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Life Cycle Assessment of PV Systems

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1. Introduction

According to reporting by the Intergovernmental Panel on Climate Change (IPCC), global warming brings a variety of adverse effects including record-high temperatures, flooding due to increased rainfall, expansion of arid areas and a higher risk of drought, and stronger typhoons. Accordingly, it is necessary to mitigate emissions of greenhouse gases (GHGs; CO₂, CH₄, N₂O and others), which cause global warming. However, as GHGs are invisible, the amounts in which they are released are generally unclear.

Life cycle assessment (LCA) - the main topic of this chapter - is useful in calculating emissions. Although it is not ideally suited for evaluation on a macro scale (investigation from a global viewpoint, for example), it is highly appropriate for micro-scale analysis (e.g., consideration of products and generation systems). The results of LCA can clarify major emissions, thereby enabling consideration of measures for their reduction.

This chapter discusses LCA in relation to photovoltaic (PV) systems. First, an overview is given and the scheme of LCA is described, and evaluation indices, LCA limitations, inventory analysis, impact assessment and interpretation are outlined. Then, guidelines for LCA in regard to PV systems are discussed with a focus on important matters for related evaluation. Next, the collection of LCA data is outlined, and finally, calculations from example papers are introduced in relation to LCA for PV modules, PV systems and balance of system (BOS) technologies.

2. What is LCA?

Life cycle assessment (LCA) is an approach to environmental management system implementation involving the quantitative evaluation of a product's overall environmental impact. Energy requirements and CO₂ emissions throughout the whole life cycle of the product (including its manufacture, transport, use, disposal, etc.) are estimated in order to enable such evaluation, and the results can be used for related environmental assessment. However, since life cycle is related to a broad range of variables and is complicated, it is difficult to comprehend the exact significance of the results. Accordingly, it is very important to set a purpose for the evaluation. An LCA operator should implement research that matches the purpose and interpret the outcomes appropriately.

The research and analysis scheme for LCA consists of the four stages shown in Fig. 1 as follows: 1. goal and scope definition; 2. inventory analysis; 3. impact assessment; and 4. interpretation. The results of inventory analysis are referred to as life cycle inventory (LCI) data. LCA is applicable to any product or service, but its results are affected by objects,

assumptions, data availability and accuracy. Hence, it is impossible to generalize the method in a very clear way. As a result, LCA operators and users must properly understand the limitations of LCA and the assumptions that can be drawn from its results. The essentials of LCA are standardized in ISO 14040 and ISO 14044, which stipulate the details and basic points of the approach.

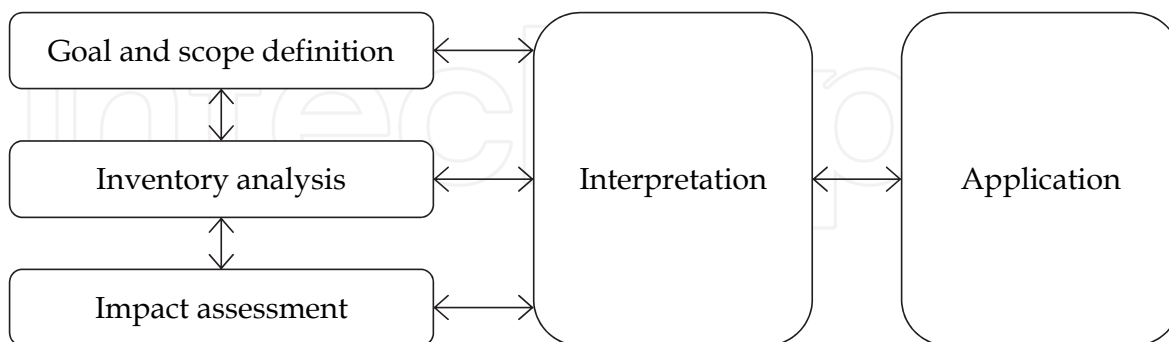


Fig. 1. Scheme of LCA

3. LCA for photovoltaic systems

In any LCA study, the purpose depends on the operator. However, when the operator evaluates a photovoltaic (PV) system, the main research point or characteristic relates to energy generation. This is a significant difference between PV systems and other products. When a building developer discusses new energy supply systems (e.g., in relation to buildings with low carbon emissions and high energy efficiency), LCA can highlight the potential of PV systems and useful materials. This is expected to provide two advantages, the first of which is PV system optimization. When a developer studies the installation of a PV system, the environment of the installation site must be considered. To ensure optimization, a variety of variables (e.g., cost and CO₂ emissions) are discussed. If LCA is used, the system can be optimized from an environmental viewpoint.

The second advantage is comparability. When comparing energy generation technologies (e.g., when researching the possible installation of a PV system as a supply of alternative energy as opposed to other generation systems, or when installing energy supply systems based on multiple generation technologies), the evaluation methods and rules applied must be uniform. In such cases, LCA can provide quantitative results, thereby enabling comparison of each technology on an equal footing.

3.1 Evaluation indices

In LCA study, evaluation indices are decided based on the purpose at hand. As PV systems generate electricity, the new index of energy payback time (EPT or EPBT) can be evaluated. EPT expresses the number years the system takes to recover the initial energy consumption involved in its creation throughout its life cycle via its own energy production. An equation for estimating EPT is shown below. The total initial energy for PV systems in Equation (1) is calculated using LCA, and the annual power generation aspect is described in Sections 4 and 5.

$$\text{EPT [years]} = \frac{\text{Total primary energy use of the PV throughout its life cycle [kWh]}}{\text{Annual power generation [kWh/year]}} \quad (1)$$

The CO₂ emission rate is a useful index for determining how effective a PV system is in terms of global warming. Generally, this index is used for comparison between generation technologies. As a PV system does not operate in the same way as a tree, there is no payback of CO₂ emissions as such. However, some research on comparisons between PV systems and other fossil fuel generation technologies have used CO₂ payback time as a metric. In these studies, PV systems were viewed as an alternative to fossil fuels and as offering a corresponding reduction in CO₂ emissions, which allowed calculation of the CO₂ payback time. However, this paper does not deal with the concept of CO₂ payback time.

$$\text{CO}_2 \text{ emission rate [g-CO}_2\text{/kWh]} = \frac{\text{Total CO}_2 \text{ emission during life-cycle [g CO}_2\text{]}}{\text{Annual power generation [kWh/year]} \times \text{Lifetime [year]}} \quad (2)$$

3.2 Boundaries of LCA

As using different boundaries obviously creates different results, defining and making boundaries known is important. Figure 2 shows typical boundaries for LCA of a PV system from the mining of its raw materials to its final disposal. The next consideration is the boundary for each stage. Boundaries involve products and services related to the item's life cycle. As the details vary in each case, it is important to fit the definition to the purpose of the product. For example, factors including the type of PV module used, efficiency, array, foundation, installation method and operation method should be identified to build a suitable system. Indirect factors should also be considered as much as possible.

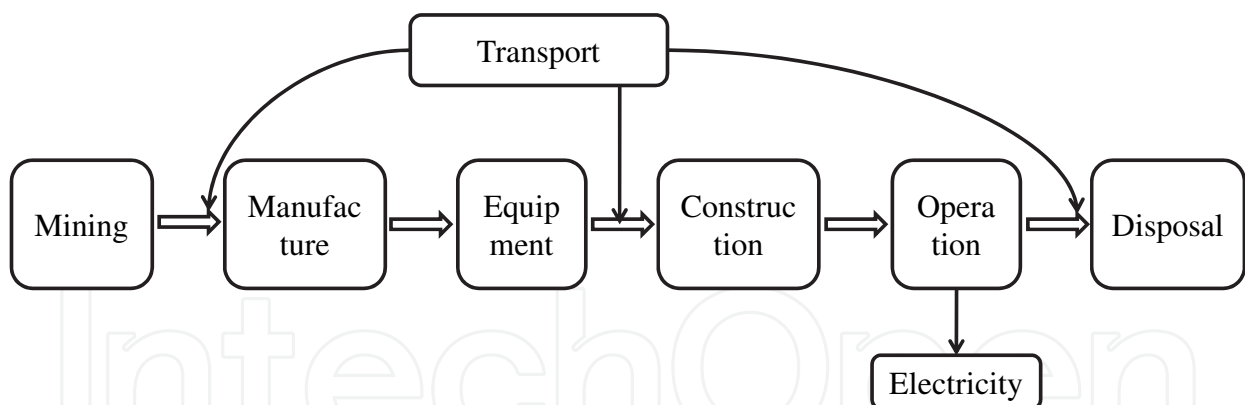


Fig. 2. Boundaries of LCA for a PV system

3.3 Inventory analysis

Inventory analysis is performed to evaluate the amounts of environment-influencing materials consumed or produced during the object's life cycle. It involves pinpointing the processes involved in the life cycle and evaluating them quantitatively, then identifying all related environment-influencing materials. The object's data are subsequently evaluated as a whole. However, as it is difficult to collect all information on related processes, the results may have simplified or missing data. Accordingly, it is important to understand the applicable boundaries, the quality of data and the assumptions involved in calculation when performing LCA study.

3.4 Impact assessment

Impact assessment consists of three processes; classification, characterization and weighting. In classification, environment-influencing materials are categorized in terms of related influence events. For example, CO₂ will be categorized as producing global warming, sulfur oxide (SO_x) will be categorized as producing acid rain, affecting public health and so on. Impact potential is calculated based on inventory analysis. In research on energy payback time, the amount of energy consumed is calculated and classified. In research on CO₂ emission rates, emissions are calculated and classified into a suitable category.

In characterization, amounts of output materials are calculated with characterization factors to produce impact category indicators. In particular, input energy is calculated in terms of electricity or calorific value. Greenhouse gas emissions are calculated in terms of CO₂ equivalents (CO₂eq) using global warming potential (GWP) figures as defined by the IPCC. For example, in the case of a power conditioning system (PCS), the weight of each material would be determined as relevant data, and the energy requirements/CO₂ emissions of the production process would be ascertained. Then, input and output data would be calculated using inventory analysis, and the results indicating the energy requirement and CO₂eq values would be calculated to provide the impact category indicator.

Weighting is not stipulated in international standardization because it is considered difficult to form a single indicator for the different areas of global warming potential and ozone depletion potential. However, a simple comparison method is still needed. The two possible methods for this are damage evaluation and environmental category weighting by estimation. Whichever is used, the weighting must be transparent.

3.5 Interpretation

The results of LCA may depend on research boundaries and approaches to inventory analysis. Accordingly, in related interpretation, the effects of operation methods should be discussed. Usually, the data used in LCA include estimates and referred information. For this reason, if the data affect the results significantly, sensitivity analysis should be included.

4. LCA guidelines for PV systems

Recently, a set of LCA guidelines for PV systems titled “Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity” was published by the International Energy Agency Photovoltaic Power System Programme (IEA PVPS), Task 12, Subtask 20. This is an informative and useful resource for LCA operators of PV systems that helps with the evaluation difficulties outlined in Section 3. This section describes a number of important considerations covered in the guidelines for evaluating PV systems.

4.1 Lifetime

Lifetime is difficult to quantify because most PV systems introduced are still in operation or were produced in the early stages of the technology’s development. However, many researchers have studied the life expectancy of PV systems. The guidelines follow the results of papers outlining such research, and set the lifetimes shown in Table 1.

PV modules	30 years for mature module technologies
Inverters	15 years for small plants or residential PV systems; 30 years with 10% part replacement every 10 years for large plants
Structure	30 years for rooftop- and facade-mounted units, and between 30 to 60 years for ground-mounted installations on metal supports. Sensitivity analysis should be performed.
Cabling	30 years

Table 1. List of lifetimes (data from IEA/PVPS Task 12)

4.2 Irradiation data

Irradiation data depend on the location and tilt angle of PV modules. Accordingly, the two main recommendations given are analysis of industry averages/best-case systems and analysis of average systems installed on the grid network.

4.3 Performance ratio

The performance ratio (PR) depends on the type of installation. In general, the value rises with lower temperatures and monitoring of PV systems for early detection of defects. Task 12's recommendation is 75% for rooftop-mounted and 80% for ground-mounted latitude-optimal installations. Alternatively, actual performance data can be used where available.

4.4 Degradation

Most PV modules degrade year by year to an extent that is still an active topic of research, especially for thin-film PV systems. However, 0.5% per year seems to be a typical number for crystalline silicon PV modules. Accordingly, the guidelines set the degradation rate for flat-plate PV modules. Mature module technologies are considered to maintain 80% of their initial efficiency at the end of the 30-year lifetime under the assumption of linear degradation during this time.

5. Collection of LCA data

LCA data are usually categorized into foreground and background types. Foreground data relates to the materials from which products are made, such as arrays, foundations and cable. Background data relate to materials that are indirectly involved, such as array steel, foundation cement and cable copper. Foreground data are usually provided by producers, while database values are used for background data due to the difficulty of collecting such information. Such databases summarize the input and output data for various materials. For example, LCA data for galvanized steel in an LCA database would show that the unit is 1 kg; the input data are the weight of coal, limestone, iron ore, natural gas, crude oil and so on used in production; and the output data are the weight of related emissions of CO₂, nitrogen oxide (NO_x), SO_x, biochemical oxygen demand (BOD) and so on.

These data can be obtained from an LCA database or by using LCA software. Ecoinvent (Switzerland) and the Life Cycle Assessment Society of Japan (JLCA) have well-known LCA databases. The Ecoinvent resource is an inventory database with more than 4,000 entries developed from research for the company's environment reports, summaries of references and questionnaire surveys. The JLCA database includes inventory data, impact category indicators and reference data, which are based on a five-year project implemented by the

New Energy and Industrial Technology Development Organization (NEDO). Although inventory data are limited to about 280 entries, these are typical data obtained in collaboration with industry associations, thus making them highly reliable. There are also approximately 300 reference data entries made by industry associations themselves.

Calculation for small systems or products can be performed manually, but this is difficult for large systems. Accordingly, LCA software is produced to support such operations. As this type of software generally already includes LCI data, the operator does not need to input individual values. SimaPro developed by PRé Consultants, GaBi Software by PE International and MiLCA by the Japan Environmental Management Association for Industry are examples of such programs.

Irradiation data are also required for LCA calculation in regard to PV systems. If it is possible to use actual long-term generation data for such systems, there is no need for irradiation data. However, environmental reporting is needed before a PV system is installed. If irradiation data are available, PV system generation can be estimated and pre-LCA can be evaluated. Meteonorm developed by Meteotest (Switzerland) is a well-known irradiation database. It also provides a function to calculate irradiation in relation to tilted planes, thereby eliminating the need to use complex metrological models. A further resource is the System Advisor Model (SAM) energy analysis software developed by the National Renewable Energy Laboratory (NREL, USA), which also includes a function for calculating PV system generation. METPV and MONSOLA developed by NEDO are other irradiation databases with data related exclusively to Japan.

LCA databases	Ecoinvent, JLCA
LCA software	SimaPro, GaBi, MiLCA
Irradiation databases	Meteonorm, System Advisor Model, METPV

Table 2. List of databases

6. LCA calculations from example papers

This section introduces four interesting papers on PV system LCA and their results. The studies in question addressed PV modules, rooftop systems, balance of system (BOS) technology and large PV systems.

6.1 LCA study on PV modules

This paper describes PV module LCA with a focus on emissions, including not only greenhouse gases (GHGs) but also NO_x, SO_x, cadmium (Cd) and heavy metals. The results for GHGs are summarized, and heavy metals form the main topic of the paper.

The use of cadmium telluride (CdTe) PV modules is growing rapidly because of their high efficiency and low price. However, Cd can have adverse health effects, and there is now a tide of concern regarding the safety of CdTe PV modules. However, this paper indicates that emissions from such modules are much lower than those of oil power plants on a like-for-like basis. LCA is a good method for highlighting this type of finding.

Data on GHGs, NO_x and SO_x are summarized in the paper assuming three cases: Case 1: current electricity mixture for silicon (Si) production from the CrystalClear project and the Ecoinvent database; Case 2: combination of the Co-ordination of Transmission of Electricity (UCTE) grid mixture and the Ecoinvent database; and Case 3: the U.S. grid mixture and the

Franklin database. In Case 1, GHG emissions of Si modules for the year 2004 are 30 – 45 g CO₂eq/kWh, and the EPT is 1.7 – 2.7 years. These figures are for rooftop installation. The GHG emissions and EPT of a CdTe frame without PV modules are 24 g CO₂eq/kWh and 1.1 years for ground-mounted installations. CdTe has about half the GHG emissions of crystalline Si. A summary is shown in Table 4.

Paper title	Emissions from photovoltaic life cycles ¹
Author(s)	Fthenakis, V.M. Kim, H.C. and Alsema, E.
Journal	Environmental Science & Technology 2008; 42 (6): 2,168 – 2,174
Irradiation	1,700 kWh/m ² /year, 1,800 kWh/m ² /year
PV type	ribbon-Si, multi-Si, mono-Si, CdTe
System configuration	0.75 – 0.8 performance ratio, rooftop- and ground-mounted
Lifetime	30 years
Results	20 – 55 g CO ₂ eq/kWh, 40 – 190 mg NO _x /kWh, 60 – 380 mg SO _x /kWh (reading from figure)
Year	2006

Table 3. Summary of the paper

PV type	Assumption	GHG emissions	EPT
Si modules	Rooftop-mounted, 0.75 PR, 1,700 kWh/m ² /yr	30 – 45 g CO ₂ eq/kWh	1.7 – 2.7 years
CdTe	Ground-mounted 0.8 PR, 1,800 kWh/m ² /yr 30-year lifetime	24 g CO ₂ eq/kWh	1.1 years

Table 4. GHG emissions and EPT

PV type and fuel type	Atmospheric Cd emissions
Ribbon-Si	0.8 g/GWh
mc-Si	0.9 g/GWh
Mono-Si	0.9 g/GWh
CdTe	0.3 g/GWh
Hard coal	3.1 g/GWh
Lignite	6.2 g/GWh
Natural gas	0.2 g/GWh
Oil	43.3 g/GWh
Nuclear	0.5 g/GWh
Hydro	0.03 g/GWh
UCTE average	4.1 g/GWh

Table 5. Atmospheric Cd emissions

¹Fthenakis VM, Kim HC, Alsema E. (2008). Emissions from photovoltaic life cycles. Environmental Science & Technology; 42 (6): 2,168 – 2,174

Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption are also evaluated for ribbon-Si, mc-Si, mono-Si, CdTe, hard coal, lignite, natural gas, oil, nuclear, hydro, and UCTE average, and the results are given as 0.8, 0.9, 0.9, 0.3, 3.1, 6.2, 0.2, 43.3, 0.5, 0.03 and 4.1 g/GWh (10^9 Wh), respectively, shown in Table 5. Compared to the emissions from oil at 43.3 g/GWh, PV system emissions are much lower.

Atmospheric emissions of arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg) and nickel (Ni) are also evaluated. The CdTe PV module shows the highest level of performance, and replacing the regular grid mix with it affords significant potential to reduce these atmospheric heavy-metal emissions.

6.2 LCA study on BOS in a 3.5 MW PV system (USA)

This paper was published in 2006. At the time, there were not many large PV systems such as those operating at over a megawatt. Accordingly, this study provided worthwhile LCA results. Even now, it is difficult to find such a detailed LCA study focusing on BOS. The investigation did not include PV modules.

Paper title	Energy payback and life-cycle CO ₂ emissions of the BOS in an optimized 3.5 MW PV installation ²
Author(s)	Mason, J. E. Fthenakis, V. M. Hansen, T. and Kim, H.C.
Journal	Progress in Photovoltaics, 2006. 14 (2): 179 – 190
Location/country	Springerville, AZ/USA
Irradiation	1,725 kWh/kW (actual performance data used for LCA), approx. 2,100 kWh/m ² /yr (average)
PV capacity/PV type	3.5 MW/mc-Si
System configuration	Ground-mounted fixed flat-plate system
Lifetime	PV metal support structure: 60 years; inverters and transformers: 30 years (parts: 10 years)
Results	BOS: 542 MJ/m ² , 29 kg CO ₂ eq/m ² , 0.21 years of EPT, \$940 US/kW
Year	2006

Table 6. Summary of the paper

The 3.5 MW Tucson Electric Power (TEP) Springerville PV plant is located in eastern Arizona, USA. The high elevation of this site and its low-temperature environment enables higher efficiency for its PV modules, which are the crystalline silicon type. Electricity from the plant is used to power a water pump at a coal-fired plant. PV support structures are anchored to the ground with 30-cm nails, thereby eliminating the need for concrete foundations. The structures' design wind speed is 160 km/h. The annual average AC electricity output in 2004 was 1,730 kWh/kW. The arrays each weigh 46.6 kg (including 5.44 kg of Al frame), cover an area of 2.456 m² and have a rated efficiency of 12.2%. The modules are the frameless PV type.

The total installed cost of the BOS components is \$940/kW. This does not include financing or end-of-life dismantling and disposal expenses. However, the salvage value is assumed to equal the costs of dismantling and disposal. The corresponding cost for inverters and related

²Mason JE, Fthenakis VM, Hansen T, Kim HC. (2006). Energy payback and life-cycle CO₂ emissions of the BOS in an optimized 3.5 MW PV installation. Progress in Photovoltaics; 14 (2): 179 – 190

support software is \$400/kW, that for the wiring system is \$300/kW, and that for the PV support structures is \$150/kW.

The life expectancy of the PV metal support structures is assumed to be 60 years. Inverters and transformers are considered to have a life of 30 years, but parts amounting to 10% of the total mass must be replaced every 10 years.

The total primary energy in the BOS life cycle is 542 MJ/m². Using the average US energy conversion efficiency of 33% produces an EPT of 0.21. Under the average irradiation of the US (1,800 kWh/m²/year), the EPT becomes 0.37 years.



Fig. 3. PV system power plant of Tucson Arizona Public Service (photo by author)

6.3 LCA study on the 2 MW Hokuto mega-solar plant (Japan)

This paper describes a comparative study on LCA for 20 different types of PV systems. Usually, comparative PV studies use different types of PV modules, but each module has only one or two pieces. However, in this PV project, each PV module is about 10 kW, making it necessary to evaluate the array size rather than the module size. On the other hand, the LCI data used were not for the PV modules themselves; they were from the NEDO PV project^{3,4}, which researched LCA for six types of PV modules including mono-crystalline silicon (mono-Si), amorphous silicon (a-Si)/mono-Si, multi-crystalline silicon (mc-Si), a-Si, micro-crystalline silicon (μ c-Si)/a-Si and copper indium selenium (CIS). The data are listed in Table 8.

The installed PV modules are shown in Table 9. Six crystalline Si, one a-Si/mono-Si, seven mc-si, one a-Si, two μ c-Si/a-Si, and two CIS PV modules were installed and evaluated. The

³NEDO, *Research and development of fabrication technologies for Life-Cycle Assessment of PV systems* (2009)

⁴Komoto, K. Uchida, H. Ito, M. Kurokawa, K. Inaba, (2008). A. Estimation of energy payback time and CO₂ emissions of various kind of PV systems. *Proceedings of 23rd EUPVSEC*; 3,833 - 3,835

table shows that mc-Si PV modules have average or higher efficiency, while sc-Si PV modules are lower than average. This should be noted and understood, as pointed out in the paper.

The results showed an energy requirement ranging from 19 to 48 GJ/kW and an energy payback time of between 1.4 and 3.8 years. CO₂ emissions were between 1.3 and 2.7 t CO₂/kW, and CO₂ emission rates ranged from 31 to 67 g CO₂/kWh. The multi-crystalline (mc-Si) and CIS types showed good results. In particular, the CIS module generated more electricity than expected with catalogue efficiency. The single-crystalline silicon PV module did not produce good results because, considering the energy requirement, installed sc-Si PV modules do not have high efficiency.

Paper title	A comparative study on life cycle analysis of 20 different PV modules installed at the Hokuto mega-solar plant ⁵
Author(s)	Ito, M. Kudo, M. Nagura, M. and Kurokawa, K.
Journal	Progress in Photovoltaics: Research and Applications, Volume 19, Issue 3
Location/country	Hokuto City, Japan
Irradiation	1,725 kWh/m ² /year at a 30-degree tilt angle
PV capacity/PV type	600 kW/mc-Si, sc-Si, a-Si/sc-Si, thin-film Si, CIS, μ c-Si/a-Si
System configuration	Ground-mounted fixed flat-plate system
Lifetime	30 years; inverters: 15 years
Year	2011

Table 7. Summary of the paper

	Module efficiency in reference	Energy requirement	CO ₂ emissions
PV module			
mono-Si	14.3%	3,986 MJ/m ²	193.5 kg CO ₂ /m ²
a-Si/mono-Si	16.6%	3,679 MJ/m ²	178.0 kg CO ₂ /m ²
mc-Si	13.9%	2,737 MJ/m ²	135.2 kg CO ₂ /m ²
a-Si (in 2000)	-	1,202 MJ/m ²	54.3 kg CO ₂ /m ²
a-Si/ μ c-Si	8.6%	1,210 MJ/m ²	67.8 kg CO ₂ /m ²
CIS	10.1%	1,105 MJ/m ²	67.5 kg CO ₂ /m ²
10 kW inverter		0.57 GJ/kW	43 kg CO ₂ /kW
Cable, conduit		1,068 GJ/600 kW	62.0 t CO ₂ /600 kW
Array (galvanized steel)		22.5 GJ/t	1.91 t CO ₂ /t

Table 8. LCI data from NEDO, Japan, on PV modules

⁵Ito, M. Kudo, M. Nagura, M. and Kurokawa, K. (May 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*, Volume 19, Issue 3

Type	Nominal power [W]	Module efficiency [%]	Capacity [kW]
mono-Si	84	13.2	30
a-Si/mono-Si	186	15.9	30
mono-Si	160	12.6	10
mono-Si	160	12.6	10
mono-Si	150	11.8	10
mono-Si	200	12.0	30
mono-Si	173	12.0	30
mc-Si	167	12.6	30
mc-Si	179	14.0	100
mc-Si	167	13.2	30
mc-Si	180	12.3	10
mc-Si	190	13.0	10
mc-Si	240	12.4	30
mc-Si	170	13.5	10
a-Si	60	6.1	30
μ c-Si/a-Si	110	8.8	10
μ c-Si/a-Si	130	8.3	10
CIS	70	8.8	30
CIS	125	11.2	3

Table 9. List of installed PV modules



Fig. 4. The 2 MW Hokuto mega-solar plant

6.4 LCA study on a VLS-PV (very large-scale PV) power plant in the desert (IEA PVPS)

This research differs from the other papers because it involved a simulation study rather than an actual system. However, the concept is interesting. It focused on a huge PV system that can generate the same amount of power as an existing power plant.

The concept of the VLS-PV was developed under IEA/PVPS Task 8. The objectives of Task 8 are to examine and evaluate the potential of very large-scale photovoltaic power generation (VLS-PV) systems. It was started in 1998, and the approaches of related evaluation are from technological, financial, environmental and local people's viewpoints. LCA is also performed as part of Task 8 to evaluate the potential of VLS-PV plants. It is assumed that very large-scale PV systems are installed in desert areas. This section discusses LCA studies on the VLS-PV system.

Paper title	Energy from the Desert: Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects ⁶
Author(s)	Komoto, K. Ito, M. Van Der Vleuten, P. Faiman, D. Kurokawa, K.
Publisher	Earthscan
Location/country	Gobi Desert/China
Irradiation	2,017 kWh/year at a 30-degree tilt angle
PV capacity/PV type	1,000 MW/mc-Si, sc-Si, a-Si/sc-Si, thin-film Si, CIS, CdTe
Lifetime	30 years; inverters: 15 years
System configuration	Ground-mounted fixed flat-plate system
Year	2009

Table 10. Summary of the paper

The VLS-PV systems evaluated would have a capacity of 1 GW, and six kinds of PV modules were supposed: mono-crystalline silicon (mono-Si), multi-crystalline silicon (mc-Si), amorphous silicon/single-crystalline silicon hetero junction (a-Si/sc-Si), amorphous silicon/micro-crystalline thin-film silicon (thin-film Si), copper indium diselenide (CIS) and cadmium telluride (CdTe). The array structures were assumed to be conventional ones with concrete foundations. For comparison, an earth-screw approach is also discussed.

The installation site was assumed to be in Hohhot in the Gobi Desert in Inner Mongolia, China. Annual irradiation there was assumed to be 1,702 kWh/m²/year, and the in-plane irradiation at a 30-degree tilt angle was 2,017 kWh/m²/year. The annual average ambient temperature was 5.8°C. Most of the equipment for the VLS-PV system was assumed to have been manufactured in Japan and transported by cargo ship. However, the foundation and steel for the array structure were assumed to have been produced in China. For these materials, land transport was assumed over a distance of 600 km, and marine transport was assumed to have covered 1,000 km. The lifetime of the VLS-PV system was assumed to be 30 years, while that of the inverter was 15 years. It was assumed that after the end of the equipment's lifespan, all of it would be transported to a wrecking yard and used as landfill.

⁶Komoto, K. Ito, M. Van Der Vleuten, P. Faiman, D. Kurokawa, K. (September 2009). *Energy from the Desert - Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects*, Earthscan, ISBN-13: 978-1844077946

From comparison, the value for the concrete foundation was 2,458 kt CO₂/system, and that for the earth-screw approach was 2,597 kt CO₂/system. Usually, the earth-screw option would be favorable, but not in this study. The paper pinpoints the reason as the low efficiency of steel production in China. If this study had also included the recycling stage, the results would have been different, as steel can be recycled easily.

Energy consumption was from 35 to 46 TJ/MW, and CO₂ emissions were from 2,300 to 3,200 t CO₂/MW. The energy consumption of CIS was the smallest among the six types of PV modules, and the CO₂ emission of mc-Si was the smallest. Figures 5 and 6 show the EPT and CO₂ emission rate of the VLS-PV system. It was calculated that the EPT would be 2.1 - 2.8 years, and the CO₂ emission rate would be 52 - 71 g CO₂/kWh. This means that the VLS-PV would be able to recover its energy consumption in the lifecycle within three years and provide clean energy for a long time. Furthermore, the CO₂ emission rate of the VLS-PV system would be much smaller than that of a fossil fuel-fired plant. In particular, a PV system generates during the day when fossil fuel-fired plants are also operational.

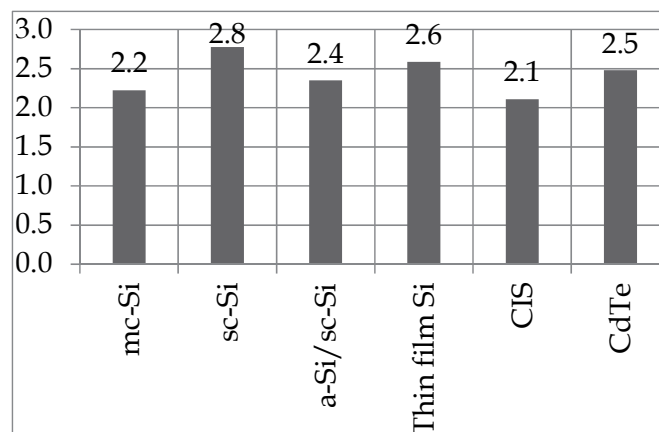


Fig. 5. Energy payback time [years] of the VLS-PV system with six types of PV module

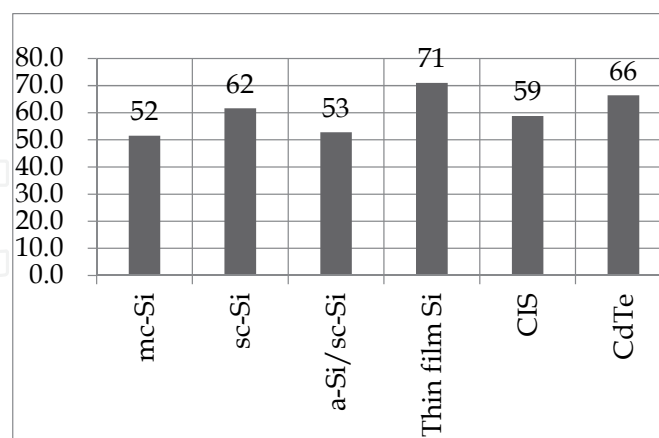


Fig. 6. CO₂ emission rate [g CO₂/kWh] of the VLS-PV system with six types of PV module

7. Summary

This paper describes life cycle assessment (LCA) of PV systems. An overview of LCA is given in Section 2 outlining the method for quantitatively determining the environmental

effects of products. Section 3 describes LCA for PV systems, outlining evaluation indices, boundaries of LCA, inventory analysis, impact assessment and interpretation. Section 4 details LCA guidelines for PV systems, outlining important considerations for related evaluation. Section 5 deals with the collection of LCA data, and outlines ways to obtain the large amounts of information required for such analysis.

Section 6 presents LCA calculation by introducing related example papers. LCA of PV modules, PV systems and BOS is described. According to VM. Fthenakis et al., greenhouse gas (GHG) emissions from Si modules are 30 – 45 g CO₂eq/kWh, and the EPT of such modules is 1.7 – 2.7 years. The corresponding figures for CdTe frames without PV modules are 24 g CO₂eq/kWh and 1.1 years for ground-mounted installations. According to JE. Mason et al., the total primary energy in the BOS life cycle is 542 MJ/m². Taking the average US energy conversion efficiency of 33%, the EPT is 0.21 years. From the author's paper, the results showed an energy requirement ranging from 19 to 48 GJ/kW and an energy payback time of between 1.4 and 3.8 years. CO₂ emissions were from 1.3 to 2.7 t CO₂/kW, and CO₂ emission rates ranged from 31 to 67 g CO₂/kWh. According to Komoto et al., the EPT of a VLS-PV system would be 2.1 – 2.8 years, and the CO₂ emission rate would be 52 – 71 g CO₂/kWh.

Since the lifetime of PV systems exceeds 20 years, a low ETP means that a system can recover the energy required to pay for itself more quickly. These figures for CO₂ emission rates are also much lower than those for fossil fuel plants. It can therefore be concluded that PV systems have significant potential to mitigate global warming.

8. Abbreviations

a-Si	Amorphous silicon
BOD	Biochemical oxygen demand
BOS	Balance of system
Cd	Cadmium
CdTe	Cadmium telluride
CH ₄	Methane
CIS	Copper indium diselenide
CO ₂	Carbon dioxide
EPBT	Energy payback time
EPT	Energy payback time
g CO ₂ eq	Grams of carbon dioxide equivalents
GHG	Greenhouse gas
GJ	Gigajoule = 1,000,000,000 J
GW	Gigawatt = 1,000,000,000 W
GWh	Gigawatt hour = 1,000,000,000 Wh
GWP	Global warming potential
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JLCA	Life Cycle Assessment Society of Japan
kWh	Kilowatt hour = 1,000 Wh
LCA	Life cycle assessment
LCI	Life cycle inventory
mc-Si	Multi-crystalline silicon

MJ	Megajoule = 1,000,000 J
MW	Megawatt = 1,000,000 W
N ₂ O	Nitrous oxide
NEDO	New Energy and Industrial Technology Development Organization
NO _x	Nitrogen oxide
NREL	National Renewable Energy Laboratory
PCS	Power conditioning system
PR	Performance ratio
PV	Photovoltaic, Photovoltaic System
PVPS	Photovoltaic power system programme
ribbon-Si	Ribbon silicon
sc-Si	Single-crystalline silicon
Si	Silicon
SO _x	Sulfur oxide
TEP	Tucson Electric Power
TJ	Terajoule
UCTE	Union of the Co-ordination of Transmission of Electricity
VLS-PV	Very large-scale photovoltaic power generation system
μc-Si	Micro-crystalline silicon

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The exciting world of crystalline silicon is the source of the spectacular advancement of discrete electronic devices and solar cells. The exploitation of ever changing properties of crystalline silicon with dimensional transformation may indicate more innovative silicon based technologies in near future. For example, the discovery of nanocrystalline silicon has largely overcome the obstacles of using silicon as optoelectronic material. The further research and development is necessary to find out the treasures hidden within this material. The book presents different forms of silicon material, their preparation and properties. The modern techniques to study the surface and interface defect states, dislocations, and so on, in different crystalline forms have been highlighted in this book. This book presents basic and applied aspects of different crystalline forms of silicon in wide range of information from materials to devices.

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