Broader Perspectives

Application of Life-cycle Energy Analysis to Photovoltaic Module Design

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This paper highlights results from a collaborative life-cycle design project between the University of Michigan, the US Environment Protection Agency and United Solar Systems Corporation. Energy analysis is a critical planning and design tool for photovoltaic (PV) modules. A set of model equations for evaluating the life-cycle energy performance of PV systems and other electricity-generating systems are presented. The total PV life-cycle, encompassing material production, manufacturing and assembly, use and end-of-life management, was investigated.

Three metrics — energy payback time, electricity production efficiency and life-cycle conversion efficiency — were defined for PV modules with and without balance-of-system (BOS) components. These metrics were evaluated for a United Solar UPM-880 amorphous silicon PV module based on average insolation in Detroit, Boulder and Phoenix. Based on these metrics, a minimum condition for assessing the sustainability of electricity-generating systems was proposed and discussed. The life-cycle energy analysis indicated that the aluminum frame is responsible for a significant fraction of the energy invested in the UPM-880 module. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

Photovoltaic (PV) systems, as well as other renewable energy systems, must be both energy efficient and cost competitive with centralized fossil fuel power-generating stations if they are to emerge as a prominent mode of electricity production. Life-cycle energy analysis (LCEA) is a critical tool in guiding the development of PV technologies and their applications in the direction of energy efficiency and cost competitiveness. Life-cycle energy analysis results for a PV or other electricity-generating system depend directly on the boundaries of the system under investigation.

Conversion efficiency, defined as the percentage of solar insolation converted to electricity, has been one of the primary performance metrics for evaluating alternative PV technologies. Unfortunately, conversion efficiency only addresses the operational energy efficiency of a PV device. A more comprehensive energy analysis includes the total life-cycle of the PV system, encompassing raw material production,

manufacturing, use, maintenance and end-of-life management. Several investigators have studied the life-cycle energy performance of PV devices, [1–8] but LCEA has not yet been used as a standard tool by the industry.

The life-cycle design (LCD) framework was developed to guide the environmental improvement of a product system while also optimizing performance, cost and legal requirements.[9] The objective of LCD is to minimize aggregate life-cycle environmental burdens and impact, including energy consumption, solid waste generation and human and ecological health effects related to air and waterborne pollutant emissions. The scope of this investigation was limited to an analysis of electricity-generating system energy performance.

Manufacturing costs of PV devices have restricted the widespread deployment of this technology. While economic factors may determine the current viability of PV technologies, LCEA is useful to distinguish alternative technologies in terms of their energy performance. For example, a systematic comparison of crystalline and amorphous PV technologies can be made to contrast the higher conversion efficiency and manufacturing energy of crystalline technologies with the lower conversion efficiency and manufacturing energy of amorphous technology. Comparisons of the results from LCEA studies conducted on PV systems has so far been hindered by the lack of a well-established methodology or commonly used metrics.

The objective of this study was to define LCEA metrics for guiding the design of PV modules. This paper presents a detailed description of the LCEA methodology and the application of this methodology in a case study. The case study investigated a United Solar Systems Corporation tandem junction amorphous silicon PV module. Although a comprehensive analysis was precluded by some unavailable data, by explicitly stating assumptions and boundary conditions the results of this LCEA provided valuable insight and allowed recommendations to be made for improving the design of PV modules.

METHODOLOGY

Life-cycle assessment (LCA) guidelines and methodologies offer an excellent foundation for conducting an LCEA.[10,11] Life-cycle assessment characterizes and assesses the total environmental burdens associated with a product system, from raw materials acquisition through to end-of-life management. The life-cycle inventory (LCI) component of LCA quantifies the material and energy inputs and outputs related to a product life-cycle. Consequently, LCEA is a component of LCI analysis. Both LCI and LCEA begin with a clear definition of the scope and boundaries of the system under study. A model for comprehensive LCEA will be presented here and the simplified LCEA model used in the United Solar case will be described.

System definition

The system boundaries should be defined with careful consideration of the product function or service. If the scope of the analysis is to evaluate the total energy requirements for electricity generation and delivery to the point of use, then the product system would also include the additional components needed to connect the PV module to electricity transmission lines ('the grid') and from the grid to a building's junction box. Electricity generated by a PV module is direct current and must be converted to alternating current by an inverter before it can be transmitted on the grid, although PV modules with integrated inverters are now becoming available. Balance-of-system (BOS) components include the supporting structure and hardware for mounting PV modules into an array. The model equations presented in this paper account for all components of an energy-generating system, including BOS components. The United Solar case study focused on the life-cycle of the PV module exclusively.

Well-defined system boundaries are necessary in order to develop meaningful metrics that can be used to compare different PV systems to each other as well as to other types of electricity-generating systems, such as coal-fired power plants. The product life-cycle is a logical system to use to determine boundaries for energy analysis because it traces the total set of material and energy flows associated with PV electricity generation.
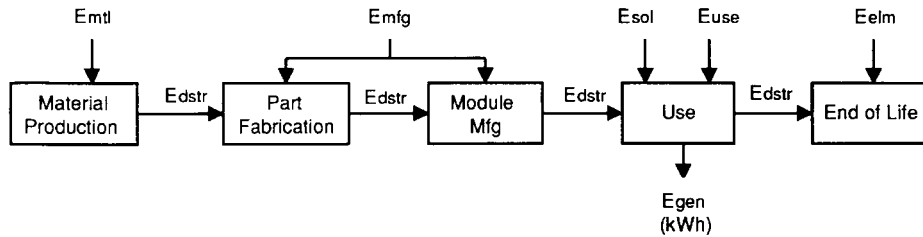
Figure 1. Life-cycle stages of a PV system (E_{mtl} = material production energy, E_{mfg} = manufacturing energy, E_{sol} = insolation, E_{use} = use energy requirements, E_{elm} = end of life energy, E_{dstr} = distribution energy, E_{gen} = energy generated)

The product life-cycle, illustrated in Figure 1, encompasses material production, manufacturing, use and service and end-of-life management as shown above. The stages can be divided further into substages. Material production, for example, can be divided into raw material acquisition (mining, drilling for petroleum, harvesting) and material processing (smelting, polymerization), while manufacturing can be split into part and component fabrication processes and system assembly.

Each stage of the life-cycle can also be organized into product, process and distribution components.[9] The product component in the case of a PV system consists of materials that are incorporated into the PV module, such as stainless steel and ethylene–vinyl acetate (EVA), and follows these materials from raw material acquisition through to end-of-life management. The process component includes the transformation and assembly steps involving the product materials. Specific process components of the manufacturing stage are the process materials, manufacturing facilities and equipment. Process materials are distinguished from product materials in that process materials are not incorporated into the final product. The distribution component includes the packaging and transportation modes that are required to transfer product materials between stages of the life-cycle. Stainless-steel substrate, for example, is transported by rail or truck from the mill to the PV manufacturer.

UPM-880 product system

The United Solar UPM-800 is an amorphous silicon commercial power-generation module. It is a tandem junction module that is manufactured using thin-film technology. The stabilized efficiency of the UPM-800 is 5%, although United Solar has recently begun manufacturing triple junction amorphous silicon modules with stabilized efficiencies nearing 10%.

The PV module consists of active PV layers that are deposited on a 5-mil thick stainless-steel substrate, encapsulated in a polymer matrix for protection from environmental degradation, reinforced with a steel backing plate and installed in an extruded aluminum frame for mounting and structural integrity. This module has a rated output of 22 W, is $119.4 \times 34.3 \times 3.8$ cm ($47.1'' \times 13.5'' \times 1.5''$) in size and weighs 3.6 kg (8.3 lb). The case study considered both the standard UPM-880 module and a frameless version, identical to the standard module but without the aluminum frame. The primary product materials used to manufacture the UPM-880 PV module are listed in Table I, although some trace materials are excluded.

Life-cycle stages of the UPM-880 system

Material production

Specific material production energies for the product materials were compiled from the literature and industry sources, in units of MJ kg^{-1}. The quality of these data varies widely due to differences in collection methodology, age of the data and the use of specific plants versus industry average sources. Some data were estimated by industry contacts while other data were obtained from sources following more rigorous life-cycle methodology. Material production energy data values represent the primary energy consumption for material acquisition and processing activities, including energy for the total fuel

Table I. UPM-880 product materials

Function	Material	Per cent of module mass
Frame	Anodized extruded aluminum	38.0
Encapsulation	EVA, Tefzel, other[a]	25.2
Backing plate	Galvanized mild steel	24.8
Substrate	Stainless steel (type 430)	11.4
Busbar	Copper, solder (Pb–Sn)	[b]
Current collection grid	Silver, other[a]	[b]
Deposition materials	Silane, phosphine, other[a]	[b]
Back reflector	Aluminum, zinc oxide	[b]
Transparent Conductive Oxide (TOC)	Indium, oxygen	[b]

[a]'Other' means materials that are used in very small amounts or are proprietary.
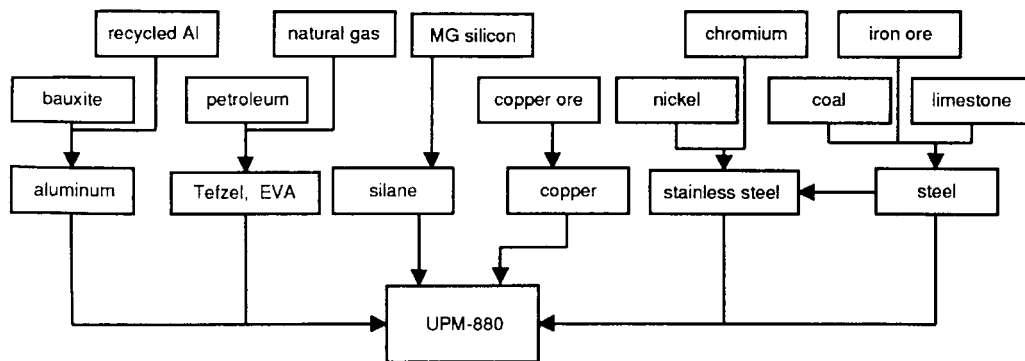[b]Less than 0.05%.

Figure 2. Major UPM-880 product material constituents and their raw material sources

cycle of process fuels (precombustion and combustion energy) and, in the case of plastic resins, the energy embodied in the feedstock material. The energy of plastic resin feedstock materials is determined from their higher heating values. For example, the feedstock energy for polyvinyl chloride (PVC) produced by the suspension process is 30.5 MJ kg^{-1} and the total material production energy is 64.9 MJ kg^{-1}.[12] Figure 2 traces the major product material constituents of the UPM-880 module back to their raw material sources.

The actual energy consumption of a specific material production process will vary depending on the mix of primary sources (coal, natural gas, etc.) used to produce the electricity consumed. In the USA an average of 11.3 MJ of primary energy (precombustion + combustion) in the form of coal, natural gas and other fuels is required to generated 3.6 MJ (1 kWh) of electricity.[13] Alternatively, the LCEA could be based on a PV array providing the electrical energy for material production, a scenario that would likely yield a substantially different result.

Manufacturing
The UPM-880 module manufacturing process steps are shown in Figure 3. Measurements of electricity use were taken from each process machine on a 'per module' basis to determine manufacturing process energy requirements. Electrical energy was converted to primary (thermal) energy using the average conversion efficiency for the US grid. Data for plant overhead energy and the life-cycle energy associated with process materials were not available in this study, although process materials were not expected to contribute much to manufacturing energy burden.

An alternative means of evaluating manufacturing process energy is to divide the total plant energy requirements by the number of modules produced to find the energy burden on a 'per module' basis.
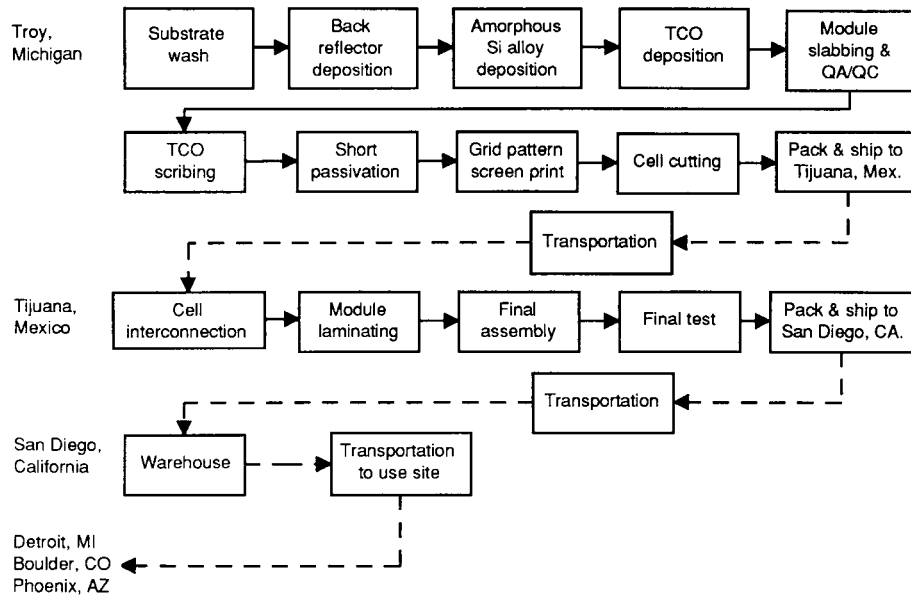
Figure 3. UPM-880 manufacturing process steps. Solid lines denote in-plant material movement, dashed lines denote movement between plants

Energy burdens associated with administrative and research and development activities could also be allocated to the PV system.

Use
The use phase of the PV life-cycle includes initial installation of the module into an array, electricity generation and any necessary maintenance and repair activities. The electrical energy generated by a PV module is a function of the location-dependent insolation (kWh m^{-2}) and the size and conversion efficiency of the module. To illustrate the effect of location on energy performance, three use locations were analyzed in this case study: Detroit, Michigan; Boulder, Colorado; and Phoenix, Arizona. A variety of module lifetimes were also considered because this is a key parameter in determining the total electricity generated by the PV system.

End-of-life management
The end-of-life management options for PV modules are difficult to predict because of the module's relatively long useful life (20–30 years) and uncertainty in the development of new separation and material recycling technologies. Manual disassembly of components and materials is usually not economically viable. In light of current infrastructure conditions, two scenarios appear most likely: retired modules may be disposed of in landfills; large quantities of modules may be shredded in hammer mills, just as automobiles and white goods are currently processed at the end of their useful lives. The energy requirements for shredding are relatively low, of the order of 97 J kg^{-1}.[14] End-of-life management strategies are discussed in more detail elsewhere by the authors.[8]

Life-cycle energy metrics
Three metrics for evaluating the energy performance of electricity-generating systems were defined: energy payback time, electricity production efficiency and lifetime module conversion efficiency. These metrics are computed from a detailed energy balance of the generating system, accounting for energy inputs (consumption) and outputs (generation).

Energy inputs

Energy inputs for each stage of the life-cycle are stated in Equations (1)–(7). The distribution energy for the system is summarized in Equation (5). The total material production energy is calculated from

$$E_{\mathrm{mtl}} = \sum_i (E_{\mathrm{mtl\ pd},i} \cdot m_{\mathrm{mfg},i}) \qquad (1)$$

where $E_{\mathrm{mtl\ pd},i}$ is the specific energy for material production (in MJ kg^{-1}) for material i and $m_{\mathrm{mfg},i}$ is the total mass of product material i required for manufacturing the system, in this case the PV module and BOS components. The difference between $m_{\mathrm{mfg},i}$ and the mass of material actually incorporated in the module is due to waste and scrap associated with module manufacturing.

The energy investment in the manufacturing stage includes process fuels consumed, the material production energy of process materials and the energy invested in and consumed by manufacturing equipment and facilities. Human labor, research and development activities and administrative functions that support manufacturing can also be included in the analysis, however, these activities have been generally excluded in previous LCI studies. The manufacturing energy, E_{mfg}, is given by

$$E_{\mathrm{mfg}} = E_{\mathrm{fuels}} + E_{\mathrm{mtl\ pc}} + E_{\mathrm{fac}} + E_{\mathrm{eqp}} + E_{\mathrm{lbr}} + E_{\mathrm{R\&D}} + E_{\mathrm{adm}} \qquad (2)$$

where E_{fuels} is the total energy for process fuels consumed in process equipment and operations, $E_{\mathrm{mtl\ pc}}$ is the material production energy of process materials including the energy content of material resources, E_{fac} is the energy invested in the construction, operation, maintenance and retirement of the manufacturing buildings, E_{eqp} is the energy required to produce and maintain manufacturing equipment, E_{lbr} is the human energy requirement including commuting, $E_{\mathrm{R\&D}}$ is the energy investment in R&D activities that can be allocated to the system under study and E_{adm} is the energy allocated from administrative services. Process material life-cycles are nested within the manufacturing state of the system life-cycle so that material production energy for process materials is reported as part of the total manufacturing energy. The energy invested in the production of the process equipment and facilities is often neglected because it is generally small relative to the process fuel energy and the energy used for space conditioning and lighting over the lifetime of the facility.

The use phase energy inputs are given by

$$E_{\mathrm{use}} = E_{\mathrm{inst}} + E_{\mathrm{op}} + E_{\mathrm{mnt\&rp}} \qquad (3)$$

where E_{inst} is the installation energy requirement, E_{op} is the energy required for operation of the system and $E_{\mathrm{mnt\&rp}}$ is the energy required for routine maintenance and repair over the life of the system. E_{op} is zero for many PV installations but some energy is consumed during operation in the case of arrays that have tracking systems. Operation and maintenance energy requirements can be combined and expressed as an average rate over the life of the module, $\tilde{E}_{\mathrm{om}}$, changing Equation (3) to

$$E_{\mathrm{use}} = E_{\mathrm{inst}} + \tilde{E}_{\mathrm{om}} \cdot t \qquad (4)$$

The end-of-life management energy requirements, E_{elm}, depend on whether the module is recycled, remanufactured, processed for energy recovery or disposed of in a landfill. Energy is required even in the case of landfill disposal to 'bury' the waste and operate leachate collection systems.

Equation (5) details energy requirements for the distribution of product materials between the ith and ith + 1 life-cycle stage (material production, manufacturing, use, end-of-life), including transportation and packaging

$$E_{\mathrm{dstr}} = \sum_i (E_{\mathrm{trans}_{i \to i+1}} + E_{\mathrm{pkg}_{i \to i+1}}) \qquad (5)$$

where E_{trans} is the energy for transporting product materials between the ith and ith $+ 1$ life-cycle stage and E_{pkg} is the energy investment in packaging associated with the ith to ith $+ 1$ transport linkage. The transportation energy component E_{trans} is generally approximated by the fuel energy consumed. Distribution of product materials between facilities within the manufacturing stage is accounted for as part of the manufacturing energy. Distribution of process materials to the manufacturing facility is considered part of the process material production energy.

The total life-cycle energy inputs are given by

$$E_{\text{in}} = E_{\text{mtl}} + E_{\text{mfg}} + E_{\text{use}} + E_{\text{elm}} \tag{6}$$

Substituting Equations (1), (2), (4) and (5) into Equation (6) yields the following generalized equation for total life-cycle energy inputs

$$E_{\text{in}} = \sum_i (E_{\text{mtl pd},i} \cdot m_{\text{mfg},i}) + E_{\text{fuels}} + E_{\text{mtl pc}} + E_{\text{fac}} + E_{\text{eqp}} + E_{\text{lbr}} + E_{\text{R\&D}} + E_{\text{adm}}$$
$$+ E_{\text{inst}} + \tilde{E}_{\text{om}} \cdot t + E_{\text{elm}} + \sum_i (E_{\text{trans}_{i \to i+1}} + E_{\text{pkg}_{i \to i+1}}) \tag{7}$$

Energy outputs

The sum of the electricity generated by the PV module, E_{gen}, and energy lost in BOS components, $E_{\text{BOS loss}}$, is the energy output of the system, calculated in Equation (8). Electrical energy delivered by the system to the system boundary is denoted as E_{out}

$$E_{\text{out}} = E_{\text{gen}} - E_{\text{BOS loss}} \tag{8}$$

If the scope of analysis includes the delivery of electricity to the grid, then inverter and transmission losses make up the bulk of BOS losses

$$E_{\text{BOS loss}} = E_{\text{inverter loss}} + E_{\text{trans loss}} \tag{9}$$

The energy generated by the PV module over the time period t is given by

$$E_{\text{gen}} = \theta \cdot A \cdot F_{\text{sol}} \cdot t \tag{10}$$

for a PV module with conversion efficiency $\theta(\%)$ and area $A(\text{m}^2)$ that receives an average solar flux of F_{sol} (kW m^{-2}) for time t.

Metrics

Energy payback time. The time required to recover the total energy investment made in a PV system can be determined by calculating the energy payback time. Energy payback time without BOS components is given by

$$t_{\text{epb}} = E_{\text{in}}/P_{\text{gen}} \tag{11}$$

Substituting Equation (6) for E_{in} and then solving for t_{epb} explicitly gives

$$t_{\text{epb}} = (E_{\text{mtl}} + E_{\text{mfg}} + E_{\text{inst}} + E_{\text{elm}} + E_{\text{dstr}})/(P_{\text{gen}} - \tilde{E}_{\text{om}}) \tag{12}$$

This definition differs from the conventional definition for energy payback time because E_{elm} is accounted for as part of the total energy investment. A portion of this energy is readily determined, while the energy requirement for maintenance of a landfill, to operate a leachate collection system for example, is indeterminate. If it were necessary to monitor and treat leachate indefinitely, this energy requirement would eventually exceed the energy generated by a module. This fact illustrates the importance of sustainable end-of-life management practices.

With BOS components included, t_{epb} becomes

$$t_{epb'} = \frac{(E_{mtl} + E_{mfg} + E_{inst} + E_{elm} + E_{dstr})}{(P_{gen} - P_{trans\ loss} - P_{inverter\ loss} - \tilde{E}_{om})} \tag{13}$$

Electricity production efficiency. The overall energy performance of the PV module system can be evaluated by comparing the total energy input with the total energy output. The ratio of these two quantities is referred to here as the electricity production efficiency. The electricity production efficiency $\eta(t)$ is defined as

$$\eta(t) = E_{out}/E_{in} \tag{14}$$

where $\eta(t)$ is a function of time because both E_{out} and E_{in} are time dependent. Schaefer and Hagedorn defined a total yield factor similar to Equation (14) to measure the energy performance of electricity-generating systems.[3] Their metric accounted for material production, manufacturing and use, but not for end-of-life energy requirements.

Without BOS components, the expression for $\eta(t)$ is

$$\eta(t) = (\theta \cdot A \cdot F_{sol} \cdot t)/(E_{mtl} + E_{mfg} + E_{inst} + \tilde{E}_{om} \cdot t + E_{elm} + E_{dstr}) \tag{15}$$

Including BOS components, the expression for $\eta(t)$ becomes

$$\eta(t)' = \frac{(\theta \cdot A \cdot F_{sol} \cdot t - t \cdot P_{trans\ loss} - t \cdot P_{inverter\ loss})}{E_{mtl} + E_{mfg} + E_{inst} + \tilde{E}_{om} \cdot t + E_{elm} + E_{dstr}} \tag{16}$$

Life-cycle conversion efficiency. Measurement of the net energy productivity of the PV system with respect to the total solar input, E_{sol}, is another useful means of assessing the energy performance of the system. This quantity is called life-cycle conversion efficiency $\phi(t)$, and is defined as

$$\phi(t) = (E_{out} - E_{in})/E_{sol} \tag{17}$$

Without accounting for BOS components, the life-cycle conversion efficiency ϕ and the conventionally defined module conversion efficiency θ are related as

$$\phi = \theta(1 - 1/\eta) \tag{18}$$

In the limit, as module life approaches infinity, ϕ approaches θ.

RESULTS AND DISCUSSION

Energy analysis

The total energy investment, including material production, distribution and manufacturing, is 597.9 MJ for the United Solar UPM-880 standard module. The energy investment is 366.6 MJ for the frameless module. These results do not account for manufacturing facility overhead and process material energy, as specified in the methodology. Specific energy requirements for material production, distribution and manufacturing are detailed below.

Material energy

Material production energy for one PV module's components are indicated in Table II. When more than one material is required for a function, it is noted as 'various' in the material column. This convention was

Table II. Product material energy use (MJ per module)

Function	Material	Material production energy			Transport energy
		Best available	Low	High	
Frame	Aluminum	197.5	15.6	527.3	7.8
Encapsulation	Various	86.8	84.0	114.8	7.7
Substrate	Stainless steel	10.5	58.7	73.0	3.8
Backing plate	Steel	40.4	9.7	65.4	6.1
Deposition materials	Various	7.7	7.7	7.7	0.1
Busbar	Various	2.1	0.8	3.6	0.1
Back reflector	Various	0.3	0.2	0.7	[a]
Grid	Various	[a]	[a]	[a]	[a]
Transparent Conductive Oxide (TOC)	Various	[a]	[a]	[a]	[a]
Standard, total material energy[b]		345.3	357.1	831.4	25.5
Frameless, total material energy[c]		147.7	161.1	265.4	17.7

Source: see Appendix B in Ref. 8; energy data represent the most current published data source that follows life-cycle inventory methodology.
[a]Less than 0.05.
[b]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.
[c]Frameless: low and high cases reflect the range of values reported in the literature.

Table III. Manufacturing equivalent primary energy (EPE)

Process step	EPE (MJ)	Per cent of total
Encapsulation	56.2	24.8
Amorphous Si alloy deposition	37.9	16.7
Transparent Conductive Oxide (TOC) deposition	32.7	14.4
Back reflector deposition	30.3	13.3
Aluminum extruding process	26.0	11.4
Substrate wash	23.1	10.2
Transparent Conductive Oxide (TOC) etch	7.0	3.1
Short passivation	7.0	3.1
Grid pattern screen print	7.0	3.1
Testing and packaging	[a]	[a]
Standard, total manufacturing energy	227.1	100.0
Frameless, total manufacturing energy	201.2	

[a]Negligible.

used to simplify data presentation or preserve confidentiality. A comparison of the total standard module energy and the frameless module energy in Table II shows the significance of the aluminum frame in the UPM-880 module energy use. The frame is an anodized extruded aluminum channel assumed to consist of 70% primary and 30% secondary aluminum. Primary aluminum is produced from bauxite, while secondary aluminum is produced from recycled material and has a much lower energy requirement. Data for hardware, including the junction box assembly and some screws, were not included in the analysis.

Manufacturing energy
The energy required for the manufacturing process steps, converted to equivalent primary energy (EPE), is shown in Table III. This energy is of the same order of magnitude as the material energy in Table II. The bulk of this energy is invested in processes that require elevated temperatures for a long period of time

Table IV. Energy payback time calculations

Location insolation & transport energy	Conversion efficiency (%)	Energy generated per year (kWh)	Payback time	
			Standard[a]	Frameless[b]
Detroit, MI	5	22.3	7.4	4.6
1202 kWh m^{-2} year^{-1}	6	26.8	6.2	3.8
19.31 MJ	7	31.3	5.3	3.3
	8	35.7	4.7	2.9
	9	40.2	4.1	2.5
Boulder, CO	5	36.7	4.5	2.8
1974 kWh m^{-2} year^{-1}	6	44.0	3.8	2.3
8.97 MJ	7	51.4	3.2	2.0
	8	58.7	2.8	1.7
	9	66.0	2.5	1.5
Phoenix, AZ	5	46.1	3.6	2.2
2480 kWh m^{-2} year^{-1}	6	55.3	3.0	1.8
3.01 MJ	7	64.5	2.6	1.6
	8	73.7	2.3	1.4
	9	82.9	2.0	1.2

[a]Standard module production energy $= E_{mtl} + E_{mfg} + E_{dstr} = 166.1$ kWh (597.9 MJ).
[b]Frameless module production energy, calculated as for standard module production energy, is 101.8 kWh (366.6 MJ).

(encapsulation) or at greatly reduced pressure (all of the deposition steps). Efforts to reduce process energy expenditure would logically focus on the encapsulation step first, perhaps searching for materials that have equivalent performance but that use either a lower cure temperature or a quicker cure time.

Life-cycle metrics

Energy payback time

Energy payback times (in years) for various locations and module conversion efficiencies are presented in Table IV. Energy generated per year is calculated according to Equation (10) as the product of average yearly insolation, conversion efficiency and module size. Data for transport of the module to the use site are shown in Table IV and are included in module production energy. The conversion efficiency of the UPM-880 is currently around 5%, but energy payback times were calculated for a range of conversion efficiencies from 5% to 9% in order 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. The inclusion of facility overhead energy, energy investment and losses associated with BOS components and end-of-life management energy would increase the payback time.

The methodology presented here results in payback times that are higher than previously reported. Comparisons with other studies, however, should carefully consider differences in assumptions, data sources and methodology. Hagedorn estimates a payback time of 3.5 years for a 5% efficient module framed with plastic and glass produced in a facility proposed for construction.[2] Srinivas reported payback times for 5% efficient, amorphous silicon modules produced in batch production facilities outside North America.[4] These single-junction modules use one layer of UV-cured encapsulant material. Srinivas' data for manufacturing energy is roughly equivalent to that for the UPM-880, but his material production energy estimates for a framed module with a backglass are comparable to the lowest energy estimates for a frameless UPM-880. The discrepancy in material production energy is mostly due to the use of different materials, and not to different estimates for the same materials. Insolation levels in Srinivas' study were roughly equivalent to the Detroit case in this study. Srinivas' payback times ranged from 2.18 years for a

Table V. Electricity production efficiency calculations[a]

Location & generation	Module life (years)	Energy generated per year year (kWh)	Electricity production efficiencies	
			Standard[b]	Frameless[c]
Detroit, MI	10	223.3	1.34	2.19
22.3 kWh year^{-1}	15	335.0	2.02	3.29
	20	446.6	2.69	4.39
	25	558.3	3.36	5.48
Boulder, CO	10	366.8	2.21	3.60
36.7 kWh year^{-1}	15	550.2	3.31	5.40
	20	733.6	4.42	7.20
	25	917.0	5.52	9.00
Phoenix, AZ	10	460.8	2.77	4.52
46.1 kWh year^{-1}	15	691.2	4.16	6.79
	20	921.6	5.55	9.05
	25	1152.0	6.94	11.31

[a]Assumes 5% module conversion efficiency and includes module transport energy (noted in Table IV).
[b]Standard module $E_{mtl} + E_{mfg} + E_{dstr} = 166.1$ kWh (597.9 MJ).
[c]Frameless module $E_{mtl} + E_{mfg} + E_{dstr} = 101.8$ kWh (366.6 MJ).

frameless module on a glass superstrate to 2.6 years for the same module with a backglass, framed in plastic. All these construction and material factors seem to indicate a module with a shorter lifetime than the UPM-880. Because the lifetime of this design is unknown, it is not possible to realistically compare its electricity production efficiency with the UPM-880. The UPM-880 is currently warrantied for 10 years.

Electricity production efficiency
Electricity production efficiency results calculated using Equation (15) are presented in Table V. Photovoltaic electricity generation is based on a module with 5% conversion efficiency and a module life ranging from 10 to 25 years. For comparative purposes, the US electricity grid has an average production efficiency of 0.32.[13] Fossil-fueled generating facilities have an ongoing requirement for primary fuel energy inputs, only a fraction of which emerges from the facility as electrical energy. All of the electricity production efficiency values in Table V are much higher than the grid. Many of these cases result in efficiencies substantially greater than unity: they generate far more electrical energy over their lifetime than they consume as total primary energy inputs, a result that is not possible for fossil-fueled generating facilities. Inclusion of the BOS components in this analysis would decrease the electricity production efficiency.

Life-cycle conversion efficiency
Table VI contains data for calculating life-cycle conversion efficiency and the results of these calculations, expressed as a percentage. In Detroit, for example, an average of 4466.7 kWh of energy is incident on one module in 10 years, and 223.3 kWh of electricity is generated by the module during that time. These two data, along with the module production energy, were used in Equation (17) to calculate the life-cycle conversion efficiency. The upper bound for life-cycle conversion efficiency is the conversion efficiency of the module, which is 5% in this case.

CONCLUSIONS

Life-cycle energy analysis is a fundamental tool for evaluating and guiding the development of PV technology. Comprehensive modeling of a PV system is essential for assessing its full potential as a

Table VI. Life-cycle conversion efficiency calculations[a]

Location & insolation	Module life (years)	Energy generated per year year (kWh)	Incident energy (kWh)	Life-cycle conversion efficiencies (%)	
				Standard[b]	Frameless[c]
Detroit, MI	10	223.3	4466.7	1.28	2.72
1202 kWh m^{-2} year^{-1}	15	335.0	6700.1	2.52	3.48
	20	446.7	8933.5	3.14	3.86
	25	558.3	11166.9	3.51	4.09
Boulder, CO	10	366.8	7335.6	2.74	3.61
1974 kWh m^{-2} year^{-1}	15	550.2	11003.3	3.49	4.07
	20	733.6	14671.1	3.87	4.31
	25	917.0	18338.9	4.09	4.44
Phoenix, AZ	10	460.8	9215.9	3.20	3.89
2480 kWh m^{-2} year^{-1}	15	691.2	13823.9	3.80	4.26
	20	921.6	18431.8	4.10	4.45
	25	1152.0	23039.8	4.28	4.56

[a]Assumes 5% module conversion efficiency and includes module transport energy (noted in Table IV).
[b]Standard module case $E_{mtl} + E_{mfg} + E_{dstr} = 166.1$ kWh (597.9 MJ).
[c]Frameless module case $E_{mtl} + E_{mfg} + E_{dstr} = 101.8$ kWh (366.6 MJ).

sustainable energy technology. The model equations presented here provide a means for evaluating the life-cycle energy performance of a PV system. The organization of the product system into product, process and distribution components facilitates tracking of material and energy flows for a PV system. The boundaries of the system under investigation depend on the specific scope and objectives of each analysis. A comparison of two alternative PV modules, for example, may exclude BOS components whereas a comparison of a PV technology with a conventional technology should consider the inverter in order that both systems have equivalent AC output.

The three metrics that were defined — energy payback time, electricity production efficiency and life-cycle conversion efficiency — each serve a different purpose in evaluating the energy performance of a particular energy-generating system. Energy payback time is useful for considering short-term energy investment. This metric assesses the time period necessary for a PV project to become 'profitable' from an energy perspective. Equation (12) presents a modification of the conventional definition for energy payback time by accounting for the estimated energy necessary for end-of-life management. The refined energy payback metric incorporates energy 'losses' associated with end-of-life management. Electricity production efficiency should be the metric of choice when comparing competing electricity-generating systems. The maximum electricity production efficiency of a PV system is a function of its useful life, so this metric can evaluate the lifetime energy performance of an electricity-generating system. Energy payback time, in contrast, does not address ultimate efficiency of the system being measured. Life-cycle conversion efficiency is a useful metric for directly comparing alternative solar technologies because it measures how efficiently a system converts sunlight into net energy in the form of electricity. Life-cycle conversion efficiency allows another meaningful comparison between various PV devices, such as crystalline and amorphous silicon modules.

It was demonstrated in this investigation of the United Solar UPM-880 module that even a partial LCEA can provide valuable data for design decision-making. In this study, LCEA highlighted the energy contribution of individual life-cycle stages, process steps, parts and components and specific materials. In particular, the significance of the aluminum frame in the energy performance of the module was quantified. This finding demonstrates the importance of LCEA in enlightening material selection decisions for PV module design. Comparisons of standard and frameless modules indicate that the frame almost doubles energy payback time and reduces electricity production efficiency by about one-half. The spatial boundaries of this PV system were also investigated by considering the energy for transporting product materials and by analyzing the insolation rates for three geographic locations. Analysis of spatial

boundaries is important in siting new PV manufacturing facilities and selecting appropriate PV systems for each specific application.

Criteria for determining the sustainability of electricity-generating systems must address a wide range of issues such as non-renewable resource use, impacts on ecosystems and equity issues related to allocation and distribution of resources. One necessary condition for sustainability of a PV electricity-generating system is defined by the constraint $t'_{epb} < t_{ul}$, where t_{ul} is the useful life of the system. This condition is equivalent to an electricity production efficiency of greater than unity at $t = t_{ul}$, an indication that the device is able to produce sufficient energy over its lifetime to at least reproduce itself. For comparison, the current US grid has an electricity production efficiency of about 0.32. Although an electricity production efficiency greater than unity is a necessary condition for sustainability, it should be noted that this is not a sufficient condition. In addition to primary energy consumption, other life-cycle environment burdens and impacts, such as consumption of non-renewable resources, waste generation, product and process material toxicity and emission levels, should be assessed to guide the sustainable development of PV technology. Human and environmental health effects and safety risks associated with PV manufacturing have been investigated by Moskowitz *et al.*, Huber and Kolb and Hill and Baumann.[15–18] In addition, these factors should be assessed within the context of projected demand for PV technology.

A more refined model would enable the evaluation of metrics based on cases where energy input requirements are met by PV electricity-generating systems or other renewable sources. Such a model would require material production energy, manufacturing energy and other energy inputs to be disaggregated into specific renewable and non-renewable categories. Substitution of electricity for other energy carriers, such as natural gas and fuel oil, could also be considered. This scenario may result in a situation where the substitution leads to more primary energy consumption than the conventional fuels case. For example, an electrically heated boiler is less efficient on a primary energy basis than a natural gas boiler, likely resulting in higher total energy consumption.

Multiobjective analysis of environmental, performance, cost and regulatory/policy issues over the life-cycle of a PV system will ultimately provide the most complete basis for design, planning and implementation. This full set of information and data offers a more powerful means for promoting PV technology as an effective source of sustainable energy. Recognizing this goal, LCEA remains one of the most fundamental components of a multiobjective analysis of an electricity-generating system.

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