate due to its low life-cycle energy needs and relatively high conversion efficiency. Meanwhile, the mono-Si PV system depicts the worst because of its high energy intensity during the solar cells manufacturing process. The LCA result shows that PV technologies are already justified to be very sustainable and environmental-friendly. With the emerging of new manufacturing technologies, the environmental robustness of PV technologies is assumed to be further enhanced in the near future.

Keywords: LCA; EPBT; GHG; Life –cycle energy requirement; Manufacturing technology.

1. Introduction

With the population expansion and economic progress, humans wish more and more energy to develop a congenial living habitat. Hence, there is immediate urge to manage with the problem of energy scarcity and environmental degradation (Michael Dale, 2013).

With regard to energy systems, many projects focused at the mitigation of these problems are being planned, also to fulfil the more and more restrictive environmental laws. Many countries have inducted new policies to widespread the installation of new renewable source plants in order to reach the Kyoto protocol benchmarks, and often a specific mention to photovoltaic plants is reported (<<http://unfccc.int/> national , Dec 1, 2013; <<http://unfccc.int>, Nov 21,2013). Life cycle assessment (LCA) is a method for analyzing various aspects involved with the development of a product and its potential effect throughout a product's life (ISO 14040,1997). LCA stage includes definition of goal and scope, inventory analysis, impact assessment and interpretation of results as shown in Fig. 1 (ISO 14041,1998; ISO 14042,2000; ISO 14043,2000). The goal and scope describes the underlying question (objective), the system, its boundaries and the definition of a functional unit. The Flows of pollutants,

materials, resources are estimated in inventory analysis. These elementary flows (emissions, resource consumption, etc.) are characterize and aggregated for various environmental problems in impact assessment and finally conclusions are drawn in interpretation stage. The framework of LCA methodology is shown in Fig. 1

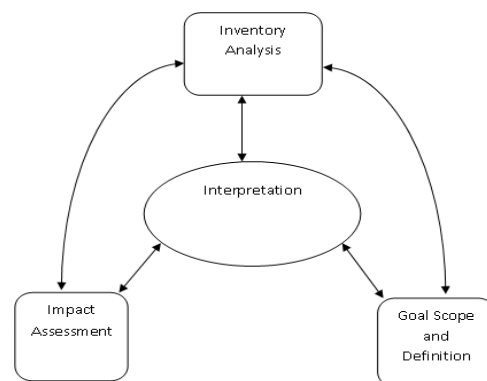


Fig.1. Framework of LCA Methodology

LCA applications are comparisons of different product and systems, or different materials production or recycling methods. LCA can be used as a tool to detect potential for improvements with the objective to minimize impact on human health, environment and resource depletion. Solar photovoltaic (PV) module transforms solar energy

*Corresponding author **Anand Kumar** is a student; **Soumya Das** is working as Asst Prof; **Pradip Kumar Sadhu** as Prof and HOD and **Nitai Pal** as Associate Prof.

Table 1 Energy Break Down for manufacturing mono-Si PV module

Authors	MG-Silicon (MJ _p /m ²)	Si feedstock (MJ _p /m ²)	CZ of mono-Si (MJ _p /m ²)	Wafer (MJ _p /m ²)	Cell P.P. (MJ _p /m ²)	Module A.P. (MJ _p /m ²)	Frame (MJ _p /m ²)	TOTAL (MJ _p /m ²)
(Kato et al ,1998)	298	797	9808		261	509	N/A	11673
(Alsema et al ,1998)	500	1900	2400	250	600	350	Frameless	6000
(Alsema et al , 2000)	450	1800	2300	250	550	350	Frameless	5700
(Knapp et al , 2001)	3950		4100		473	394	Frame (236)	5253
(Wild-Scholten et al , 2009)	728		1266		389	477	Frameless	2860

Table 2 Energy Break Down for manufacturing multi-Si PV module

Authors	Si F.P. (MJ _p /m ²)	Casting, cutting, W.P.(MJ _p /m ²)	Cell P.P. (MJ _p /m ²)	Module A.P. (MJ _p /m ²)	Frame (MJ _p /m ²)	Others (MJ _p /m ²)	Total (MJ _p /m ²)	Remark
(Kato et al ,1998)	1562	717	353	709	N/A	39	3380	30
(Alsema et al ,1998)	2250	1000	600	350	Frameless	N/A	4200	Low
(Alsema and Frankl	2200	1000	300	200	Frame(400)	500	4600	Si
(Battisti et al, 2005)	3904	535	115	556	N/A	40	5150	
(Alsema et al , 2005)	1759	1078	473	276	Frame(236)	118	3940	
(Pacca et al ,2007)	1075		3247		N/A	N/A	4322	
(Wild-Scholten et al	1400	550	400	500	Frame(270)	N/A	3120	

directly into electricity and bring about environmental benefits such as greenhouse gas (GHG) and pollution minimization (E, Alsema et al, 1997). The two most widely-used environmental indicators, energy payback time (EPBT) and greenhouse gases (GHG) emission rate, can be utilized to easily evaluate the sustainability and environmental benefits of PV systems. PV technology, directly producing electricity from solar energy, is devoid of fossil energy consumption and greenhouse gases (GHG) emission during its operations.

The EPBT indicator is defined as the years needed for a PV system to generate a certain amount of energy (converted into equivalent primary energy) for compensation of the energy consumption over its life cycle, comprising energy requirements in PV modules' manufacturing, assembly, transportation, system installation, operation and maintenance, and system decommissioning or recycling (Fthenakis, VM.,2006). EPBT of PV system is accounted by a number of factors such as type of PV module, manufacture technologies, module conversion efficiency, installation location (facade or roof-top or ground mounted) and technique (integrated or mounted), array support structure, frame or frameless, application type (stand-alone or grid-connected) and performance ratio (all losses included) (E, Alsema et al, 1997).

Compared with the conventional fossil-based power plants, one important merit of PV power systems is the potential to alleviate GHG emissions. To ease the comparison and estimate the environmental impacts of different power generation technologies, a useful indicator of GHG emission rate can be accounted. GHG emission rate depicts that how many greenhouse gases would emit

while per unit of electricity power is produced. This paper seeks to fully examine the energy payback performance and the environmental impacts of solar PV systems by performing a thorough analysis on their EPBT and GHG emission rate.

2. Life –Cycle Energy Requirement of PV modules

2.1. Energy requirement of crystalline silicon PV modules

Since before 1990s when the PV industry just started to groom, some scholars started to examine the energy requirement of crystalline silicon PV system to evaluate its sustainability. (Hunt,1976) estimated the total energy use for manufacturing silicon solar cells from raw materials of SiO₂ and concluded that, the energy payback times were 12 and 24 years for terrestrial cells and space cells, respectively. In 1990, an analysis of energy investment for manufacturing PV modules in commercial production lines of France was conducted (H Zibetta et al, 1991). It was estimated that the average EPBTs of amorphous silicon modules and crystalline silicon modules were 1.2 and 2.1years, respectively. The accumulated energy used in manufacturing process of PV modules and construction of PV plants as well as the corresponding GHG emissions were studied in detail (G Hagedorn et al, 1992). (EA Alsema et al ,1995) examined the environmental assessment of multi-Si PV module in1995.The embodied energy needed for multi-Si module was found to be 1145kWh/m² (cell accounts for 970 kWh/m², while frame accounts for 175kWh/m²). The energy utilized for producing PV modules in manufacturing lines of India was analyzed (NK Bansal et al, 1995).

(EA Alsema et al, 1998) analyzed many past studies on energy analysis and found a “best estimate” condition for evaluating embodied energy needed of mono-Si and multi-Si modules. For crystalline silicon modules, the main uncertainty of energy requirement was the preparation of silicon feedstock. They concluded that for PV applications, dedicated silicon purification routes are used, and thus the lower energy estimate was probably more representative than the higher one for near-future technology.

(K. Knapp et al, 2000; T jester et al ,2001) performed an empirical investigation on PV modules’ production to estimate process energy and materials’ embodied energy. The total process energy of mono-Si and CIS was 2742 and 1725 kWh/kWp, respectively, and the corresponding embodied energy of materials was 2857 and 1345 kWh/kWp, respectively. The embodied energy for the manufacturing of the crystalline silicon PV module and BOS components was also analyzed (G N Tiwari et al, 2006).

Tables 1 and 2 present the findings of past energy requirement breakdowns for mono-Si and multi-Si PV module, respectively. It is estimated that, the energy consumption of per unit area of crystalline silicon cell gradually reduced from higher than 10000 MJ_p/m² in 1990s to less than 3000MJ_p/m² in 2010 with the rapid increase of PV industry and the continuous improvement of cell production technologies. The main reasons of the reduction are accounted as efficient use of silicon material by reducing the wafer thickness and decreasing the silicon loss in the wafering process, new crystallization processes which can minimize the energy needed for manufacturing mono-Si, replacing the standard electronic-grade silicon purification process with dedicated silicon purification process for PV industry, which results in lower purity as well as lower energy consumption, recycling and reusing silicon material.

2.2 Energy requirement of thin film PV modules

In the early commercialization stage of crystalline silicon solar cell, the high cell cost and large energy consumption in its manufacturing process obstructed its large-scale proliferation. To solve this cost barrier, researchers started focusing on advancement of more cost-effective and lower energy consumption thin-film PV modules. Compared with crystalline silicon solar cell, the manufacturing of thin-film solar cell requires much less material with much lower cost. The production process is relatively simple without high-temperature process, thus the process consumes much less energy.

(GA Keoleian et al,1996; G Lewis et al, 1997) performed a case study on producing of amorphous silicon PV modules with life cycle design. The total process energy was about 491MJ/m². While there were low case and high case for estimating the embodied energy in product materials, and they were 864 and 1990MJ/m², respectively. If the frame was omitted, the above embodied energy would be sharply reduced to 386 and 640 MJ/m², respectively. It can be seen that the aluminium frame would significantly increase the energy requirement

of a-Si thin film PV module. Thus the authors suggested that it was very helpful for minimising the energy requirement by re-using frame or designing frameless modules. The embodied energy of a frameless a-Si module was estimated to vary from 710 to 1980 MJ/m² (P Frankl et al, 1998) . (EA Alsema ,2000) stated that the differences in energy requirement of a-Si thin film modules were mainly due to the selection of substrates or encapsulation materials, as well as the energy requirement for manufacturing the production equipment. If glass encapsulation is replaced by a polymer cover the energy requirement saved by 150 MJ/m².

A life cycle energy analysis on a-Si PV module was studied (GM Lewis et al, 1997). Life-cycle conversion efficiency, electricity production efficiency and energy payback time, were defined to comprehensively evaluate the life cycle energy performance of PV systems as well as guide the development of PV technology. The total energy needed for framed PV module was about 1458MJ/m². While the energy needed for frameless PV module was only about 894MJ/m². (Alsema,1998) conducted the energy analysis study of thin film PV modules. The author analyzed the results from six outstanding studies on a-Si modules and three studies on CdTe modules and depicted the best estimate for the energy requirement of a-Si and CdTe thin film frame less modules at that time, which was between 600 and 1500MJ/m². The difference in energy requirement was caused by the different types of cells and their encapsulations. (H Fujihara et al, 2001) estimated that the total primary energy PV module was around 1803 MJ/m², 1514MJ/m² and 1272MJ/m² at 10MW/yr, 30MW/yr and 100MW/yr production scale respectively. They stated that the total primary energy requirement was approximately equivalent to a-Si module, but the production of CdS/CdTe PV modules needed more direct process energy and less material embodied energy compared with the production process of a-Si PV module.

The gross energy demands of CIS and CdTe were reported to be 27,700 and 7,600 MJ/kWp, respectively (S Ulgiati et al , 2007) .For large-scale PV plants, the energy requirements were estimated to be 1069MJ/m², 918MJ/m², 1202MJ/m², 2044MJ/m² for CIS, CdTe, a-Si and multi-Si module, respectively (K Kurokawa et al, 2008).

The previous energy requirement breakdowns for thin-film PV modules are collected in Table 3. Among the common three types of thin film PV modules, the CIS module consumes the most energy while the CdTe module consumes the least. Compared with crystalline silicon solar cell, the total energy needed for thin film PV modules is reduced significantly (K Kurokawa et al, 2010). For thin film PV modules, the energy consumption can be classified into two categories, viz. direct process energy and material embodied energy. With the improvement of production technology, there are still spaces to reduce the direct process energy in future, but it is difficult to further reduce the material embodied energy unless cheaper and easily available substrate and encapsulation materials can be developed. The frame adds about 15–25% energy to the total energy demand of thin film modules, thus the frameless design is especially

Table 3 Energy Break Down for manufacturing Thin-film PV module

Authors	Solar cell	C.M. (MJ _p /m ²)	Substrate +E.M. C.P.P.(MJ _p /m ²)	Process energy (MJ _p /m ²)	C.E. (MJ _p /m ²)	Module A.P. (MJ _p /m ²)	Frame (MJ _p /m ²)	BOS (MJ _p /m ²)	Total (MJ _p /m ²)
(Kato and Murata,19 98)	a-Si	1078		449			Frame	N/A	1587
(Frankl et al ,1998)	a-Si	400		400			Frameless (300-770)	400	1200
(Alsema ,2000)	a-Si	40	300-400 (two glass sheets) 170-250 (glass/polymer)	500-840	100–200	N/A	Frameless frame (50-500)	N/A	940-1480 (Frameless)
(Alsema ,1998)	CdTe	40	300–400 (two glass sheets) 170–250 (glass/polymer)	350-650	100–200	N/A	Frameless Frame (50-500)	N/A	790-1270 (Frameless)
(E ieuwlaar et al, 2000)	a-Si	50	350	400	N/A	N/A	Frame(400)	400 (overhead operation and equip. manf.)	1600
(T jester et al , 2000)	CIS	1380		1770		N/A	Frameless	N/A	
(Hibino et al, 2001)	CdS/C dTe	N/A	591	637	N/A	310	Frame(280)	128 (overhead)	

C.M.-Cell material E.M.- Encapsulation Matter C.P.P.- Cell Production Process C.E...Capital Equipment

important for reducing the total energy requirement of thin film PV modules. Table 3 presented the findings of past energy requirement breakdowns for thin-film PV modules. In order to have a more insightful comparison of energy requirements between various PV technologies, the typical results of energy requirements in previous work are summarized and compared in Fig. 2

There is no specific silicon purification process to manufacture silicon feedstock for PV industry before 2005, and it is also found that the different energy distribution cases for silicon wafer production resulted in a large difference in energy requirement in early work. Therefore, for crystalline silicon PV modules, only the results after 2005 are included in this figure. It is clear that the life cycle energy requirements of thin film PV systems are far less than that of crystalline silicon PV systems.

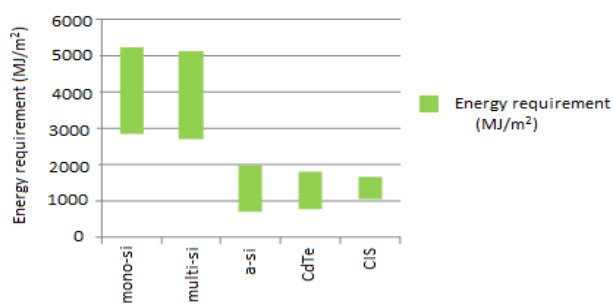


Fig.2 Review of energy requirements during life cycle of different PV system.

3. Factors Effecting EPBT Calculation

To calculate the EPBT for a specific PV system, its energy

output during life cycle should be estimated.

3.1. Solar irradiation

Solar irradiation is one main determining factor in the energy output of PV systems. To facilitate the calculation, most past literature studies about LCA analysis chose to use the approximate annual values for local solar irradiation, such as 1700kWh/m² for South Europe (P Frankl et al, 2009; GJM Phylipsen et al 1995; MJ, Wild-Scholten et al, 2005), 1000kWh/m² for Central Europe, 1117 kWh/m² for Switzerland (R Frischknecht et al, 2007), 2017kWh/m² for Gobi Desert of China (E.J. Hu et al, 2010), 1800kWh/m² for U.S. (HC Kim et al, 2005), 1427kWh/m² for Japan (P Frankl et al, 2009), 1530kWh/m² for Italy (P C Andrei et al, 2011). The approximate annual solar irradiation of a specific country or territory can also be found in NASA's website (<<https://eosweb.larc.nasa.gov/>,2013). However, some studies introduced a series of models to simulate the hourly solar irradiation based on local weather data for more accurate estimation (R Seals et al, 1990; D Menicucci, et al 1987; HX Yang et al, 2010).

3.2 Application type

System can be stand alone or the grid-connected. For stand-alone PV system, an energy storage system is needed.

3.3 Conversion efficiency

The nominal energy conversion efficiencies for the analyzed PV modules were accounted. The expected life time for the analyzed PV modules was assumed. The life time of crystalline silicon PV modules was usually assumed to be 30years (MJ Wild-Scholten et al, 2006; MS Cardona et al, 2011; K Kurokawa et al, 2003). The life time of thin film PV modules was generally assumed to be 20–25 years according to the warranty prescribed by the manufacturers (S Ulgiati, et al 2005; Keoleian GA. et al ,2007). For large scale PV plant, the life time of inverters is set to 30 years with 10% replacement every 10 years (M D Wild-Scholten et al, 2011; K Kurokawa et al, 2011). For low capacity inverters, the life time of electronic components inside the inverter is usually set at 15 years (VM, Fthenakis, 2006; JM Mason et al,2006; EA Alsema,2006), and there placement of electronic components in inverter is needed after 15 years' of operation.

3.4 Performance ratio

The performance ratio for analyzed PV systems, including all losses generated in the inverter, cable and transformer, is generally assumed. The performance ratio was assumed to be 0.75 by (Alsema et al ,2006), 0.78 by (Ito et al ,2003) considering the conditions and co-efficient of temperature in Gobi Desert, 0.80 by (Fthenakis and Kim,2005), 0.81 in (K Sakuta et al ,1997), and 0.835 according to the measurement at the grid connected side (W Nasse,2004).

In the methodology guide lines on LCA of PV systems (M Held et al, 2011) it is recommended to use site specific value for the performance ratio, viz. 0.75 for roof-top PV systems and 0.8 for ground-mounted PV systems (VM Fthenakis,2008; T Hensen,2006).

3.5 Electricity generation efficiency

The average electricity generation efficiency is considered. The average conversion efficiency of US electricity was considered to be 0.29 (HC Kim, 2005) and 0.33 (AnnualEnergyReview,2003) based on a U.S. average fuel mix and power-plant efficiency. (Alsema and Wild-Scholten,2006) took 0.31 as the overall conversion efficiency of Western-European continent electricity grid (UCTE region), while it was assumed 0.32 in some other literature (S Ulgiati, 2007).

3.6 GHG emissions rate

The GHG emissions rate of local electricity of the PV module manufacturers and installation location is determined based on the local mixture of fuel types. The GHG emission rate of Western-European continent electricity grid (UCTE region) was assumed to be 0.48–0.53kg CO₂-eq. /kWh (MJ Wild-Scholten, 2006; JO Odden et al ,2008). In addition, 0.671 kg CO₂-eq. /kWh was reported for Hong Kong (HC Kim, 2007) and 0.012 kgCO₂-eq. /kWh for Norwegian electricity supply mixes (JO Odden et al, 2008). The mixture of electricity production and the GHG emission rate of various countries (A Stoppato et al, 2008) can be utilized to know environmental impact.

4. EPBT and GHG Emission Rate of Various PV Technologies

Energy payback time is defined as the time needed for a renewable energy system to produce the same amount of energy (either primary or kWh equivalent) that was used to produce the system itself.

$$\text{Energy Payback Time (EPBT)} = (E_{mat} + E_{manu} + E_{trans} + E_{inst} + E_{eol}) / (E_{agen} - E_{aoper}) \dots \dots \dots (1).$$

Where E_{mat}, primary energy demand to produce materials comprising PV system; E_{manuf}, primary energy demand to manufacture PV system; E_{trans}, primary energy demand to transport materials used during the life cycle; E_{inst}, primary energy demand to install the system; E_{eol}, primary energy demand for end-of-life management; E_{agen}, annual electricity generation in primary energy term; E_{aoper}, annual energy demand for operation and maintenance in primary energy term. The annual electricity generation (E_{agen}) is presented as primary energy based on the efficiency of electricity transformation at the demand side. The CO₂ emission rate is a convenient index to know how much the PV system can alleviate global warming. Although there are no energy use and GHG emissions during PV systems' operation, but a large amount of energy is utilised and GHG emissions occur during their whole life time, especially in the production process. To address the issues pertaining the environmental

Table 4 LCA results review of Mono C-Si PV system

Authors/years	Location /irradiation (kW h/m ² /yr)	Module efficiency (in %)	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO ₂ -eq./kWh _e)	Remark
(Wilson and Young ,1996)	UK/573–1253	12	20	.80	7.4-12.1	N/A	Frame
(Kato and Murata et al ,1998)	UK/573–1253	12.2	20	.81	8.9	61	Multi-Si and SiCl ₄ shared the energy requirement and CO ₂
(Alsema and Wild-Scholten,2005)	South-European/1700	13.7	30	.75	2.6	41	Frame
(Alsema and Wild-Scholten,2006)	South-European/1700	14	30	.75	2.1	35	Slant-roof, frame, mounted
(Jungbluth and Dones,2007)	Switzerland/1117	14	30	.75	3.3	N/A	Frameless, on-roof installation
(Wild-Scholten,2009)	South-European/1700	14	30	.75	1.75	30	Very large scale PV systems installed in desert.
(Ito and Komoto, 2010)	China/1702	N/A	N/A	.78	2.5	50	Slant-roof frame mounted
(Kreith F et al ,2006)	US/1359	8.5	30	NA	NA	280	Frame
(Sukuta K et al, 1998)	Japan/1427	NA	20	.81	15.5	91	
(Hagedorn G. et al, 2011)	Neither land	14	30	.77	3.2	60	

performance of PV systems which include EPBT, GHG emission, environmental life-cycle assessment and so on, an expert workshop was specially held by (E Nieuwlaar,1998). Estimation of the EPBT and GHG emission rate of PV systems in a specific region is very difficult, because it is affected by so many parameters, such as life cycle energy requirement, electricity mix of PV modules' place of origin, local irradiation, local weather conditions as well as systems' life time. Actually, most GHG emissions during the PV systems' life-cycle are related to the energy consumption (T Jester et al, 2001).

CO₂ emissions rate [g-CO₂/kWh] = Total CO₂ emission on life-cycle (g-CO₂)/ Annual power generation [kWh/year] × lifetime [year].

Their results showed that the EPBTs were in the range of 2.5–4.9 years for different types of PV systems with the irradiation of 1117 kWh/m²/yr. It was also pointed out that the difference in EPBT was mainly due to different factors such as types of installation, types of solar cells and types of PV modules. The GHG emissions rate of the average PV electricity mixes in different countries were debated, with results between 48 and 83 gCO₂-eq. /kWh. The EPBT and GHG emission rate of PV systems installed in regions with low solar irradiation were estimated (R Laleman,2011). It was found that the EPBT of six different PV-technologies were all less than 5 years under

an irradiation of 900–1000kWh/m²/yr and the GHG emission rate was about 80 gCO₂-eq. /kWh with a life time of 30 years. The authors also pointed out that the PV systems' life time had an important effect on the GHG emission rate of PV generated electricity, for example if the lifetime is shorted to 20 years, the GHG emission rate of PV electricity power would increase to 120–130 gCO₂-eq./kWh.

4.1 Mono-Si PV System

Mono-Si PV system possesses the highest conversion efficiency among the studied solar cells, but also requires the largest energy requirement during its life cycle. (Wilson et al, 1996) investigated the energy payback time of two mono-Si PV systems applied in UK buildings in 1996, and stated that their EPBTs were 7.4–12.1 years for an optimistic scenario without battery bank in an ideal location. The LCA analysis of mono-Si PV system showed that the EPBT and GHG emission rate was 8.9 years and 61 gCO₂-eq. /kWh, respectively under radiation of 1427kWh/m²/yr (A Murata et al,1998). If the module production scale expanded from 10 to 100MW/yr, the energy requirement and CO₂ emission rate would be decreased to two-thirds. The GHG emission rates of mono-Si and multi-Si PV power plants in Switzerland ranged from 39 to 110g CO₂-eq. /kWh in 2000 and the EPBTs for different PV systems varied from 3 to 6 years (R Dones et al, 2005).

Table 5 LCA results review of Multi C-Si PV system

Authors	Location/irradiation (kW h/m ² /yr)	Module efficiency (in %)	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO ₂ -eq./kWh _e)	Remark
Phylipsen and (Alsema,1995)	South-European/ 1700	13	25	.75	2.7	N/A	Frame
(Kato and Murata,1998)	Japan/ 1427	11.6	20	.81	2.4	20	Frame, 10MW/Yr production scale
(Alsema ,2000)	South-European/1700	13	30	.75	3.2	60	Frame, roof top installation
(Ito and Kato ,2003)	Gobi Desert of China/1675	12.8	30	.78	1.7	12	Large scale PV installed in desert.
(Battisti and Corrado,2005)	Italy/1530	10.7	30	.8	3.3	NA	Frame
(Alsema and Wild- Scholten ,2006)	South-European/1700	13.2	30	.75	1.9	32	Frame, roof top inst.
(Pacca and Sivaraman,2007)	U.S./1359	12.9	20	N/A	2.1	72.4/54.6	
(Ito M et al,1995)	China/1605	12.8	30	.76	1.7	12	
(Honda H. et al, 1998)	Japan/1547	10	20	.78	NA	53.4	
(Battisti R et al, 2013)	Italy/1987	10.7	20	.81	3.3	26.4	

Garcia Valverde et al. studied the energetic performance and environmental impact of a 4.2kW_p stand-alone mono-Si PV system with life-cycle assessment. Their result concluded that the EPBT and GHG emission rate is 9.08 years and 131 gCO₂-eq. /kWh respectively. In addition, the effects of transportation and recycling on the EPBT and GHG emission rate were estimated and the results showed that they had limited effects on the total embodied energy and GHG emission (A Urbina et al, 2009). A new EPBT calculation method was presented and applied to estimate the energy payback time of a stand-alone multi-Si PV system in Greece. The EPBT of stand-alone system ranged from 3.5 to 6 years (E Kondili et al, 2010). Table 4 presents the previous results of energy payback period and GHG emission rate of mono-Si PV systems.

4.2 Multi-Si PV System

Multi-Si PV system has almost same transformation efficiency as the mono-Si system, but consumes less energy during its life cycle. Therefore, multi-Si system may have a lesser EPBT and lower GHG emissions rate than mono-Si system. The EPBT of multi-Si ground-field and roof-top PV systems was likely to be 3–8 years under 1700 kWh/m²/yr irradiation by (Alsema et al. ,1998), and was expected to be 1.2–2.4 years in future. The life cycle assessment of multi-Si PV systems in Japan showed that the EPBT and GHG emission rate were 2.4 years and 20 gCO₂-eq. /kWh respectively with the irradiation of 1427 kWh/m²/yr (K Sakuta, 1998). The EPBTs of multi-Si and a-Si thin film modules were about 2.5–3 years for roof top systems and 3–4 years for large ground-mounted systems with irradiation of 1700kWh/m²/yr where as the CO₂ emission rates were in the range of 50–60gCO₂-eq. /kWh (EA Alsema, 2000). Ito et al. investigated the viability to

build a 100 MW large-scale PV plant in Gobi Desert of China from both environmental and economic perspectives. Their estimated results depicted that the EPBT and CO₂ emission rate of multi-Si PV plant were less than 2 years and 12gCO₂-eq. /kWh, respectively (K Kurokava et al, 2003).

Based on the measured data from a number of multi-Si PV manufacturers, Alsema and Wild-Scholten calculated the EPBT and the life-cycle CO₂ emission rates to be 2.2 years and 35 gCO₂-eq. /kWh, respectively with the South-European irradiation of 1700kWh/m²/yr (M.J. Wild-Scholten et al, 2005) . Muller et al. studied the recycling processes of end-of-life multi-Si PV modules. They concluded that compared with new wafers, a module made of recovered wafers from the recycling process would reduce 70% energy input and the corresponding EPBT of module was reduced by 50% (K, Wambach. et al,2006)

It was found that producing solar-grade silicon using Elkem solar silicon (ESS) technology could save 66% energy compared with the conventional Siemens process. Accordingly, the EPBT of rooftop PV system using ESS technology was as short as 1.1 years, which was 0.5 years lesser than the Siemens process under the 1700 kWh/m²/yr irradiation level, and the life-cycle GHG emission rate of whole multi-Si PV system was estimated to be 23g CO₂-eq./ kWh (<http://www.shell.com/> , 2013). Sumper et al. studied the previous works related to the environmental impacts of PV systems and performed a life cycle assessment on a 200kW roof-top PV system in Spain. From their result the EPBT ranged from 1.7 to 9 years, while the GHG emission rate ranged from 22 to 180 gCO₂-eq. /kWh. In addition, a sensitivity analysis about the effect of solar irradiation on the EPBT was conducted by the authors. The result depicted that with the solar irradiation increasing from 1408 to 1930 kWh/m²/yr, the

Table 6 LCA results review of a-Si PV system

Authors	Location/ irradiation (kW h/m ² /yr)	Module Efficiency (In %)	Life time (yr)	Performance. ratio	EPBT (yr)	GHG emissions rate (g CO ₂ -eq/ kWh _e)	Remarks
(Lewis and Keoleian, 2003)	USA/1974	5	25	NA	3	NA	Frameless, low energy consumption case
(Alsema, 1998)	NW-European/ 1000	6	NA	.75	3.2	NA	Frame
(Pacca and Sivaraman, 2007)	U.S./1359	6.3	20	NA	3.2	34.3	Frame
(Meier PJ. Et al ,2011)	U.S./1614	5.7	30	NA	NA	34	Frame
(Ito M.kato et al, 2005)	China/1702	6.9	30	.74	2.5	15.6	Frame

Table 7 LCA results review of CdTe PV system

Authors	Location/irradiatio n (kWh/m ² /yr)	Module efficiency (In %)	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO ₂ -eq./ kWh _e)	Remarks
(Alsema,1998)	NW-European/	6	NA	.75	3.2	NA	Frame
(Fthenakis and Kim et al ,2005)	U.S./1800	9	30	.80	1.2	23.6	Frameless
(Alsema and Wild- Scholten et al, 2006)	South-European/ 1700	9	30	.75	1.1	25	Ground-mount system, U.S. production, frameless
(Jungbluth and Dones, 2007)	Switzerland/ 1117	7.1	30	.75	2.5	NA	Frameless, slanted-roof, integrated Frame
(Raugei and Bargigli et al ,2007)	South-European/ 1700	9	20	.75	1.5	48	Frameless, on-roof installation
(Wild-Scholten et al,	South-European/ 1700	10.9	30	.75	.84	16	

EPBT of multi-Si PV system decrease from 4.94 to 3.67 years (J P Andres et al, 2011).

The EPBT of multi-Si PV systems, as shown in Table 5, varies from 1.7 to 3.3 years and the GHG emissions rate is in the order of 12–72 g CO₂-eq. /kWh. The differences were caused mainly due to factors such as solar irradiation, module efficiency and type of installations. Table 5 presents the previous results of EPBT and GHG emission rate for multi-Si PV systems

4.3 a-Si System

Srinivas reported that the EPBT of amorphous silicon modules with 5% efficiency was about 2.6 years under the solar radiation about 1200kWh/m²/yr. However, if the module was not framed with plastic and glass, its EPBT would be reduced to 2.18 years. The results showed that even with the highest energy requirement, the EPBT was only 11 months for operating in Southern Europe (3kWh/m²/day) with conversion efficiency of 10%. If the PV modules operate in Northern Europe and Southwest of USA, the EPBT would be 10–17 and 4–7months, respectively (KS Srinivas, 1991).The EPBT for a-Si framed modules with high energy consumption case and low energy consumption case were 8.1 and 4.5 years respectively with their radiation of 1974 kWh/m²/yr and cell conversion efficiency of 5% in 1997. If the PV modules were frameless, the EPBT would consequently

further decrease to 3.7 and 3.0 years, respectively as the frame accounted for 40–50% of the energy consumption in the a-Si module production (VM, Fthenakis, 2006). The EPBT and GHG emission rate of a-Si PV system were estimated to be 2.1 years and 17 gCO₂-eq. /kWh respectively under the irradiation of 1427 kWh/m²/yr (K Sakuta, 1998). The encapsulation materials and the direct processing energy contributed to the major part of the energy consumption for thin film modules. Nieuwlaar and Alsema studied about energy analysis of thin-film (a-Si and CdTe) PV modules, and pointed out that the EPTB of frame less modules was below 2 years in 1997 under the irradiation of 1700kWh/m²/yr (E, Nieuwlaar,2007). Table 6 presents the previous results of energy payback period and GHG emission rate of a-Si PV systems.

4.4 CdTe PV System

Hynes et al. conducted life cycle analysis on two types of cadmium telluride (CdTe) thin film modules which prepared of different deposition technologies for the absorber and window layers. One type of module used chemical bath deposition and electrode position for window and absorber layers (type1). The other one used thermal evaporation deposition for these layers (type2). The energy requirements and EPBT for these two types of CdTe modules were analyzed. The results showed that the total energy requirements for type 1 and type 2 were

Table 8 LCA results review of CIS PV system

Authors	Location/irradiation (kWh/m ² /yr)	Module efficiency (in %)	Life time (yr)	Perf. ratio	EPBT (yr)	GHG emissions rate (g CO ₂ -eq./kWh _e)	Remarks
(Jungbluth and Dones ,2007)	Switzerland/ 1117	10.7	30	.75	2.9	N/A	Frame, slanted roof mounted
(Jungbluth and Dones ,2007)	South-European/ 1700	11	20	.75	2.8	95	Frame
(Ito and Kato,2008)	China/ 2017	11	30	N/A	1.6	10.5	Frame,100MW very large
(Wild-Scholten, 2009)	South-European/ 1700	10.5	30	.75	1.45	21	Frameless, on-roof installed
(Ito and Komoto, 2010)	China/ 1702	11	N/A	.78	1.8	46	Very large scale PV

992.52 and 1187.7MJ/m², respectively. The corresponding EPBTs of the above CdTe modules (10% conversion efficiency) were 5–11 and 6–13months, respectively, depending on different solar insolation level (R Hill, 1994). Depending on the location of installation in Europe, the corresponding Greenhouse Gas (GHG) emissions of PV power for ground mounted power plants are between 19 and 30 g CO₂-eq. /kWh and between 0.7 and 1.1 years in terms of EBPT (EA Alsema et al, 1998). It was reported that for cadmium telluride thin film modules, the fabrication process and the disposal decommissioning stage had the most potential to result in severe environmental pollution (AE Baumann et al ,1994). Table 7 presents the previous results of energy payback period and GHG emission rate of CdTe PV Systems.

4.5 CIS PV Systems

Concerning the energy requirement, the energy requirement is smallest for the CIS and biggest for the mono-Si. The energy pay-back time of the CIS’s VLS-PV system is approximately 1.8 years, and C-Si is 2.5 years. The others are approximately 2.0–2.3 years. Characteristics of the CO₂ emissions rate are almost same as energy pay-back time. The CO₂ emissions rate is 43–54 g-CO₂/kWh (NH Reich et al, 2011) . Kato K et al. designed VLS-PV systems using typical PV modules of multi-crystalline silicon (12•8% efficiency), high efficiency multi-crystalline silicon (15•8%), amorphous silicon (6•9%), cadmium tellurium (9•0%), and copper indium selenium (11•0%), and evaluated them by Life-Cycle Analysis (LCA). Cost, energy requirement, and CO₂ emissions were calculated. In addition, the authors evaluated generation cost, energy payback time (EPT), and CO₂ emission rates . Table 8 presents the previous results of energy payback period and GHG emission rate of CIS PV systems.

In order to compare the energy benefits and environmental impact of different PV technologies, the review results of EPBT and GHG emission rate of the studied five PV systems are presented in Figs.3 and 4, respectively. From these two figures, it is found that the CdTe PV system has the shortest EPBT and the least GHG emission rate while the mono-Si and a-Si PV systems have the worst performance due to their large energy requirements in life cycle and low energy conversion efficiency, respectively.

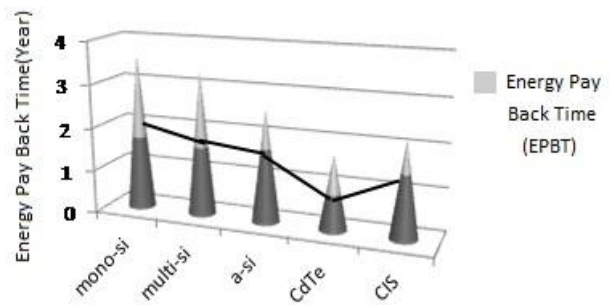


Fig.3 Review of Energy payback time for various PV systems.

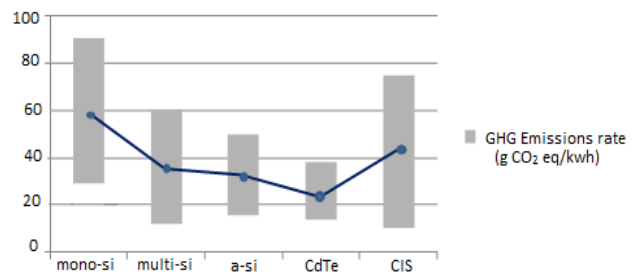


Fig.4 Review of GHG emission rates of electricity generated by various PV systems.

5. New technologies and their effects on EPBT and GHG emission rate

A reduction of silicon consumption in the PV manufacturing process is an obvious measure which may significantly lessen environmental impacts. In addition, silicon feedstock processes with lower energy consumption, such as fluidized bed reactor (FBR) technology, also have a large impact in reducing energy consumption and both measures also have a cost saving potential. The new technologies and measures which can help to reduce the life cycle energy requirement of PV systems are summarized as below.

As early as 2000, dedicated silicon feedstock production for PV applications, improving casting methods and reducing silicon utilisation, were achieved, as a result the energy requirements of multi-Si and mono-Si modules were expected to reach as low as 2600 and 3200 MJ/m², respectively (EA Alsema, 2000). A number of important options to reduce energy consumption and

environment impacts during the crystalline silicon PV module production processes was studied and reported. The future options includes introducing new silicon feedstock processes, reducing silicon consumption, increasing energy-efficiency in ingot growing, recycling Si-C slurry, enhancing energy-efficiency in cell processing and module assembly, and effectively recycling module materials in the end-of-life (MJ Wild-Scholten, 2007). Fthenakis analyzed the sustainability of thin-film modules from the viewpoints of direct costs, resource availability, and environmental impacts. It was found that reducing the thickness of solar cells and effectively recycling the modules at the end of their useful life would be crucial for resolving the problems of costs, resources, and environmental impacts to achieve a considerable sustainable growth (VM Fthenakis, 2009).

Simplified life cycle analysis was conducted by Frankl et al. through investigating previous applications and conducting parametric analysis for possible improvements in the BOS components. The authors found that compared with conventional PV power plants in open fields the main advantages of building-integrated PV systems are the saving of construction materials (energy consumption of BOS could be reduced by 50 to 66% for BIPV systems), the substitution of building envelope materials and the thermal energy dissipated by PV modules. The EPBTs of mono-Si PV systems with various installation methods ranged from 4 to 12 years with the least for BIPV system combined with a heat recovery unit (P Frankl et al, 1998). The dual-effects of the heat recovery system, namely heat recovery and cooling down cell temperature for achieving higher cell efficiency, can help further reduction of the EPBT for a tilted roof-top PV system with thermal energy recovery to half of the EPBT of PV power plant. In order to increase the overall energy efficiency of PV systems, a solution of recovering thermal energy from module was considered. This can not only improve the electrical output efficiency (by decreasing the higher module temperature), but also provide available thermal energy for utilization. If the thermal energy recovered from module was accounted, the EPBT would be cut down by 50% (R Corrado, 2005). Pacca et al. pointed out that by replacing conventional electricity with PV generation electricity for PV modules' manufacturing, the GHG emission rates for multi-Si and a-Si PV systems could be reduced by 68 and 82%, respectively (Keoleian GA. et al, 2007). It was also reported that the GHG emission rates of multi-Si and CdTe PV systems would be reduced by 6 and 2 g/kWh, respectively if replacing 30% of the total conventional electricity by PV electricity during the production processes (HC Kim, 2008). Reich et al. investigated the variation of GHG emissions of crystalline silicon module under different electricity supply options during the whole PV module production chain (NH Reich et al, 2011).

The indicators depicted that the integration of PV systems in buildings clearly increases the environmental benefits of present PV technology. These benefits will further enhance with future PV technologies. Future optimized PV roof-integrated systems are expected to have an energy pay-back time of around 1.5 years (1 year with heat recovery) and to save during their lifetime more than

20 times the amount of CO₂ emitted during their manufacturing (34 times with heat recovery).

6. Conclusions

The life cycle assessment of five common types of PV systems (mono-Si, multi-Si, a-Si, CdTe thin film, and CIS thin film) is compared in terms of energy requirement, energy payback time and GHG emission rate during whole life cycle. The reported values of primary energy requirement, EPBT and GHG emission rates of different PV systems vary significantly from case to case due to the variation of influencing factors, such as solar cell type, module type, manufacturing processes and technologies, installation methods, locations, weather conditions of location, estimation methods, etc. For mono-Si PV systems, life cycle energy requirement ranged from 2860 to 11673 MJ/m², and EPBTs varied from 1.75 to 15.5 years. These differences were mainly due to the energy estimation for silicon purification and crystallization processes. The GHG emission rate is in the order of 30–280 g CO₂-eq. /kWh, which is an order of magnitude smaller than that of fossil-based electricity. For multi-Si PV system, the cumulated energy requirement is 2699–5150 MJ/m². The EPBT and GHG emission rate is 1.7–3.3 years and 12–72.4 gCO₂-eq. /kWh, respectively. For thin film PV systems (a-Si, CdTe and CIS), the life cycle total energy input ranged from 710 to 1990 MJ/m². Consequently, the EPBT and GHG emission rates were within the range of 0.84–3.2 years and 10.5–95 gCO₂-eq. /kWh, respectively. Among the three thin film PV systems, the CIS consumed the largest amount of primary energy, and the a-Si had the longest EPBT due to its lower conversion efficiency. CdTe possessed the shortest EPBT and the lowest environmental impacts.

In general, mono-Si PV systems had the highest life cycle energy requirement, while thin film PV systems (especially CdTe and a-Si systems) had the lowest energy demand. The CdTe thin film PV technology gives the best environmental benefits such as the shortest EPBT and the least GHG emission rate due to its lower life cycle energy demand and relatively higher conversion efficiency. Meanwhile, although the energy requirement of a-Si PV system is lower, its high EPBT can be attributed to the extremely low transformation efficiency. In the aspect of GHG emission rate, mono-Si would generate more GHG emissions during its life cycle because of the high energy intensity of solar cells production processes. These results are in line with the other case study examined. New manufacturing technologies and application methods, such as advanced production processes, reducing silicon and other raw materials consumption, increasing material recycling rates, and building-integrated PV technologies, PV-thermal technologies, will further reduce the estimation values and improve the environmental performance of PV systems in the near future.

References

- Michael Dale, (2013) A Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies. *Applied Science*. 3 325-337.

- <http://unfccc.int/national_reports/accounting_reporting_and_review_under_the_kyoto_protocol/items/1029.php>, Accessed on (Dec 1, 2013).
- <http://unfccc.int/kyoto_protocol/items/2830.php>, Accessed on Nov 21, 2013.
- ISO 14040. Environmental management – life cycle assessment – principles and framework; 1997.
- ISO 14041. Environmental management – life cycle assessment – goal and scope definition and inventory analysis; 1998.
- ISO 14042. Environmental management – life cycle assessment – life cycle impact assessment; 2000.
- ISO 14043. Environmental management – life cycle assessment – life cycle interpretation; 2000.
- HC, Kim, Fthenakis, VM. (2006) Life cycle energy demand and greenhouse gas emissions from an amonix high concentrator photovoltaic system, *IEEE 4th World Conference on Photovoltaic Energy Conversion, Walikoloa, HI*, pp.628-631.
- E, Nieuwlaar, E, Alsema, (25–27 June, 1997) Environmental aspects of PV power systems. *IEA PVPS Task 1 Workshop. Utrecht, The Netherlands*, <http://www.ecotopia.com/apollo2/pvenv1997.pdf> Accessed on Nov 28, 2013.
- LP, Hunt, (November 15–18, 1976) Total energy use in the production of silicon solar cells from raw materials to finished product., *12th Photovoltaic Specialists Conference., Baton Rouge, La.*, pp.347-352.
- W Palz, H Zibetta, (1991) Energy pay-back time of photovoltaic modules. *International Journal of Solar Energy*, Volume 10 Issue 3–4 211–216.
- H Schaefer, G Hagedorn, (1992) Hidden energy and correlated environmental characteristics of PV power generation. *Renewable Energy, Volume 2, Issue 2*, 159–66.
- GJM Phylipsen, EA Alsema, (1995) Environmental life-cycle assessment of multi-crystalline silicon solar cell modules, Utrecht, Netherlands, <<http://stuff.mit.edu/afs/athena/dept/cron/project/urban-sustainability/Old%20files%20from%20summer%202009/Bjorn/solar/LCA%20silicon%20solar%20cell%20modules%201995.pdf>>, Accessed on Nov.29, 2013.
- R Prakash, NK Bansal, (1995) Energy analysis of solar photovoltaic module production in India. *Energy Sources* 17605–13.
- EA Alsema, P Frankl, K Kato, (1998) Energy pay-back time of photovoltaic energy systems: present status and prospects, *2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna*, 6–10 July 1998, pp.1-6.
- K Knapp, T Jester, (2001) Empirical investigation of the energy payback time for photovoltaic modules. *Solar Energy* 71-3, 165–72.
- K, Knapp, T, Jester, (2000) Initial empirical results for the energy payback time of photovoltaic modules, *16th European Photovoltaic Solar Energy Conference. Glasgow, UK*, May 1–5, pp.1-4.
- I Nawaz, G N Tiwari, (2006) Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. *Energy Policy* 34,3144–52.
- K Kato, A Murata, K Sakuta, (1998) Energy pay-back time and life-cycle CO₂ emission of residential PV power system with silicon PV module. *Progress in Photovoltaics Research and Applications* 6, 105–15.
- EA Alsema, (2000) Energy pay-back time and CO₂ emissions of PV systems, *Progress in Photovoltaics Research and Applications* 8, 17–25.
- M D Wild-Scholten, (2009) Energy pay back times of PV modules and systems, *Workshop Photovoltaik-Module technic*, Koln, 26–27 November,.
- R Battisti, R Corrado, (2005) Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology, *Energy* 30, 952–67.
- E.A. Alsema, M.J. Wild-Scholten, (2005). Environmental impacts of crystalline silicon photovoltaic module production. *Proceedings of Materials Research Society Fall Meeting, Boston*, Nov. 29–Dec 2.
- S Pacca, D Sivaraman, Keoleian GA. (2007) Parameters affecting the life cycle performance of PV technologies and systems, *Energy Policy* 35,3316–26.
- EA Alsema, MJ Wild-Scholten, (2007) Reduction of the environmental impacts in crystalline silicon module manufacturing, *22nd European Photovoltaic Solar Energy Conference and Exhibition. Milan, Italy*, pp. 829–836.
- G Lewis, GA Keoleian, (1996) Amorphous silicon photovoltaic modules: a life cycle design case study, *IEEE International Symposium on Electronics and the Environment, Dallas*, pp. 141–7.
- G Lewis, GA Keoleian, (1997) Life cycle design of amorphous silicon photovoltaics modules, EPA/600/SR-97/081, October, <http://www.umich.edu/~npcepub/research/pv.pdf>, Accessed on Nov 30, 2013.
- GA Keoleian, GM Lewis, (1997) Application of life-cycle energy analysis to photo-voltaic module design, *Progress in Photovoltaics: Research and Applications* 5, 287–300.
- EA Alsema, (1998) Energy requirements of thin film solar cell modules—a review, *Renewable and Sustainable Energy Reviews* 2, 387–415.
- K Kato, T Hibino, K Komoto, S Ihara, S Yamamoto, H Fujihara, (2001) A life-cycle analysis on thin-film CdS/CdTe PV modules, *Solar Energy Materials & Solar Cells* 67, 279-87.
- M Raugèi, S Bargigli, S Ulgiati, (2007) Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si, *Energy* 32, 1310–8.
- M Ito, K Kato, K Komoto, T Kichimi, K Kurokawa, (2008) A comparative study on cost and life-cycle analysis for 100 MW very large-scale (VLS-PV) systems in deserts using m-Si, a-Si CdTe and CIS modules, *Progress in Photovoltaics Research and Applications* 16, 17–30.
- M Ito, K Komoto, K Kurokawa, (2010) Life-cycle analyses of very-large scale PV systems using six types of PV modules. *Current Applied Physics* 10, S271–3.
- EA Alsema, E Nieuwlaar, (2000) Energy viability of photovoltaic systems, *Energy Policy* 28, 999–1010.
- M Raugèi, P Frankl, (2009) Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks, *Energy* 34 392–399.
- AE, Alsema, MJ, Wild-Scholten, (2005) The real environmental impacts of crystal-line silicon PV modules: an analysis based on up-to-date manufacture data, *Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona*, 6–10 June.
- N.Jungbluth, R Dones, R Frischknecht, (2007). Life cycle assessment of photo-voltaics; update of the eco invent database, 14th SETAC LCA Case Studies Symposium, Göteborg.
- A. Nishimura., Y. Hayashi, K. Tanaka, M. Hirota, S. Kato, M. Ito, K. Araki, E.J. Hu, (2010) Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system, *Applied Energy* 87 2797–2807.
- VM, Fthenakis, HC Kim, (2005) Energy use and greenhouse gas emissions in the life cycle of thin film CdTe photovoltaics, *Proceedings of Symposium G-Life Cycle Analysis, Materials Research Society Fall Meeting. Boston*, Nov. 29– Dec 2.
- P C Andrei, (2011) Simulation Results Of Life-Cycle Assessment Of 30 KwP Pv System Installed At University Politehnica Of Bucharest Romania, *Scientific Bulletin of the Electrical Engineering Faculty – Year 11 No. 3* (17). Accessed on Nov 25, 2013 <<https://eosweb.larc.nasa.gov/sse/RETSscreen/>>..
- R Perez, P Ineichen, R Seals, (1990) Modeling of daylight availability and irradiance components from direct and global irradiance, *Solar Energy* 44 (5), 271–89.
- R Perez, R Seals, P Ineichen, R Stewart, D Menicucci, (1987) A new simplified version of the Perez diffuse irradiance model for tilted surfaces. *Solar Energy* 39 (3), 221–31.
- JE Hay, JA Davies, (1979) Calculation of the solar radiation incident on an inclined surface, *Proceeding of First Canadian Solar Radiation Data Workshop.- Toronto*, pp. 59–72.
- DT Reindl, WA Beckman, JA Duffie, (1990) Evaluation of hourly tilted surface radiation models. *Solar Energy* 45(1), 9–17.
- DHW Li, GHW Cheung, (2005) Study of models for predicting the diffuse irradiance on inclined surfaces, *Applied Energy* 81(2), 170–86.
- L Lu, (2004), Investigation on characteristics and application of hybrid solar-wind power generation systems, *Ph.D Dissertation*, The Hong Kong Polytechnic University;
- KP Cheng, (2008), Energy payback time and greenhouse gas emission analysis of a roof-mounted BIPV in Hong Kong, M Eng. Dissertation, *The Hong Kong Polytechnic University*;
- L Lu, HX Yang, (2010) Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong, *Applied Energy* 87, 3625–31.
- EA Alsema, MJ Wild-Scholten, (2006) Environmental impacts of crystalline silicon photovoltaic module production, *Materials Research Society Symposium Proceedings* 895 (G03-05), 1–9.
- Paula Sanchez-Friera Michel, Piliouguine Javier Pelaez, J Carretero, MS Cardona, (2011) Analysis of degradation mechanisms of crystalline

- silicon PV modules after 12 years of operation in Southern Europe, *Progress in Photovoltaic Research and Applications* 19, 658–66.
- M Ito, K Kato, H Sugihara, T Kichimi, J Song, K Kurokawa, (2003) A preliminary study on potential for very large-scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints, *Solar Energy Materials & Solar Cells* 75, 507–17.
- M, Raugei, S, Bargigli, S Ulgiati, (2005) Energy and life cycle assessment of thin film CdTe photovoltaic modules, *Proceedings of the 20th European Photo-voltaic Solar Energy Conference, Barcelona, Spain*, pp.1886–1889.
- V Fthenakis, R Frischknecht, M Raugei, H C Kim, E Alsema, M Held, M D Wild-Scholten, (2011) Methodology guidelines on life cycle assessment of photovoltaic electricity, *IEA PVPS Task 12, Subtask 20, LCA Report*, November.
- M Ito, M Kudo, M Nagura, K Kurokawa, (2011) A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant, *Progress in Photovoltaics Research and Applications* 19, 878–86.
- EA, Alsema, MJ, Wild-Scholten, VM, Fthenakis, (2006). Environmental impacts of PV electricity generation—a critical comparison of energy supply options, *Proceedings of 21th European Photovoltaic Solar Energy Conference, Dresden, Germany*, 4–8 September.
- JM Mason, VM Fthenakis, T Hensen, HC Kim, (2006) Energy pay back and life-cycle CO₂ emissions of the BOS in an optimized 3.5 MW PV installation, *Progress in Photo voltaic Research and Applications* 14 (2), 179–90.
- EA Alsema, MJ Wild-Scholten, (2006) Environmental impacts of crystalline silicon photovoltaic module production, *13th CIRP International Conference on Life Cycle Engineering, Leuven*, 31 May–2 June
- M Ito, K Kato, H Sugihara, T Kichimi, J Song, K Kurokawa, (2003) A preliminary study on potential for very largescale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints, *Solar Energy Materials & Solar Cells* 75 507–517.
- K Kato, A Murata, K Sakuta, (1997) An evaluation on the life cycle of photovoltaic energy system considering production energy of off-grade silicon, *Solar Energy Materials & Solar Cells* 47, 95–100.
- U Jahn, W Nasse, (2004) Operational performance of grid-connected PV systems on buildings in Germany, *Progress in Photovoltaics Research and Applications* 12 (6), 441–8.
- VM Fthenakis, HC Kim, E Alsema, (2008) Emissions from photovoltaic life cycles, *Environmental Science & Technology* 42(6), 2168–74.
- AnnualEnergyReview(2003).EnergyInformationAdministration, <<http://www.eia.gov/>>, Accessed on Nov 27, 2013.
- R Glöckner, JO Odden, G Halvorsen, R Tronstad, MJ Wild-Scholten, (2008) Environmental life cycle assessment of the Elkem solar metallurgical process route to solar grade silicon with focus on energy consumption and greenhouse gas emissions, *Silicon for the Chemical and Solar Industry IX*, Oslo, Norway, June 23–26. DHW Li, GHW Cheung, Study of models for predicting the diffuse irradiance on inclined surfaces, *Applied Energy* 81(2) (2005), 170–86.
- A Stoppato, (2008) Life cycle assessment of photovoltaic electricity generation. *Energy* 33 ,224–32.
- E Nieuwlaar, E Alsema, (1998) PV power systems and the environment: results of an expert workshop. *Progress in Photovoltaics: Research and Applications* 6, 87–90.
- VM Fthenakis, HC Kim, (2007) Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study, *Energy Policy* 35, 2549–57.
- N, Jungbluth, M, Tuchschnid, M De Wild-Scholten, (2008) Life cycle assessment of photovoltaics : update of eco invent data v2.0, Working paper: <http://esu-services.ch/fileadmin/download/jungbluth-2008-LCA-PV-web.pdf> Accessed on Nov 29, 2013.
- R Laleman, J Albrecht, J Dewulf, (2011) Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation, *Renewable and Sustainable Energy Reviews* 15 , 267–81.
- R Wilson, A Young, (1996) The embodied energy payback period of photovoltaic installations applied to buildings in the UK, *Building and Environment* 31 (4), 299–305.
- N Jungbluth, C Bauer, R Dones, R Frischknecht, (2005) Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power, *International Journal of LCA* 10 (1), 24–34.
- R Garcia-Valverde, C Miguel, R Bejar Martinez, A Urbina, (2009) Lifecycle assessment study of a 4.2kWp stand-alone photovoltaic system. *Solar Energy* 83, 1434–45.
- JK Kaldellis, D Zafirakis, E Kondili, (2010) Energy pay-back period analysis of stand- alone photovoltaic systems, *Renewable Energy* 35, 1444–54.
- A, Muller, K, Wambach, EA Alsema, (2006) Life cycle analysis of solar module recycling process, *Materials Research Society Symposium Proceedings* 895, 0895/G03/07.1-0895/G03/07.6.
- A Sumper, M G Robledo, R R Villafafila, J B Jane, J P Andres, (2011) Life-cycle assessment of a photo voltaic system in Catalonia (Spain), *Renewable and Sustainable Energy Reviews* 15, 3888–96. <<http://www.shell.com/>> Accessed on Nov 20, 2013.
- KS Srinivas, (1991) Energy investments and production costs of amorphous silicon PV modules, Bern: *Swiss Federal Department of Energy*;
- GA Keoleian, G Lewis, (2003) Modeling the Life Cycle Energy and Environmental Performance of Amorphous Silicon BIPV Roofing in the US, *Renewable Energy* 28, 271-293.
- KM Hynes, AE Baumann, R Hill, (1994) An assessment of the environmental impacts of thin film Cadmium Telluride Modules based on life cycle analysis, *IEEE 1st World Conference on Photovoltaic Conversion (WCPEC)*, HI, , pp.958–961.
- KM Hynes, AE Baumann, R Hill, (1994) Life cycle analysis of PV modules based on cadmium telluride, *12th EC PVSEC*; pp. 309–312.
- NH Reich, EA Alsema, WGJHM Van Sark, WC Turkenburg, WC Sinke, (2011) Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options, *Progress in Photovoltaic Research and Applications* 19, 603–13.
- VM Fthenakis, (2009) Sustainability of photovoltaics: the case for thin-film solar cells, *Renewable and Sustainable Energy Reviews* 13, 2746–50.
- YB Jiao, A Salce, W Ben, F Jiang, XY Ji, E Morey, et al. (2011) Siemens- like processes for producing photovoltaics: energy payback time and life- time carbon emissions. *Journal of the Minerals Metals and Materials Society* 63 (1), 28–31.
- P Frankl, A Masini, M Gamberale, D Toccalci, (1998) Simplified life-cycle analysis of PV systems in buildings: present situation and future trends, *Progress in Photovoltaics Research and Applications* 6, 137–46.