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Modern Technologies in the Context of a Growing Renewable Energy Market

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Energy Payback Time of a SolFocus Gen1 Concentrator PV System

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ABSTRACT

Energy payback time of a solar cell technology is a useful metric of sustainability as well as environmental impact. Herein, we apply a synthesis of old and new methodologies to present a realistic energy analysis for the SolFocus Gen1 high concentration photovoltaic system. Taking into account embodied energy in materials, energy demand for production, labor and transportation, the energy payback time for the Gen1 module is 1.5 years for a system installed in California and 1.3 years for a system installed in Arizona. Areas of high energy consumption are identified and strategies to mitigate these areas are presented.

INTRODUCTION

Energy payback time (EPBT) is the time required for a photovoltaic (PV) system to deliver the amount of energy that was required for its manufacture, transport and installation. It is a powerful metric that captures both the upstream costs and the use-phase capabilities of a photovoltaic. As a measure of manufacturing efficiency, energy-use reflects material consumption, manufacturing equipment use, process throughput, and defect rate. From an environmental point of view, energy use is an important metric that drives other environmental metrics such as global warming potential, emissions of conventional air pollutants (SO_2, NOx, etc), and the ecological footprint.

Energy payback time is also an extremely effective communication tool. The concept of economic payback time is prevalent; making this related metric accessible to consumers, investors, and the public at large. Energy payback time is increasingly a point of competition within the solar industry, indicating the efficiency and sophistication of any PV technology. Examples of EPBT values for various PV technologies are found in Table 1.

Technology	EPBT (yrs)	Reference
Crystalline Silicon	3.1 - 4	Alsema (2000)
Amorphous Silicon	2.5 - 4	Alsema (2000)
CdS/CdTe	1.1 - 1.7	Kato et al. (2001)
Flatcon (CPV)	0.7 - 1.3	Peharz and Dimroth (2005)

Table 1: Estimates of energy payback times for various solar technologies.

SolFocus is a startup company based in Silicon Valley that desires their PV product to provide an environmentally benign source of electricity. To achieve this goal, knowledge of their system's energy payback time is required. Cost tends to scale with energy consumption, and their technology promises to reduce the cost per watt when compared with flat panel PV by reducing the volume of required semiconductor material—an expensive component of silicon-based solar cell systems.

In our study, the major components of energy consumption were identified by carefully obtaining energy use information from the entire life-cycle of a SolFocus Gen1 concentrator system. This information will allow SolFocus to strategically improve the Gen1 system to reduce EPBT.

Another goal of this paper is to establish a standard EPBT methodology. At least 10 distinct PV EPBT analyses have been performed to date, yet the results are not directly comparable. We suggest four ways to build on previous studies, producing a more realistic EPBT.

SYSTEM DESCRIPTION

High concentration PV systems use expensive high efficiency photovoltaic materials, but minimize the amount of material used by highly concentrating incoming sunlight. The concentrating optics are most efficient when they are directly facing sunlight, hence tracker systems are required to ensure direct exposure to the sun.

For the SolFocus Gen1 high concentration system, the main components considered are: the multi-junction PV cell, the concentrator, the frame, the tracking system, and electronics. We also consider assembly and post-manufacturing energy use from transportation and installation, as shown in Figure 1.

We define each PV cell and concentrator as a “unit”. Each “module” is made up of 16 units and each “panel” is made up of 9 modules. The panel, along with the tracker and electronics, comprise the total system. A SolFocus Gen1 system produces a peak power of 2.25 kW [S. Horn, personal communication, Nov. 2006].

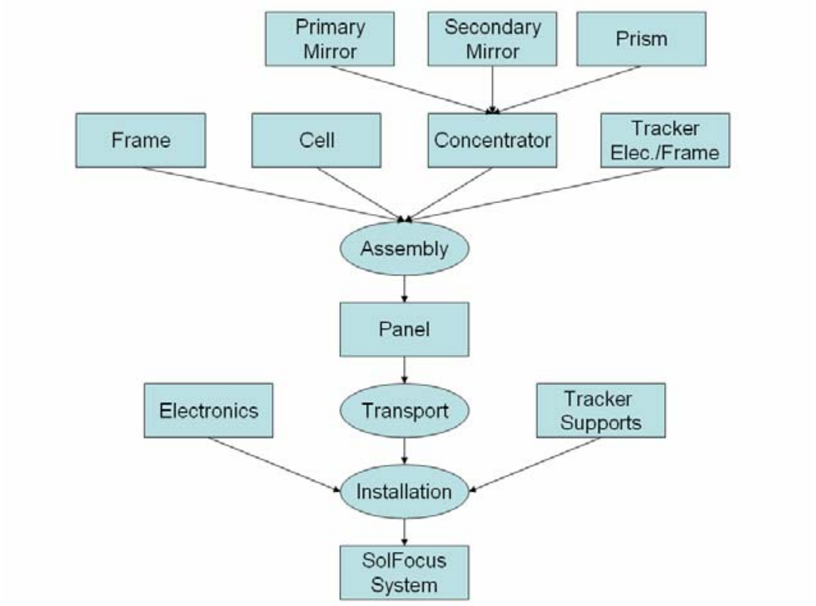


Figure 1: Flowchart illustrating main components of SolFocus Gen1 PV system.

Photovoltaic Cell

The photovoltaic material used by SolFocus is a III-V multi-junction semiconductor cell with an efficiency of ~35%, produced by Spectrolab [R. Sherif, personal communication, Oct. 2006]. Ge wafers are used as substrates for subsequent growth of GaInAs followed by GaInP via metal-organic vapor phase epitaxy (MOVPE). During this growth process, hydrogen carrier gas is used as well as metal-organic precursors for In, As, P, and Ga. The resulting multi-junction then undergoes lithography and metal evaporation for definition of contacts. Finally, the wafers are sawed into chips and soldered onto a copper heatspreader, which is responsible for passive cooling of the solar cell. A yield of 85% is assumed in fabrication of the solar cell from the Ge wafer [Peharz and Dimroth, 2005].

Concentrator

The concentrator is a three-stage optical device that uses mirrors in a configuration that closely resembles a mirror-based telescope, as shown in Figure 2. The first stage is a concave mirror known as the primary mirror that acts as the input aperture of the concentrator. The reflected light from the primary mirror is further concentrated by a convex mirror, known as the secondary mirror. Eventually, light goes through the third concentration stage, the prism, which delivers the 500x concentrated light to the PV cell located next to its output aperture [S. Horn, personal communication, Nov. 2006].

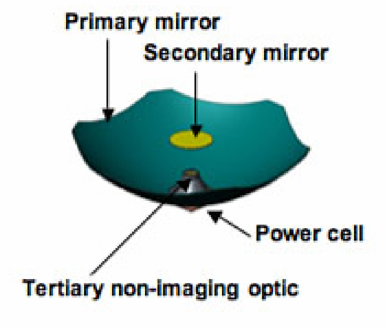


Figure 2: Main components of concentrator optics.

The primary mirror is manufactured by cutting a sheet of float glass and slumping this sheet to get the desired concave shape. Further cutting, drilling, and grinding follow the slumping process. Finally, the glass is coated with a thin layer of silver through a spraying-baking sequence. To make the secondary mirror, piece of pressed soda-lime glass is first ground to a convex shape. The convex surface is sputtered with silver to achieve 94% surface reflectivity, and the silver is then protected by a quartz layer. To make the prism, a borasilicate rod is ground on its four sides to produce a square output aperture [D. Bailey, personal communication, Nov. 2006].

Frame and Assembly

To prevent concentrator degradation, sixteen PV cells and concentrator components are arranged in an aluminum frame, covered by a sheet of float glass, and sealed to make a module. Manual assembly is currently used for the Gen 1 system [S. Horn, personal communication, Nov. 2006].

Tracker

SolFocus uses a Wattsun AZ-225 dual axis tracker to align the concentrator mirrors with the sun. A zinced steel torque tube holds aluminum rails, which support nine SolFocus modules. A low power motor and tracking sensor vary both the horizontal and vertical position of the panels to ensure direct insolation. A concrete foundation anchors the system to the ground [Wattsun, 2006].

Transportation and Installation

SolFocus uses a number of subcontractors whose parts must be shipped from their point of manufacture to Sunnyvale for final assembly. The complete system is transported from the SolFocus assembly plant in Sunnyvale, CA to the installation site. Tracker installation is completed primarily by human labor, as detailed in Appendix AA.

METHODOLOGY

Energy payback time was calculated using the following equation:

$$EPBT = \frac{E_{input}}{E_{produced/yr} - E_{tracking}} \times \eta_{elec}$$

where E_{input} is the sum of energy inputs associated with manufacturing, transportation and installation, $E_{produced/year}$ is the product of average insolation, panel efficiency, area of the panel, and inverter and cable efficiency, and $E_{tracking}$ is the energy used by the tracker per year. E_{input} is calculated in terms of primary energy (MJ) as opposed to end-use electricity equivalent energy (kWh), so η_{elec}, the average electrical conversion efficiency of the electrical industry, is used. η_{elec} is approximately 38% in the United States [Blakers and Weber, 2000].

To evaluate the total energy input, a form of life-cycle analysis (LCA) must be carried out for each component. This study's LCA deviates from previous EPBT studies in four main ways: 1) Economic Input-Output Life-Cycle Assessment (EIO-LCA) is used, 2) energy demand of labor is included, 3) transportation of goods to the manufacturing facility is included, and 4) replacement of components over the lifetime of the system is addressed.

> 1) Previous EPBT studies overlook some upstream energy use by setting finite boundaries on the analysis. Because researchers do not have infinite time, they cannot assess every single material and process that was required to make a final product. This tendency to underestimate energy use in this way can be avoided by using Economic Input-Output Life-Cycle Assessment [Carnegie Mellon, 2006]. EIO-LCA is explained in detail below.
>
> 2) Also unlike other EPBT analyses, energy of labor used in manufacturing and installation has been included. The energy per worker-hour is estimated as total domestic energy supply less industrial energy, amortized over the population and hours in a year. This yields 29 MJ of energy per hour of labor for an average US worker [Zhang and Dornfeld, 2007].

3) Until the manufacture of the SolFocus Gen1 system can be fully vertically integrated, energy used in transporting specialized components to the assembly facility must be considered.

4) The lifetime of various components has been taken into account. Tracker motors and inverters need to be replaced at least once during the life of a 20-year system, yet other EPBT analyses account for the energy of only one tracker motor and one inverter.

Embodied Energy Calculations

Embodied energy information comes from a variety of sources. Depending on the data available, one of four main methods was used to calculate the embodied energy of a material or process.

Energy per economic activity (EIO)

The EIO-LCA database [Carnegie Mellon, 2006] uses industry-level economic input-output data tables provided by the U.S. Department of Commerce and environmental data provided by the U.S. Environmental Protection Agency to determine an amount per dollar of environmental metrics such as energy use, global warming emissions, and toxic waste. The values provided by EIO-LCA include all energy associated with a dollar of activity, including computer use, airplane flights, and meals on the company bill. EIO-LCA provides accurate but not necessarily precise data, as industry-level data can be highly aggregated.

EIO-LCA data is based on producer prices, not retail prices. To approximate producer prices [Wright, 2006], a conversion factor of 1/4 was applied to retail prices found online while a conversion factor of 1/3 was applied for purchase prices obtained from SolFocus, because it was assumed that their prices are already somewhat discounted. Additionally, this producer cost was then scaled back to a 1997 price using a conversion factor of 1.255 [Sahr, 2006] as required by the most up to date EIO-LCA database.

Embodied Energy Density (ED)

The embodied energy per unit mass of specific materials is available from previous life-cycle analyses. These values are used by other EPBT studies, although it is not always clear how they were determined. This lack of transparency makes the results questionable, but they are used here when an industry sector in EIO-LCA did not specifically reflect a given material.

Nameplate (NP)

The process embodied energy in this approach has been computed based on the power draw indicated on the nameplate of the process machinery and the process throughput time. A detailed discussion on the calculation of electrical power has been presented in Appendix A. Note that a moderate power factor of 0.8 has been considered in this study. The full load power factor of an induction motor can vary from 0.5 for a small low speed motor up to 0.9 for a large high speed machine.

Publicly Available Data (PAD)

Publicly available information has been used to estimate embodied energy where nameplate power draw, throughput time, or material energy information is not available. Appropriate scaling factors have been used where needed based the amount of material processed.

Placeholder Data (PH)

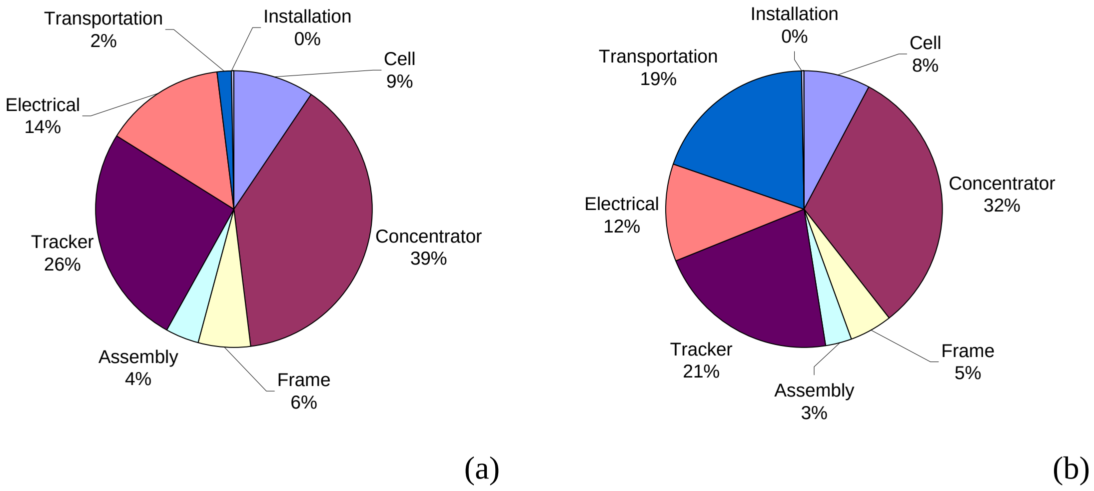
For primary mirror processing, a visit to the plant has not yet been possible, so estimated values of power draw and processing time have been used where necessary.

RESULTS

The energy payback times for a SolFocus PV system installed in Berkeley, CA and Pheonix, AZ are found to be 1.5 years and 1.3 years, respectively, as shown in Table 2. The significant differences between these two locations are the insolation and system transportation from the SolFocus production facility in Sunnyvale, CA. Contributions to the energy payback time for the main components of the SolFocus system are shown in Figure 3 for the Berkeley and Phoenix installations.

	Final Transport (mi)	Insolation (W/m^2)	EPBT (yr)
Berkeley, CA	50	1825	1.5
Phoenix, AZ	720	2520	1.3

Table 2: Energy payback time for systems installed in Berkeley, CA and Phoenix, AZ



(a) (b)

Figure 3: Contributions to the energy payback time of SolFocus systems installed in (a) Berkeley, CA and (b) Phoenix, AZ.

All components and processes that have been taken into account in the EPBT analysis for a system installed in Berkeley, CA are shown in Table 3, along with their respective energy contributions, their percentage contribution to EPBT, and the method used to calculate energy consumption. The methods have been described in the Methodology section, and detailed calculations on each component can be found in the Appendix.

It should be noted that embodied energy of the glass-processing equipment has been neglected because a visit to the production site was not possible and required information from our contacts at Corning could not be obtained.

Table 3: Energy of components and processes of a system installed in Berkeley, CA. Method abbreviation key: Energy per economic activity (EIO), Embodied energy density (ED), Nameplate (NP), Publicly available data (PAD), Placeholder value (PH). See Appendix for calculation details.

Cell		**4904**	**MJ**	**9.40**	**%**	**Method**
	Ge wafer – Cell	1437	MJ	2.75	%	PAD
	Hydrogen	11	MJ	0.02	%	PAD
	Hydride gases	13	MJ	0.02	%	PAD
	Metalorganics	1	MJ	0.00	%	PAD
	MOVPE process	478	MJ	0.92	%	PAD
	Cleanroom – Cell	1173	MJ	2.25	%	PAD
	Solvents	39	MJ	0.08	%	PAD
	Acids	3	MJ	0.00	%	PAD
	Photolithography materials	45	MJ	0.09	%	PAD
	Evaporation noble metals	321	MJ	0.61	%	PAD
	Cell technology	146	MJ	0.28	%	PAD
	Chip packaging materials	450	MJ	0.86	%	PAD
	Chip packaging	366	MJ	0.70	%	PAD
	Copper Heat Spreader	422	MJ	0.81	%	PAD

Concentrator		**20147**	**MJ**	**38.60**	**%**	
Primary Mirror	Float Glass - Primary Mirror	3284	MJ	6.29	%	ED
	Silver	48	MJ	0.09	%	EIO
	Cut	69	MJ	0.13	%	PAD
	Slump – heat	900	MJ	1.72	%	PAD
	Slump – vacuum	167	MJ	0.32	%	PH
	Cut	69	MJ	0.13	%	PH
	Drill	22	MJ	0.04	%	PAD
	Grind	190	MJ	0.36	%	NP
	Spray x2	139	MJ	0.27	%	PH
	Bake	300	MJ	0.57	%	PH
	Transportation - Conc.	13441	MJ	25.75	%	PAD
Secondary Mirror	Soda Lime Glass	59	MJ	0.11	%	ED
	Sputter (Ag)	864	MJ	1.66	%	PAD
	Coat (Quartz)	69	MJ	0.13	%	PH
Prism	Borsolicate glass	526	MJ	1.01	%	EIO

Frame		**3178**	**MJ**	**6.09**	**%**	
	Aluminum Frame	1739	MJ	3.33	%	EIO
	Glass Cover	1305	MJ	2.50	%	ED
	Sealant	134	MJ	0.26	%	EIO

Assembly		**2077**	**MJ**	**3.98**	**%**	
	Capital Equipment	178	MJ	0.34	%	EIO
	Labor - Assembly	1899	MJ	3.64	%	PAD

Tracker		**13484**	**MJ**	**25.83**	**%**	
	Zinced Steel Pipe	5249	MJ	10.06	%	ED
	Zinced Steel Drive	2233	MJ	4.28	%	ED
	Zinced Steel Torque Tube	2248	MJ	4.31	%	ED
	Motor	310	MJ	0.59	%	EIO
	Aluminum Module Rails	245	MJ	0.47	%	EIO
	Tracking Sensor and Electronics	220	MJ	0.42	%	PAD
	Concrete Foundation	2980	MJ	5.71	%	ED

Electrical		**7406**	**MJ**	**14.19**	**%**	
	AC and DC Wiring	525	MJ	1.01	%	PAD
	Interconnect Board	750	MJ	1.44	%	PAD
	Inverter	6131	MJ	11.75	%	EIO

Transportation	**857**	**MJ**	**1.64**	**%**	PAD

Installation	**144**	**MJ**	**0.28**	**%**	PAD

TOTAL	**52199**	**MJ**	**100**	**%**

Comparison to Economic Cost

Another important comparison is the economic breakdown versus the energy breakdown for this PV system, as shown in Figure 4. The similarities between the two show that energy and economic cost are somewhat correlated, and by investigating energy use with the goal of reduction, cost savings may also be achieved. It is interesting to note that the PV cell and concentrator make up half of the total for both cases.

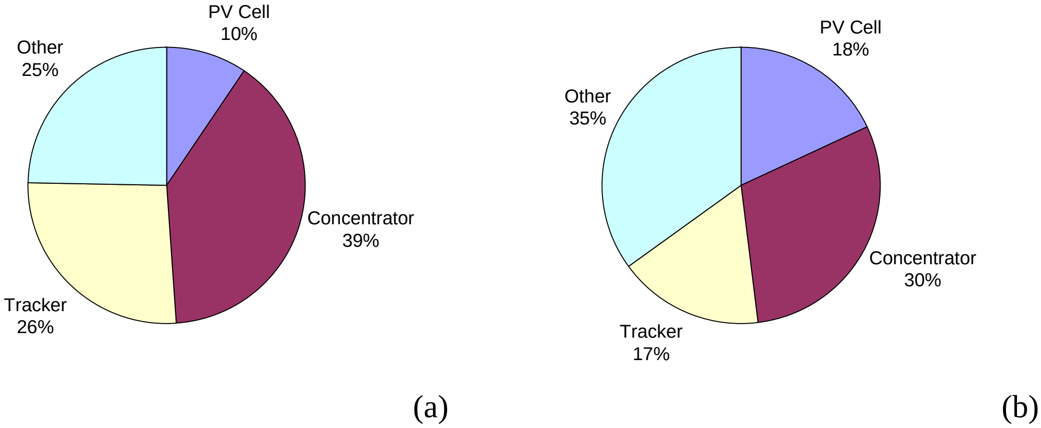


Figure 4: Contributions to (a) energy and (b) cost for a system installed in Berkeley, CA.

In Figure 4, the cost breakdown does not account for replacement tracker motor or inverter, whereas the energy calculation does.

DISCUSSION

A ranking of the 10 largest energy inputs are shown in Figure 5. Interestingly, the photovoltaic cell is not a major contributor to the system's energy intensity. This arises mainly from the relatively small amount of photovoltaic material used. At 1437 MJ, the germanium wafer has the highest energy demand value of any cell component. This result is perhaps not surprising considering that germanium, similar to silicon, undergoes very energy intensive purification and growth processes.

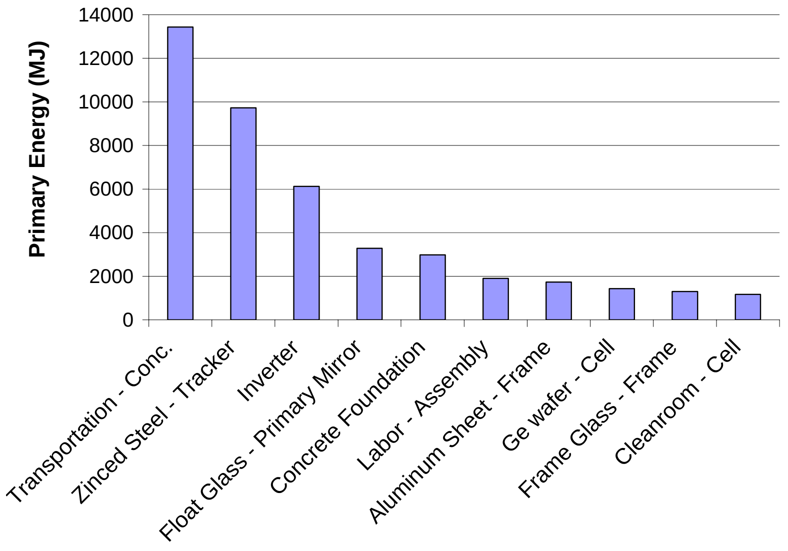


Figure 5: Primary energy of the 10 largest contributors to a system installed in Berkeley, CA.

The primary mirrors represent the largest energy input to the completed SolFocus panel. The embodied energy in the glass of these mirrors represents 3284 MJ – a consequence of using 240 kg of glass with an embodied energy value of 13 MJ/kg [Peharz and Dimroth, 2005]. Transportation of the mirrors from Corning's plant in Corning, NY to SolFocus' plant in Sunnyvale, CA takes an additional 13,441 MJ. This is the largest energy demand in the whole production chain.

Also of note, zinced steel and concrete have large energy contributions (9730 MJ and 2980 MJ respectively) due to the large amount of material needed for the tracking system. The inverter adds another large energy input of 6131 MJ, primarily due to its ten year lifetime.

Possible Energy Improvements

Our analysis has highlighted a few key areas in which SolFocus could significantly cut their product's embodied energy.

The first and foremost of these is to reduce transportation of module components to SolFocus' plant in Sunnyvale. Even though transportation of some components was neglected in this study, component transportation was still the single largest energy contributor. It is not currently possible for SolFocus to make every component in house, but they could work with their suppliers, especially Corning, to set up component production closer to the final point of assembly.

SolFocus could also reduce their energy use by using recycled aluminum. Average aluminum recycling rates were assumed in this analysis, but if SolFocus could ensure that their product was made from entirely recycled aluminum, their product's energy and economic payback time could also be significantly reduced. The initial aluminum production process is extremely energy intensive (227 MJ/kg), while the recycling process requires the comparatively small 8.1 MJ/kg [Canadian Architect, 2006].

Finally, zinced steel for the tracker was a large part of the total energy input to a SolFocus system. This material is likely used because of its strength anti-corrosive properties. However, by seeking alternatives to this material, or reducing the volume required, energy payback and possibly economic payback could be reduced.

CONCLUSION

The energy payback time of a SolFocus Gen1 high concentration PV system was calculated to be 1.3 – 1.5 years. The EPBT for a SolFocus PV system is less than 50% of that for crystalline and amorphous silicon technologies and is comparable with CdS/CdTe technology. Unlike the silicon based solar cell technologies, in which the dominant energy contribution is from semiconductor wafer processing, the optical concentrator system has the greatest energy demand for the SolFocus system. Transportation of the primary mirrors from their point of production to SolFocus' assembly plant was found to be one quarter of the energy required to produce the whole system, which readily suggests that vertical integration of the manufacturing process would improve the EPBT significantly. Furthermore, replacing some energy intensive materials, especially aluminum, with recycled materials could also lower the EPBT. Through this analysis, SolFocus' technology has been shown to be promising from an energy input standpoint. As their production process is streamlined, SolFocus could reduce their EPBT to under a year, becoming a leader in the field of manufacturing energy conservation.

APPENDIX

Appendix A: Power in AC Circuits

In a single phase AC circuit, we can represent voltage and current waveforms as below:

$$I(t) = I_m \cdot \cos(\omega \cdot t)$$

$$V(t) = V_m \cdot \cos(\omega \cdot t + \varphi)$$

where I_m and V_m are, respectively, the magnitudes of current and voltage waveforms, ω is the angular velocity of system frequency, and φ is the phase angle of voltage with respect to current. Therefore, the average consumed power may be calculated as

$$P = V_{eff} \cdot I_{eff} \cdot \cos(\varphi)$$

where $V_{eff} = V_m / \sqrt{2}$ and $I_{eff} = I_m / \sqrt{2}$ are the "effective" values of the voltage and current, respectively. In this expression, the term $\cos(\varphi)$ is called the *power factor*.

Furthermore, three types of power can be defined for an AC power system:

1- *Active power*, i.e. $P = V_{eff} \cdot I_{eff} \cdot \cos(\varphi)$ with units of W (Watt). Active power is the power that actually does useful work (e.g. turns the mechanical load, etc.) and sometimes is called *True power*.

2- *Reactive power*, i.e. $Q = V_{eff} \cdot I_{eff} \cdot \sin(\varphi)$ with units of VAR (Volt-Ampere Reactive.) Reactive power does not do any actual work but it is stored in the magnetic fields of inductors or electric fields of capacitors in an AC circuit so that those components can function properly. It decreases the useful current (and hence power) capacity of the transmission lines (or cables) and introduces more resistive loss.

3- *Apparent (or Complex) power*, i.e. $S = V_{eff} \cdot I_{eff}$ with units of VA (Volt-Ampere.) Note that $S = \sqrt{(P^2 + Q^2)}$ and $\cos(\varphi) = P/S$.

For three-phase systems based on a similar discussion, the power can be computed as

$$P = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos(\varphi)$$

where V_L and I_L are the effective values of line voltage and line current, respectively.

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