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Project Summary

Life Cycle Design of Amorphous Silicon Photovoltaic Modules

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The life cycle design framework was applied to photovoltaic (PV) module design. The primary objective of this project was to develop and evaluate design metrics for assessing and guiding the improvement of PV product systems. Two metrics were used to assess life cycle energy performance of a PV module: energy payback time and electricity production efficiency. These metrics are based on material production, manufacturing, and transportation energies, and were evaluated for several geographic locations. An aluminum frame is responsible for a significant fraction of the total energy invested in the module studied. Design options to reduce the energy impact of this and other components are discussed.

This Project Summary was developed by EPA's National Risk Management Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Interest in sustainable energy technologies that are both practical and affordable has increased with growing awareness of the environmental and political consequences of fossil fuel and nuclear electricity generation. PV modules, one variety of which is the subject of this report, offer a promising alternative to our current dependence on nonrenewable energy technologies. Photovoltaic modules convert some of the energy contained in sunlight directly into electricity without producing waste or emissions.

This life cycle design project was a collaborative effort between the University of Michigan and United Solar Systems Corporation (United Solar). United Solar is a joint venture between Energy Conversion Devices (ECD) of Troy, Michigan, and Canon, Inc. of Japan. ECD is a leader in the research and development of thin film amorphous silicon photovoltaic modules. Canon is known worldwide as a manufacturer of electronic, office, and photographic equipment.

The United Solar UPM-880 tandem junction commercial power generation module was the product chosen for this demonstration project. The UPM-880 is currently United Solar's standard power generation module and is the most directly comparable with other manufacturers' products. It employs thin film amorphous silicon as the photovoltaic material and contains two identical semiconductor junctions (hence, tandem). This module has a rated output power of 22 watts, is 119.4 x 34.3 x 3.8 centimeters in size, weighs 3.6 kilograms, and has a stabilized conversion efficiency of 5%.

The UPM-880 represents a point in the development of thin film PV technology which has since been surpassed. The opportunity to influence this technology improvement made the UPM-880 product system a good candidate for study. United Solar is exploring innovative applications of thin film PV technology including incorporation of PV into building materials such as standing seam metal roofing systems and roofing shingles that have the appearance of common asphalt shingles. Roofs, glazings, and facades all become producers of electricity in addition to performing their traditional structural or architectural functions when thin film PV materials are used to coat building surfaces. These building-integrated PV applications are made possible in part by thin film characteristics such as ruggedness, flexibility, and low cost.

Life cycle design was developed to more effectively integrate environmental considerations into product system design. The product system encompasses material production, parts fabrication and assembly, use, and retirement. Systems analysis based on the product life cycle offers a comprehensive approach for guiding improvement of photovoltaics and other products.

Objectives

The primary objective of this demonstration project was to develop and apply design metrics for assessing the energy performance of photovoltaic technologies. This study was a partial application of the life cycle design methodology which also includes the assessment of waste and emissions throughout the product life cycle. The scope of this study was limited by the availability of life cycle inventory data. The two metrics discussed here are energy payback time and electricity production efficiency.

The length of time required for a module to generate energy equal to the amount required to produce it from raw materials is called the energy payback time. Energy payback time is frequently used as a performance benchmark for renewable energy technologies, particularly PV. Fossil fuel and nuclear electricity generating plants are not evaluated by energy payback time because they effectively never pay back. Generating losses and the ongoing need for input energy (as fuel) conspire to ensure that fossil fuel plants cannot generate as much energy as they consume on a primary energy basis.

Electricity production efficiency is defined as the ratio of the total energy produced by a generating system over its lifetime to the sum of energy inputs required for the system's manufacture, operation and maintenance (including fuel), and end-of-life management. This ratio can be used to compare all types of renewable or fossil fuel based generating technologies.

Product Description

Over 26 different materials are used in the production of the UPM-880, 20 of which are actually incorporated into the finished product. Module production begins with a stainless steel substrate which is processed in the following steps: washing, back reflector deposition, amorphous silicon alloy deposition, transparent conductive oxide (TCO) deposition and scribing, short passivation, grid pattern printing, and cell cutting. All steps through TCO deposition are continuous processes.

The processed substrate is laminated inside encapsulation materials which provide environmental protection while allowing the maximum amount of light transmission to the active photovoltaic material. A sandwich of materials is assembled in the following order (from front to back): Tefzel (a Teflon based polymer), EVA, the processed substrate, an EVA/ polymer composite layer, and finally a galvanized steel backing plate (Figure 1). The steel backing plate is laminated to the material in the rest of the module by EVA, making its separation during disassembly nearly impossible. The steel backing plate and aluminum frame serve as structural components only, providing rigidity and mounting points for the module.

Methodology

Scope and Boundaries

Clearly defined boundaries that constrain data gathering and analysis are critically important in comparative product system studies. Results depend directly on boundary definition, which also determines whether the results may be compared with those of other studies. This study included data for raw material extraction and processing (for both product and process materials), transporting processed materials to manufacturing facilities, manufacturing, transporting modules to the use site, and module use. All data were determined on a per module basis. Not included were data on installation or balance-of-system (BOS) components. BOS components include mounting and support structures, tracking hardware (unless the array is fixed), wiring and terminals for interconnection of modules in the array, power inverters to convert the DC output of the PV module into utility-grade AC and to interface with the utility electricity grid, energy storage (if the array is not grid-connected), and labor for installation, operation and maintenance. Energy used for the manufacturing facility physical plant (lighting and space conditioning) and energy involved in packaging and packaging materials were also not included.

Data on the end-of-life phase were not collected since there is no infrastructure to deal specifically with PV modules. Energy required for or credited from reuse or recycling options was not considered in this study, except as discussed in the Design Implications section below.

Data Collection and Analysis

All energy data were considered on a per module basis and were converted to equivalent primary energy (EPE) to account for losses in conversion and generation. EPE makes all energy data functionally equivalent, allowing direct comparison. For example, electric energy from the grid cannot accurately be compared to natural gas energy without taking into account production efficiencies for both electricity generation and natural gas production. Ignoring the fuel required to produce electricity significantly distorts analysis. To avoid this, the United States average electricity generating efficiency ratio of 0.32 was used to convert electricity to EPE for this study.

Materials

Published data for extracting and processing raw materials (material production energy) were not available for all materials used to produce the UPM-880. Estimates were made for some materials based on discussions with industry sources. For materials manufactured by a small number of firms, energy data are usually considered proprietary. In these cases, we substituted data for similar materials or processes.

United Solar provided a bill of materials for the UPM-880 with all data items on a per module basis. United Solar provided data on supplier location and utilization

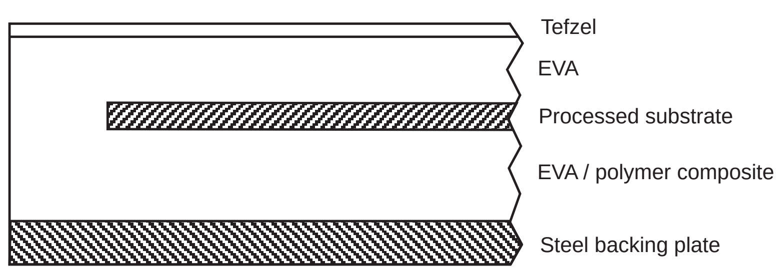

Figure 1. Laminated module, edge cross section.

efficiency for each material as well, allowing a calculation of the actual amount of material incorporated into a module and the amount of waste material per module.

The amount of energy expended to transport materials to United Solar facilities was calculated using distances determined from the location data, information on transportation energy requirements in units of energy per weight-distance (Btu per ton-mile), and material weight data from the bill of materials. It was assumed that a diesel tractor trailer was used for all overland transportation and an ocean freighter was used for all overseas transportation.

Manufacturing

There are three components of manufacturing energy: processing energy, energy in process materials, and energy for transportation to the use site. Manufacturing process energy data were provided, on a per module basis, by United Solar. Process materials were handled by the same method discussed above for product materials. In most cases, however, data on material production energy for process materials were not readily available from the literature. The amounts of process materials used per module were low relative to most product material inputs, so process materials were assumed to contribute a negligible amount to total module energy requirements.

Use

Use phase data for the energy payback time calculation consist only of insolation at the module location and the module's conversion efficiency (module size is a constant, equal to $0.372m^2$). Insolation data, as direct normal solar radiation in watt-hours per square meter per day, were taken from the National Renewable Energy Laboratory's (NREL) online computer database and converted to units of kilowatt-hours per square meter per year. Data were taken for three cities of interest: Detroit, Michigan, near United Solar and the University of Michigan; Boulder, Colorado, near NREL; and Phoenix, Arizona, a location generally considered to be an excellent site for PV use. These three cities approximately span the range of insolation available in the continental United States, from a low of around 1200 kWh/m^2/yr in Detroit to around 2000 kWh/m^2/yr in Boulder to a high of around 2500 kWh/m^2/yr in Phoenix.

Life Cycle Metrics

Material production energy includes energy for raw material extraction, processing, and transportation. These data were gathered in megajoules per kilogram. Because material production energy data vary over a wide range, low and high values were used in separate calculations, resulting in two values for each energy metric. The energy used to transport one module worth of materials to manufacturing facilities was then calculated and added to the material energy.

Energy data for each module manufacturing process step were gathered on a per module basis. This energy was all in the form of electricity and was converted to equivalent primary energy as discussed above. Transport to the use site was assumed to be by diesel tractor trailer.

Calculating energy generated by a module in use requires data for its stabilized conversion efficiency and area, along with average insolation where it will be installed. Once the energy generated by a module was known, all data necessary to calculate energy payback time and electricity production efficiency metrics were available.

Two other metrics, life cycle conversion efficiency and life cycle cost, are discussed in the full report from this project.

Energy Payback Time

Payback time in years was calculated by dividing the total amount of energy used to manufacture a module from raw materials, install and operate it over its lifetime, and deal with end of life disposition by the amount of energy a module generates in a year using Equation 1. The variables in this equation are defined as follows: E_{mat} = energy to extract, process, and transport raw materials to the manufacturing facility; E_{fab} = energy to fabricate a module from raw materials and transport it to the use site; E_{inst} = energy required for module installation (assumed to be 0); E_{elm} = energy required for any end-of-life management activity (assumed to be 0); E_{gen}/yr = energy generated by a module in one year; and $E_{o\&m}$/yr = energy used annually for operation and maintenance (assumed to be 0).

$$\text{Payback time} = \frac{E_{mat} + E_{fab} + E_{inst} + E_{elm}}{E_{gen}/yr - E_{o\&m}/yr} \quad (1)$$

Electricity Production Efficiency

Electricity production efficiency is calculated by summing the energy produced by a generating system over its lifetime (E_{gen} (lifetime)), and dividing it by the sum of the energy inputs required to manufacture (E_{mat} + E_{fab}), install, operate and maintain (E_{iom}, which = E_{inst} + (module lifetime) ($E_{o\&m}$/yr)), and dispose of or reclaim it at the end of its lifetime (E_{elm}), using Equation 2. E_{iom} and E_{elm} were assumed to be zero for this analysis; in actuality both are likely to be small numbers.

$$\text{Electricity production efficiency} = \frac{E_{gen}(\text{lifetime})}{E_{mat} + E_{fab} + E_{iom} + E_{elm}} \quad (2)$$

Electricity production efficiency was calculated for the same geographic locations as payback time. Two possible module lifetimes, 10 and 25 years, were chosen to demonstrate how this variable effects the metric (the UPM-880 is currently warrantied for 10 years).

Electricity production efficiency is presented as a ratio. A system that generates more energy than is required to produce it would have an electricity production efficiency greater than unity and could be considered to be a sustainable system.

Results and Discussion

Life Cycle Data

Energy data for production and transport of product materials are shown on a per module basis in Table 1, sorted from highest energy at the top to lowest at the bottom. When more than one material is required for a function, it is noted as "various" in the material column. Notice also that there are two totals at the bottom of the table, one for a standard module and one for a frameless module. This classification highlights the impact of the aluminum frame on the energy requirements for the UPM-880.

Energy required for manufacturing, converted to equivalent primary energy (EPE), is shown in Table 2. These data were gathered at United Solar by measuring electrical consumption of the respective machines for the amount of time necessary to process one module. The bulk of this energy is invested in processes that require elevated temperatures for a long period of time (encapsulation) or at greatly reduced pressure (all of the deposition steps).

Life Cycle Metrics

Energy Payback Time

Energy payback time results are presented in Table 3. Module production energy summarizes the material, transport, and manufacturing energy discussed in Tables 1 and 2 for both the standard and frameless cases. Table 3 presents energy payback times in years for various locations and module conversion efficiencies. Energy generated per year is calculated as the product of insolation, conversion

Table 1. Product Constituent Material Production Energy, in MJ

Function	Material	Low Case	High Case	Transport	% Module Mass
Frame	aluminum	196.0	566.1	7.8	38.0
Encapsulation	various	84.0	114.8	7.7	25.2
Substrate	stainless steel	58.7	73.0	3.9	11.4
Backing plate	steel	9.7	65.4	6.1	24.8
Deposition materials	various	7.7	7.7	0.1	*
Busbar	various	0.8	3.6	0.1	*
Back reflector	various	0.2	0.7	*	*
Grid	various	*	*	*	*
TCO	various	*	*	*	*
Standard, total material energy		357.1	831.4	25.5	
Frameless, total material energy		161.1	265.4	17.7	

* Negligible amount, <0.05.
Standard - low energy case uses lowest reported data and assumes 70% primary / 30% secondary frame material; high uses the highest available data and assumes frame is 100% primary aluminum .
Frameless - low and high cases reflect the range of values reported in the literature.
Source: Appendix B in [7].

Table 2. Manufacturing Equivalent Primary Energy (EPE)

Process Step	EPE (MJ)	% of Total
Encapsulation	56.2	28.0
Amorphous SI alloy deposition	37.9	18.8
TCO deposition	32.7	16.3
Back reflector deposition	30.3	15.0
Substrate wash	23.1	11.4
TCO etch	7.0	3.5
Short passivation	7.0	3.5
Grid pattern screen print	7.0	3.5
Testing and packaging	*	*
Total process energy	201.2	100.0

* Negligible amount.

efficiency, and module size. Energy payback time in years is calculated as module production energy (in kWh) divided by energy generated per year. The conversion efficiency of the UPM-880 is currently around 5%, but energy payback times were also calculated for a conversion efficiency of 8% to illustrate the effect of efficiency improvements on payback time. United Solar has produced a prototype module with a 10% conversion efficiency and is currently translating this technology into production.

Our methodology results in payback times higher than previously reported. Srinivas reports payback times for 5% efficient amorphous silicon modules produced in batch production facilities outside North America. His results ranged from 2.18 years for a frameless module to 2.6 years for a module framed with plastic and glass using an insolation level roughly equivalent to our Detroit case. Hagedorn estimates a payback time of 3.5 years for a 5% efficient module framed with plastic and glass produced in a proposed facility. Construction and material factors in both of these studies seem to indicate modules with shorter lifetimes than the UPM-880. Payback times calculated in this study should be compared with others published in the literature only if differences in the assumptions, data, and methodologies are carefully considered.

Electricity Production Efficiency

Electricity production efficiency results are presented in Table 4. Module production energy is identical to that noted in Table 3 and the same three locations are used, although the number under the location now represents the amount of electricity generated per year by a module at 5% conversion efficiency. Energy generated over a module's lifetime is the product of electricity generated per year and module lifetime. Electricity production efficiencies were calculated with Equation 2. Note that the high electricity production efficiency value for each case results from the low module production energy value, and vice versa, and also that values less than unity result from module production energy being greater than energy generated. For comparative purposes, the United States electricity grid has an average electricity production efficiency of 0.32.

Design Implications

Two components of the UPM-880 photovoltaic module offer major opportunities for improved design: the aluminum frame and EVA encapsulant.

Energy invested in the aluminum frame consists of material production energy and energy required to extrude and anodize the frame parts. Material production energy can be reduced by using a higher proportion of secondary (scrap) aluminum to primary material, or by using a different, less energy intensive material. A higher proportion of secondary material might cause a decrease in the frame's surface quality, but as long as its structural properties and lifetime remain unaffected, cosmetic imperfections should be tolerable. Use of the module in applications not requiring a frame obviates the material selection process for this component and also eliminates significant energy investments.

Reusing the aluminum frame is another method of reducing energy investment. In the current design, the frame is easily separable and can be used on another module with minimal processing besides transportation to the production facility. The impact of reusing the frame on energy metrics is dramatic, because the frame represents between 34 and 53 percent of the total module production energy (between 55 and 68 percent of total material production energy). Reusing the frame once halves its energy contribution and reusing it twice drops the energy cost to

Table 3. Energy Payback Time Calculations

Location and Insolation	Conver. Eff., %	Energy Gen/ Year (kWh)	Payback Times			
			Standard low	Standard high	Frame-less low	Frame-less high
Detroit, MI	5	22.3	7.5	13.4	5.0	6.3
1202 kWh/m²/yr	8	35.7	4.7	8.4	3.1	3.9
Boulder, CO	5	36.7	4.5	8.1	3.0	3.7
1974 kWh/m²/yr	8	58.7	2.8	5.1	1.8	2.3
Phoenix, AZ	5	46.1	3.5	6.4	2.3	2.9
2480 kWh/m²/yr	8	73.7	2.2	4.0	1.4	1.8

Standard: module production energy is: material production + manufacture + transport = 162.2 kWh (583.8 MJ) low case; = 293.9 kWh (1058.1 MJ) high case.

Frameless: module production calculated as above = 105.6 kWh (380.0 MJ) low case; = 134.5 kWh (484.3 MJ) high case.

Table 4. Electricity Production Efficiency Calculations*

Location and Generation	Module Life (yr)	Electricity Production Efficiencies			
		Standard low	Standard high	Frameless low	Frameless high
Detroit, MI	10	0.75	1.33	1.60	2.01
22.3 kWh/yr	25	1.87	3.33	3.99	5.03
Boulder, CO	10	1.24	2.23	2.68	3.39
36.7 kWh/yr	25	3.09	5.57	6.69	8.49
Phoenix, AZ	10	1.56	2.83	3.40	4.33
46.1 kWh/yr	25	3.91	7.07	8.51	10.83

*Assumes 5% module conversion efficiency, includes module transport energy: Detroit, 19.31 MJ; Boulder, 8.97 MJ; Phoenix, 3.01 MJ.

Standard: module production energy is: material production + manufacture + transport = 162.2 kWh (583.8 MJ) low case; = 293.9 kWh (1058.1 MJ) high case.

Frameless: module production calculated as above = 105.6 kWh (380.0 MJ) low case; = 134.5 kWh.

Table 5. Energy Metrics for Frame Reuse

Location and Metric	Number of Uses		
	1	2	3
Detroit, MI			
low energy payback time (yr)	7.5	6.8	6.8
high energy payback time (yr)	13.4	10.4	9.7
low electricity production efficiency	0.8	1.0	1.0
high electricity production efficiency	1.3	1.5	1.5
Boulder, CO			
low energy payback time (yr)	4.5	3.9	3.8
high energy payback time (yr)	8.1	6.1	5.5
low electricity production efficiency	1.2	1.7	1.8
high electricity production efficiency	2.2	2.6	2.7
Phoenix, AZ			
low energy payback time (yr)	3.5	3.0	2.8
high energy payback time (yr)	6.4	4.7	4.2
low electricity production efficiency	1.6	2.1	2.4
high electricity production efficiency	2.8	3.4	3.5

Assumes 5% module conversion efficiency; 10 year lifetime; includes transportation energy.

one third of the single-use value. Table 5 contains energy metrics calculated for various levels of frame reuse. These results assume a module with 5% conversion efficiency and include energy to transport the module back to the manufacturing facility for each frame reuse. Transportation energy was assumed to be the same for each use of the frame; distance from the module disassembly facility to United Solar was the same as the distance from the frame manufacturer to United Solar.

The useful life of a photovoltaic module is a primary design parameter, as indicated in Table 4. EVA encapsulant frequently determines a module's useful life as it either degrades in optical quality or moisture permeability. Formulations of EVA have evolved to the point where browning is no longer the concern it once was, but moisture permeability remains a main determinant of module lifetime. In addition, the current formulation of EVA requires relatively high energy for lamination. A formulation with a quicker cure time and/ or a lower cure temperature would reduce this process energy requirement.

The one other likely candidate for component reuse is the steel backing plate. In the current design, the backing plate is bonded to the module in the laminating press by a layer of EVA. If this layer of EVA could be deleted from the module, it would greatly facilitate disassembly and reuse or recycling of the backing plate while reducing material energy requirements. However, our calculations revealed that eliminating one layer of EVA and reusing the steel backing plate had only an incremental effect on values of the metrics, especially compared to the effect of reusing the frame. Even so, deleting a layer of EVA does facilitate manufacturing and end of life management and can reduce cost.

Conclusions

The application of the life cycle design framework offered many useful insights for enhancing the energy performance of photovoltaic technology. Life cycle energy analysis highlighted the energy contribution of individual life cycle stages, process steps, parts and components, and specific materials. The project team developed metrics to guide improvement of photovoltaic devices and to assess how sustainably these devices generate electricity. One of these metrics, electricity production efficiency, was discussed.

The metrics presented in Tables 3 and 4 demonstrate the relative significance of geographic locations with higher insolation and the aluminum frame. The best results are obtained with frameless applications in areas of high insolation, but either increased insolation or reduced module production energy are beneficial individually. For example, comparisons of standard and frameless modules indicate that the frame approximately doubles energy payback time and reduces electricity production efficiency by about half. The beneficial effect of increased module lifetime is also clearly demonstrated in Table 4.

Electricity production efficiency is a powerful metric for comparing photovoltaic technology with other systems for generating electricity because it puts all systems on an equivalent basis. To meet a definition of sustainability, an electricity production efficiency greater than unity is necessary: this enables the device to produce sufficient energy over its lifetime to at least reproduce itself (the current United States electricity grid efficiency is 0.32). All but one of the cases presented in Table 4 show efficiencies greater than unity; most are substantially higher.

The energy investment in a conventional power plant is generally neglected in life cycle energy analysis because it is assumed to be small relative to fuel energy inputs. This study shows that energy investment in the "power plant" for photovoltaic devices is substantial relative to their energy generating capacity and cannot be neglected. A comprehensive and fair comparison of PV and conventional generating systems would involve enumerating all terms in (2) (including any storage necessary for the PV system) and other environmental impacts such as air emissions and waste for both systems.

A simple but important conclusion from Table 5 is that increasing the number of module components that can be reused and the number of times they are reused significantly improves energy metrics. Reusing the aluminum frame will yield by far the greatest improvement in energy metrics; reusing other components affects the metrics only incrementally and may not be worth additional effort from an energy standpoint.

Energy payback time should be a critical factor in deciding whether or where to deploy photovoltaic modules, although cost is usually the sole criterion for these decisions. Accurate comparison between our values of this metric and other studies requires careful consideration of differences in methodology or data. This study is based on actual data from an operating production facility; many other studies use theoretical calculations which tend to improve metrics.

Photovoltaic technology development focuses primarily on increasing conversion efficiency and reducing cost. However, energy payback time and electricity production efficiency add valuable perspectives for guiding photovoltaic technology development. Energy payback time can be used for strategic planning and decision making when all assumptions are considered. Electricity production efficiency is a more comprehensive metric because it assesses the performance of a generating system over its entire lifetime. This metric should also be used by designers for product material selection and process design. In addition, PV manufacturers, utility companies, policymakers, and the public should use this metric to make accurate comparisons between generating technologies.

The properties of amorphous silicon thin film technology seems to make it a natural fit in building-integrated PV applications such as glazing and sheathing materials and standing seam metal roofing.

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The complete report, entitled "Life Cycle Design of Amorphous Silicon Photovoltaic Modules," (Order No. PB97-193106; Cost: $21.50, subject to change) will be available only from
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