LIFE CYCLE ANALYSIS OF HIGH-PERFORMANCE MONOCRYSTALLINE SILICON PHOTOVOLTAIC SYSTEMS: ENERGY PAYBACK TIMES AND NET ENERGY PRODUCTION VALUE

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ABSTRACT: This paper summarizes a comprehensive life cycle analysis based on actual process data from the manufacturing of Sunpower 20.1% efficient modules in the Philippines and other countries. Higher efficiencies are produced by innovative cell designs and material and energy inventories that are different from those in the production of average crystalline silicon panels. On the other hand, higher efficiencies result to lower system environmental footprints as the system area on a kW basis is smaller. It was found that high efficiencies result to a net gain in environmental metrics (i.e., Energy Payback Times, GHG emissions) in comparison to average efficiency c-Si modules. The EPBT for the Sunpower modules produced in the Philippines and installed in average US or South European insolation is only 1.4 years, whereas the lowest EPBT from average efficiency c-Si systems is ~1.7 yrs. To capture the advantage of high performance systems beyond their Energy Payback Times, we introduced the metric of Net Energy Production Value (NEPV), which shows the solar electricity production after the system has “paid-off” the energy used in its life-cycle. The SunPower modules are shown to produce 45% more electricity than average efficiency (i.e., 14%) c-Si PV modules.
Keywords: Photovoltaic, energy performance, energy rating, c-Si, cost reduction

1 INTRODUCTION

Life Cycle Analysis (LCA) is a framework for considering the environmental inputs and outputs of a product or process from cradle to grave. It is employed to evaluate the environmental impacts of energy technologies, and the results are increasingly used in decisions about formulating energy policies. The most basic indicator used in interpreting the results of LCA is the cumulative energy demand, encompassing all energy used in the production and the other stages of a power system’s life, which is often expressed in conjunction with the system’s electricity output in terms of energy payback times (EPBT) or energy return on investment (EROI). The second most basic LCA indicator is the greenhouse gas (GHG) emissions (GHG) during its life-cycle.

Early life-cycle studies report a wide range of primary energy consumption for Si-PV modules; Alsema and deWild [1, 2] reported 2400-7600 MJ/m^2 of primary energy consumption for mc-Si, and 5300-16500 MJ for mono-Si modules. These wide ranges are due to data uncertainties, and to different assumptions and allocation rules adopted from different investigators. Even greater variations were noted in the early literature on EPBT, EROI and GHG estimates, reflecting different assumptions on the solar irradiation input into the PV systems.

Early estimates fall far short of describing present-day commercial-scale PV production. A most comprehensive LCA study, based on actual LCI data from twelve PV manufacturers, was published in 2008 [3] and was updated in subsequent publications [4-14]. The group of these investigators also developed guidelines for transparent and well-balanced LCA of all PV technologies, under the auspices of the International Energy Agency (IEA) [15]. All previous studies of c-Si PV modules are based on LCI data from average efficiency PV modules. In this paper we summarize the results of a life-cycle analysis of SunPower high efficiency PV modules, based on process data from the actual production of these modules, and compare the environmental footprint of this technology with that of other c-Si technologies in the market.

2 METHODOLOGY

Our Life Cycle Assessment (LCA) complies with the ISO 14040 [16] and 14044 [17] standards and the IEA Task 12 Guidelines [15]. These guidelines prescribe a common approach and transparency for the evaluation of caused environmental impacts. The LCA addresses all the environmental impacts caused along the whole product life cycle from the extraction of raw materials, the material production, manufacturing, utilization, decommissioning, and disposal or recycling at the end-of-life stage of the modules and balance of system (BOS) components. For this assessment, all required energy and material flows, both primary and auxiliary materials, as well as wastes and emissions at each life cycle stage are accounted for.

Thus LCA involves a comprehensive consideration of the whole product life cycle, including all foreground and background data life-cycles. According to ISO 14040 and 14044, the LCA is carried out in four main steps: 1) Goal and scope definition, 2) inventory assessment, 3) impact assessment, and 4) interpretation.

Thus, the LCA study starts with the definition of the goal and scope and the boundary conditions of the study, which describe the main aim and content of the study and define the functional unit, the system boundaries, and boundary conditions. The functional unit is usually defined as one piece of product or the provision of a specific function (e.g., 1 kWh produced power). The second step is the Life Cycle Inventory (LCI), where all required data on inputs and outputs of energy, material, and emissions within the whole product life cycle are collected. Based on LCI data provided by SunPower and complemented by commercial databases (e.g., Ecoinvent, Franklin), a module and a system model for ground-mount fixed installations, are set up. This is supported by commonly used and well-established LCA software (i.e., SimaPro) that provided information on foreground and background data (e.g., the environmental profile of materials and energy production). The subsequent Life Cycle Impact Assessment (LCIA) (step 3) classifies caused emissions according to their contribution to environmental impact categories (e.g., Global Warming Potential) and characterizes them by their significance in relation to the reference unit (e.g., kg CO_2-equiv.).

The Interpretation of the results (step 4) can be used for strategic planning of product improvements, comparisons with other PV system life-cycles, or for proving the compliance to environmental directives.

2.1 System boundary

The system boundary of the LCA study considers the whole life cycle of SunPower's high-performance crystalline Si modules including all expenses to produce required energies, materials, and auxiliaries. The study does not include the transportation of produced and used modules, maintenance during the utilization phase, and recycling at the end of the system's life. These items were also excluded in all the previous LCA with which the current study draws comparisons.

2.2 Functional unit

The functional unit for the LCA is defined as 1 m^2 of module area. For conversions to power output, a module efficiency of 20.1% and a total system performance ratio of 80% for ground mounted installations are assumed. Based on this data, the environmental profiles of PV power for different installation types and U.S. average insolation, are investigated.

2.3 Geographical scope

Production is considered for various countries representing SunPower's actual cell and module production sites. All datasets on used materials and energies are based on country representative datasets. The use phase is assumed to be in the U.S. in average insolation regions (e.g., 1800 kWh/m^2/yr – over latitude tilt).

2.4 Impact categories

The most widely accepted categories are Cumulative Energy Demand (CED) and Global Warming Potential (GWP). CED provides the basis for the calculation of the Energy Payback Time (EPBT), and Energy Return on Investment (EROI).

Energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself [15].

$$\text{Energy Payback Time} = (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}) / ((E_{age}n / n_G) - E_{O\&M})$$

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
$E_{O\&M}$: Annual primary energy demand for operation and maintenance
n_G: Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

The EROI is a dimensionless ratio representing how many times over its lifetime, the system would generate the cumulative energy used in its production; the traditional way of calculating EROI is as a function of EPBT and its lifetime [15]:

$$\text{EROI} = \text{lifetime} / \text{EPBT} = T \cdot ((E_{agen}/n_G) - E_{O\&M}) / (E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL})$$

3 RESULTS

A detailed life cycle inventory (LCI) was compiled from process data supplied by the SunPower Corporation corresponding to the production in 2011 of 248,652 modules of SPR-327NE-WHT-D AR modules with a total rated capacity of 81.3 MW. This LCI was cross-referenced with the crystalline Si LCI data in the Ecoinvent database and differences were explained and documented. The SunPower cell LCI includes some chemicals that are not included in the Ecoinvent database and the SunPower solar cells are thinner than the ones described in Ecoinvent.

The life-cycle environmental profiles of the SunPower systems were determined on a "cradle to grave" basis, in accordance to the IEA LCA guidelines [15]. The SunPower cells and modules were compared to the two data sets in SimaPro from the Ecoinvent database which represent typical values used in published LCA estimates; these are: 'mc-Si' (based on 1992 LCI data) and 'single-Si' (based on 2007 LCI data, average of 4 multi-crystalline and 1 mono-crystalline cell manufacturers), referred to here as "Ecoinvent A" and "Ecoinvent B", respectively.

3.1 SunPower cells

The life cycle assessment impact results for the SunPower cells (reference case: Philippines) in comparison to the Ecoinvent cells are given in Figure 1. This comparative analysis uses the most common metrics, namely: Cumulative energy demand (CED) in units of megajoules of primary energy [MJp], and global warming potential (GWP) in units of kilograms CO2 equivalent [kg CO_2e]. Two estimates are listed for the SunPower cell; SunPower_PH corresponds to production in the Philippines which is our reference case, and SunPower_NO_UCTE corresponds to production of MG-Si in Norway and average European electricity grid for the subsequent stages of production, which are the conditions represented in the Ecoinvent cells.

The functional unit of comparison was one cell, with dimensions shown in Table I.

Calculations for this work were based on specific cell and module specifications from SunPower and compared to the modules in the Ecoinvent database.

Table I: Cell specifications

Process	Efficiency (%)	Size (cm^2)	Thickness (µm)
SunPower cell	22.5	155.3	155
Ecoinvent A cell	15.4	156	300
Ecoinvent B cell	14.3-15.4	243	270-300

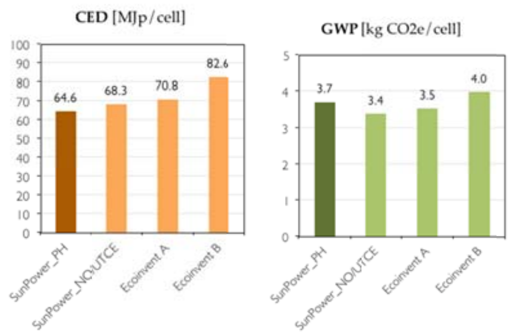

Figure 1: Life cycle impact assessment results in CED and GWP, per cell. (SunPower reference case-Phillipines; SunPower_NO_EU and Ecoinvent B corresponds to MG-Si production in Norway, and balance of production using average (UTCE) European grid electricity)

3.2 SunPower modules

The life cycle assessment impact results for the SunPower cells in comparison to the Ecoinvent modules are shown in Figure 2. Because each module has a different area and power rating (Table II), and since power, corresponding to electricity generated, is the functional unit by which the modules should be compared, a comparison in terms of MJ/W is shown in Figure 3.

Table II: Module specifications

Process	Area* (m^2)	Rated power (W)	Power density (W/m^2)
SunPower module	1.62	327	203
Ecoinvent A module	1.32	185	140
Ecoinvent B module	1.60	210	131

*area of panel without frame

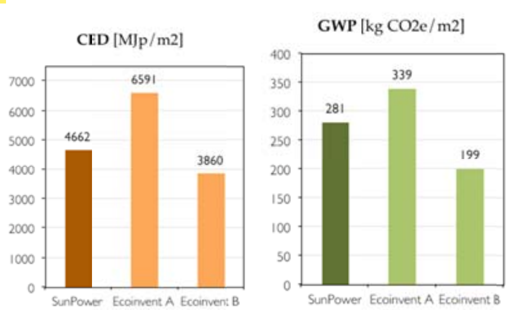

Figure 2: Life cycle impact assessment results in CED and GWP, per m^2 of module area.

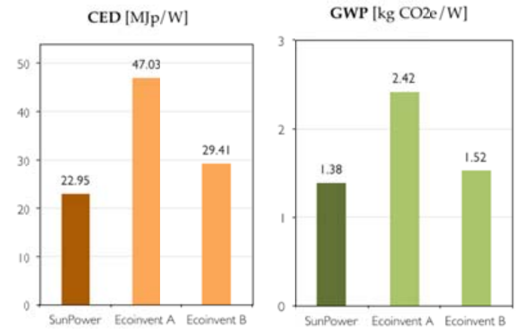

Figure 3: Life cycle impact assessment results in CED and GWP, per W of module rated power.

As shown in this figure, the SunPower module has the lowest CED and lowest GWP (i.e., 1.38 kg CO_2eq/W) on the basis of rated power due to the module's higher power density.

It is noted that using the interim French Regulation Energy Commission (FREC) guidelines will result to GWP of only 0.6421 kg CO_2eq/W (Table III), which is less than half of our estimate above, which is based on a full LCA (The reason for this discrepancy is that the FREC guidelines account for only the quantities of materials imbedded in the module, whereas a complete LCA accounts for the losses of these materials during the different processes upstream.) Furthermore, the frame and other materials used in the production of the module are not listed in the interim FREC document, whereas they were included in our analysis. As shown in Table IV, excluding the frame reduces the CED and, correspondingly, the GWP of the modules by 8%.

Table III: GWP calculation based the FREC guidelines

	Distribution		MJ/Unit	unit/module	g CO2eq/k	MJp/kWh	kgCO2 /module
Component		unit	SunPower	(no losses)			SunPower
poly-Si-solarGrade_modSiemen	0.8	kg	1595.05	0.56	487	11.6	30.048
poly-Si-ElectronGrade	0.15		2213.67	0.56	487	11.6	7.819
poly-Si-ElectronGrade_offspec	0.05		702.00	0.56	487	11.6	0.827
Ingot+wafer (125mm, 155 um)	1	wafer	14.82	96	487	11.6	59.742
cell	1	cell	17.83	96	487	11.6	71.857
module w/o frame	1	m2	336.19	1.61	487	11.6	22.724
front sheet (low-iron glass)+ten	1	kg	18.20	12.90	487	11.6	9.858
backsheet	1	kg	91.62	0.63	487	11.6	2.407
EVA	1	kg	81.61	1.37	487	11.6	4.695
				TOTAL (kg CO2eq/module)=			209.977
module rating (kWdc) =	0.327			TOTAL (kg CO2eq/kWdc)=			642.132
				TOTAL (kg CO2eq/W)=			0.6421

Table IV: Module energy breakdown

Unit	Total	Cells	Al Frame	Backsheet	Glass	EVA	Electricity	Other
MJ/m2	4662	3948	379	60	117	79	52	27
MJ/W	22.95	19.44	1.87	0.30	0.58	0.39	0.25	0.13
%		85%	8%	1%	3%	2%	1%	1%

3.3 Regional comparisons

For the above calculations, all electricity – from metallurgical-grade silicon to module production – was assumed to be from the Philippine electricity grid. Three additional scenarios were calculated using electricity from Europe, Korea, and Malaysia. The electricity grid makeup is shown in Table V.

Table V: Percentage of generation from each energy resource for each country

Resource	Philippines	Europe	Korea	Malaysia
coal	25.9%	30.6%	43.4%	26.9%
oil	8.0%	4.4%	2.7%	1.9%
gas	32.2%	16.9%	19.3%	63.6%
hydro	16.2%	13.2%	1.4%	7.7%
nuclear	0.0%	32.0%	32.3%	0.0%
geothermal	17.6%	0.0%	0.0%	0.0%
wind	0.1%	2.0%	0.0%	0.0%
other	0.0%	1.0%	0.9%	0.0%

The results for cell and module production in each country are given in Figures 4 and 5 correspondingly. In general, cumulative energy demand is lowest in the Philippines, due to the high percentage of geothermal energy generation, while greenhouse gas emissions are lowest in Europe, which has the lowest percentage of generation from fossil fuels. Nuclear energy, prevalent in both Europe and Korea, has minimal associated greenhouse gas emissions but larger energy demand, explaining the CED and GWP differences shown in Figures 4 and 5.

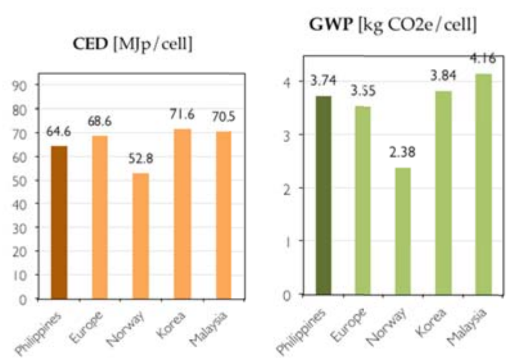

Figure 4: Life cycle impact assessment results per cell for each country.

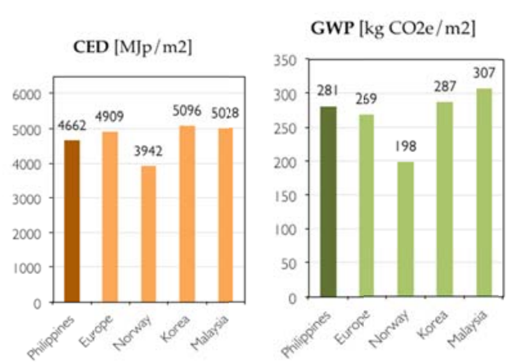

Figure 5: Life cycle impact assessment results per m2 of module area for each country.

3.4 Process contributions

The individual life cycle stages of module production were investigated to identify the process steps that contribute most to the embodied energy and greenhouse gas emissions of the module. Electricity use is a significant contributor at all life stages, further underscoring the importance of the electricity mix in determining the final environmental impact of the module.

The relative impact for each of the following life cycle stages were investigated:

- metallurgical-grade silicon (MG-Si)
- polycrystalline silicon (poly-Si)
- monocrystalline silicon (mono-Si)
- wafer production
- cell production
- module production

The results for both CED and GWP are shown in Figures 6 and 7 for production in the Philippines and Malaysia, respectively. The largest contributor to environmental impacts is the poly-silicon purification followed by its crystallization to mono-Si. Wafer, cell and module production accounts for ~37% of the CED in the Philippines's production and about 27% for production in Malaysia. The GHG emissions are about the same in the production cycles in the two countries.

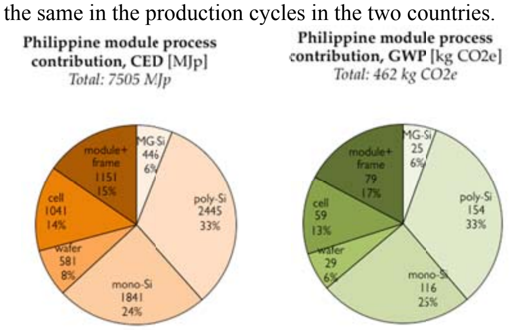

Figure 6: Contributions of each life cycle step per framed module for Philippine production.

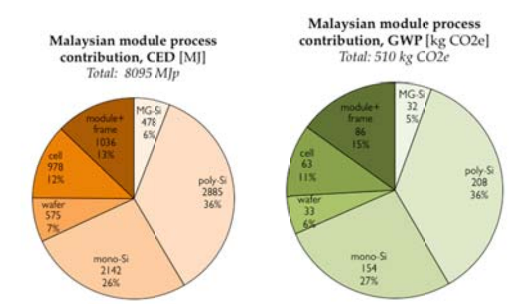

Figure 7: Contributions of each life cycle step per module for Malaysian production.

3.5 Ground-mount installation

Environmental metrics were calculated for a 1 MW ground-mount installation of SunPower modules, using data collected at the 4.6 MW Springerville plant in Tucson, AZ, scaled to 1 MWdc power. Details of the system are given elsewhere [18]. PV system performance under US average conditions is based on 1800 kWh/m^2·yr insolation, a performance ratio of 80%, and latitude optimal fixed tilt, corresponding to annual electricity generation of 1440 kWh/kW·yr in the first year. For a lifetime of 30 years and no degradation, total lifetime generation of the PV system is 43,200 kWh/kW. The system is assumed to replace average US grid electricity and the corresponding GHG emissions; the grid values given in the Ecoinvent process 'Electricity mix/US' in SimaPro were used.

The life cycle impact assessment results for the SunPower ground-mount installation per kW of rated power are given in Figure 8 for module production in the Philippines, Europe, Korea, Malaysia, and the United States for installation under average U.S. insolation. For installations in the U.S.-SW (insolation of 2300 kWh/m2/yr) the EPBT decreases to 1.1 year and the EROI increases to 28.

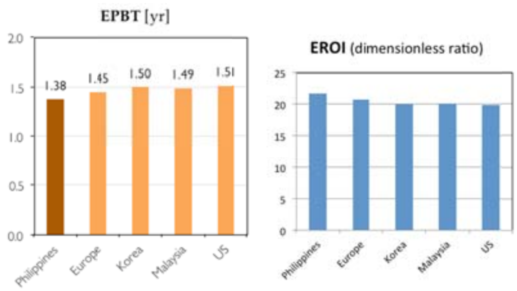

Figure 8: EPBT and EROI of ground-mount systems under average U.S. insolation (1800 kWh/m2/yr).

It is noted that the advantage of high module efficiency is not entirely captured by the EPBT and EROI metrics. If two systems have the same EPBT (thus same EROI) but one is more efficient than the other, the former will generate more clean electricity than the later during its life cycle.

3.6 Net Energy Production Calue (NEPV)

In an attempt to differentiate systems based on the efficiencies of their modules, we define a new indicator and name it Net Energy Production Value (NEPV).

$$\text{NEPV [kWh/kWp]} = (\text{Life} - \text{EPBT})\ [\text{yr}] \times \text{I}\ [\text{kWh/m}^2/\text{yr}] \times \text{PR} \times \text{Eff}$$

where Life denotes the number of years that the system is expected to operate, PR is the performance ratio accounting for all losses to the transformer, and Eff is the rated (dc) efficiency of the modules

The NEPV shows the electricity produced by a system after it has "paid-off" the cumulative energy used in its production. As shown in Table VI, the NEPV for the SunPower system operating in average U.S. conditions is 8278 kWh/kWdc, whereas an average c-Si system will generate only 5706 kWh/kWdc.

Table VI: Net Energy Production Value (NEPV) for the SunPower system and an average c-Si system

Lifetime (yrs)	EPBT (yrs)	Rated eff.	PR*	Insolation (kWh/m2/yr)	NEPV (kWh/kWp)
30	1.4	0.201	0.8	1800	8278
30	1.7	0.14	0.8	1800	5706

*PR = Performance Ratio

Thus the SunPower 20.1% efficient modules will produce a net 45% more energy than average (i.e., 14%) c-Si modules, during lifetimes of 30 years.

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