PV payback

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Critics of solar energy have been known to claim that it takes more energy to produce photovoltaic (PV) modules than the modules will produce in their lifetime. We've conducted a detailed and scientific empirical study to look into this question. We found that the skeptics' assertions are false. PVs recoup their production energy in two to four years, and go on to produce clean, renewable energy for twenty to thirty years or more!

Our study examined energy costs for two types of Siemens PV modules—single-crystalline silicon (SC-Si) and thin film copper indium diselenide (CIS). Crystalline silicon modules achieve an energy break-even in a little over three years. The energy payback time for thin film copper indium diselenide modules in full production is just under two years. Over their lifetime, these solar panels generate nine to seventeen times the energy required to produce them.

Real Costs

Our research was based on direct investigation of the energy requirements and net energy production of manufactured photovoltaic modules. Other studies employ production models with assumed process recipes, equipment sets, materials yields, and module efficiencies. None of them have used actual utility bills and accounting records.

By contrast, our study didn't have to make any assumptions about yields. We just took energy requirements right off the utility bills and the materials requirements right off the bill of materials. This allowed us to include indirect materials as well, which as far as we can tell have never been included before. These include things like argon, nitrogen, etchants, cleaners, and so forth, all the way down to the cardboard box the modules get shipped in.

Energy Payback Time

Energy payback time is one standard of measurement adopted by several analysts to look at the energy sustainability of various technologies. It is defined as the time necessary for a photovoltaic panel to generate the amount of energy used to produce it.

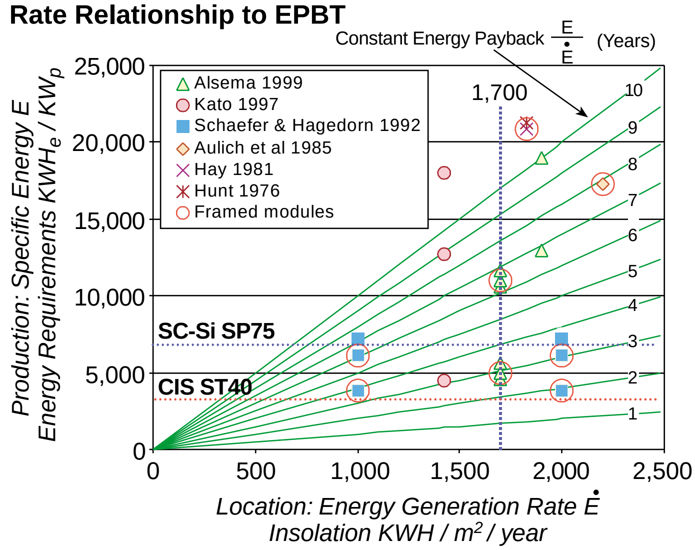
Two parameters determine the energy payback time for a PV module—how it is produced and how it is used. The energy needed to produce a product (specific energy) includes both the energy consumed directly by the manufacturer during processing, and the energy embodied in the incoming raw materials.

How a PV module is used is primarily a question of location and module efficiencey. Location determines the solar insolation, and combined with efficiency, determines the electrical output of the PV panel. But installation details are important too (fixed tilt or tracking, grid-connected or stand-alone, etc.), as are balance of system requirements such as mounting structure, inverter, and batteries. The module energy payback time is computed from this formula:

$$\textbf{EPBT} = \frac{\textbf{Specific Energy}}{\textbf{Energy Generation Rate}} = \frac{E}{\dot{E}}$$

Figure 1 shows this relationship. The vertical axis shows specific energy and the horizontal axis shows the energy generation rate (with some representative estimates found in the literature indicated). Energy payback time can be expressed as the ratio of the total energy required to manufacture a photovoltaic module to the rate that the module converts the solar energy flowing from the sun at the installation site to electricity.

Figure 1: Specific Energy and Energy Generation Rate Relationship to EPBT



Japan:1,424; Northern Europe: 1,000; U.S. Avg: 1,825; Boulder: 1,974; Phoenix 2,480; Detroit: 1,202

Lines of constant energy payback are indicated in Figure 1 by the diagonal lines. A sunnier location (a move to the right), or lower energy requirements or higher module efficiency (a move downward), reduces the payback time.

Previous Research

Several reported results for a variety of technologies, system types, and installation locations and styles are indicated in Figure 1. The analyses range from solar cells to full systems. Circled datapoints correspond to framed modules, the emphasis in this analysis. Results from our research are indicated by horizontal dotted lines.

Published results from several excellent studies of PV energy requirements vary considerably. Some of this is due to different energy findings, and some to different insolation assumptions. These variations are made a little more clear by plotting them together on this chart.

Some analyses assume the use of frameless modules. These have lower energy requirements than the more standard aluminum frames (indicated by circled datapoints), because aluminum requires a lot of energy to produce. Both SSI products studied include aluminum frames.

One of the key contributors to the energy payback field is Eric Alsema, whose work is recent, comprehensive, and clear on methodology and data. Alsema's module payback estimates for current SC-Si technology range from a low of 2.9 to a high of 6.5 years (at 1,700 KWH/m^2/year).

Methodology & Assumptions

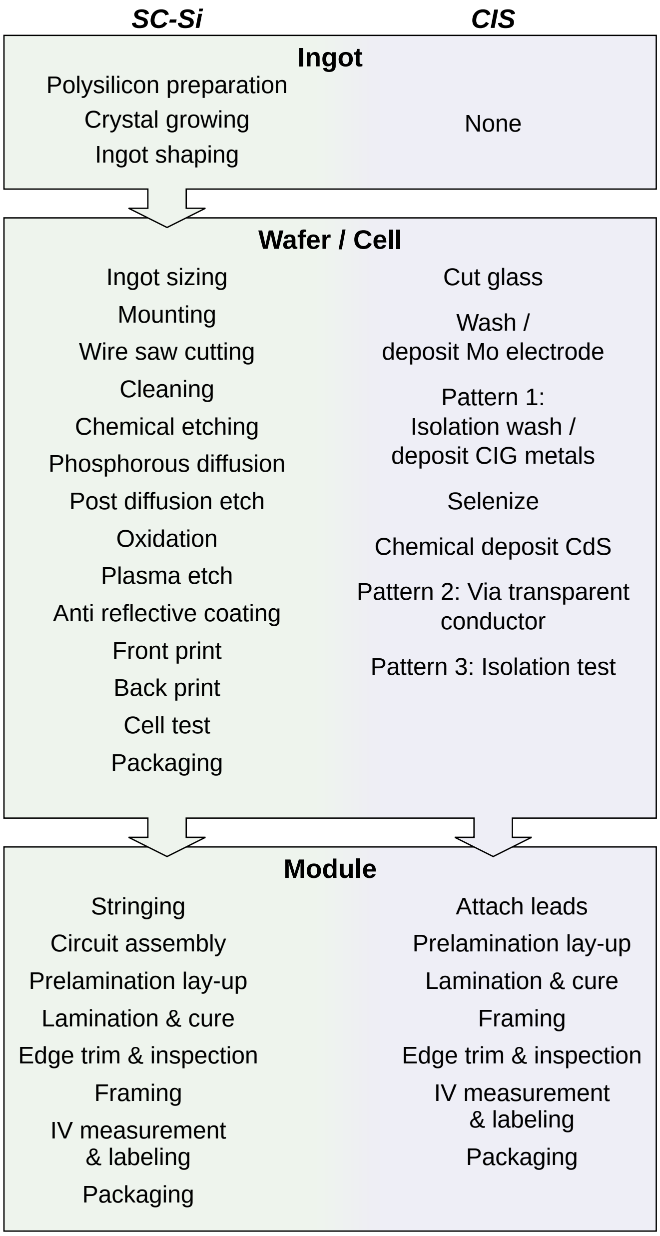
This investigation deviates from and complements earlier research. Ours was primarily an empirical endeavor. We used measured energy use, actual utility bills, production data, and complete bills of materials to determine process energy and fully yielded (total input) raw materials requirements.

The materials include direct materials that are part of the finished product, such as silicon, glass, and aluminum. They also include indirect materials that are used in the process but do not end up in the product, such as solvents, argon, or cutting wire. Many of these indirect materials turn out to be significant. We combined the best available estimate for embodied energy content for each material with records of materials use. This gave us the total embodied and process energy requirements for each major step of the process.

Energy Content

There are three basic steps in producing a crystalline silicon PV module:

Figure 2: Manufacturing Process Sequence



- Growth of the silicon crystalline ingot.
- Slicing the ingot into wafers and processing into solar cells.
- Interconnecting the cells into circuits, laminating to glass, and completing the assembly of a framed and packaged module.

CIS modules require fewer steps. Their complete circuits are fabricated directly as a coating on a glass substrate. The process steps for both technologies are illustrated in Figure 2.

The energy content of raw materials and direct process energy used at the Siemens Solar facility are included in the analysis. Excluded from the analysis are energy embodied in the equipment and the facility itself, energy needed to transport goods to and from the facility, energy used by employees in commuting to work, and decommissioning and disposal or other end-of-life energy requirements. These are all very minor factors in the total energy picture of PVs.

The energy requirements for incoming silicon includes the energy used to produce metallurgical grade silicon and refine it to polysilicon. This is consistent with most other published PV energy studies.

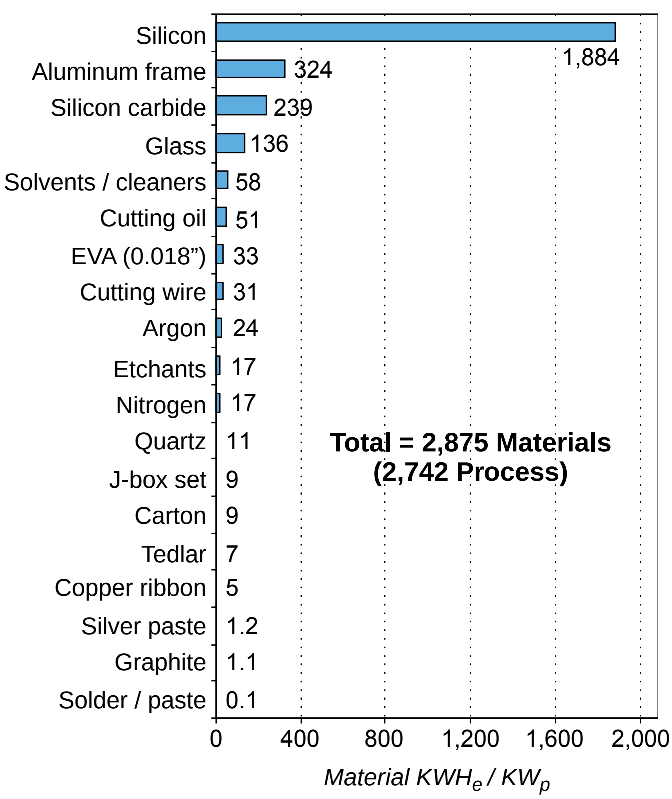
All energy forms are converted to their electrical energy equivalents, expressed in kilowatt-hours electric (KWH_e). For natural gas and thermal energy, a conversion efficiency of 35 percent was assumed. Energy and materials requirements were tallied on a per-module basis for two representative products: the 75 watt SP75 (SC-Si) and the 38 watt ST40 (CIS).

Conversions to area (m^2) and module rated peak power (KW_p) basis are easily computed from module area and power rating from the product datasheets. The resulting specific energy requirements are expressed in KWH_e/KW_p.

This choice of units is convenient and intuitive because it represents something physical—the number of full-sun hours required for energy payback. To convert to actual days or years, just divide by the average solar insolation, usually expressed in KWH/m^2/year. Then correct for any performance changes from the rating due to system losses or module operating temperature (which was not included in this analysis because it is site-specific).

The U.S. average solar insolation is 1,825 KWH/m^2/year (five full-sun hours per day). A common mid-range number used in the literature is 1,700 KWH/m^2/year (4.7 full-sun hours per day), which is more typical of Europe.

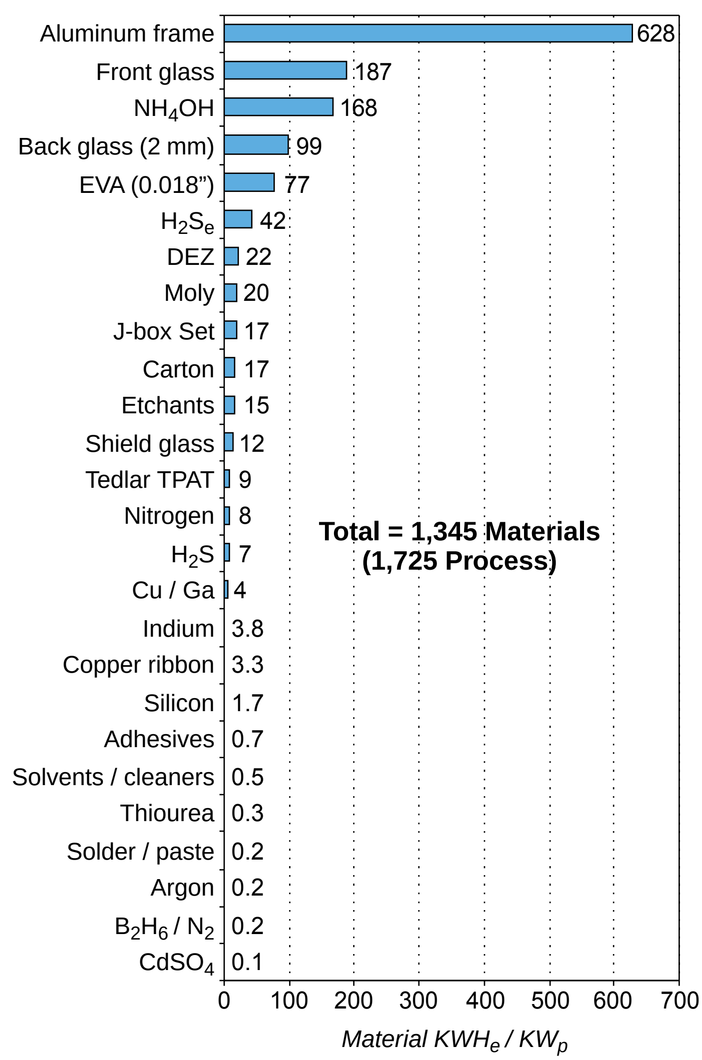
Figure 3a: Materials Energy Content: SP75



Energy Use

The process energy was derived from utility bills and monthly production data. From October 1998 through March 1999, Siemens Solar Industries (SSI) consumed a total of 20 million KWH of electricity and about 90,000 therms of natural gas. During this time, SSI produced 3 kilometers of silicon ingot (about 111 tons of incoming

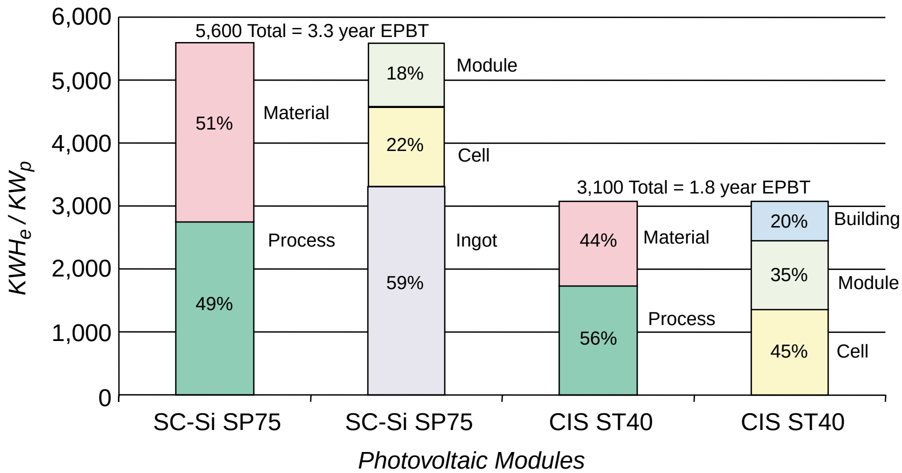
Figure 3b: Materials Energy Content: ST40



silicon), 9 MW of solar cells (about 5 million cells), and 6 MW of modules at its Vancouver and Camarillo sites.

CIS is in the early stages of production scale-up, and therefore energy requirements were estimated using empirical data applied at full production rates. Measured energy consumption along with equipment ratings from nameplates, manufacturers' specifications, or connected circuit breaker ratings were used in conjunction with the equipment duty cycle for all pieces of equipment to derive the process energy use estimates.

Figure 4: Energy Requirements Breakdown



EPBT computed at 1,700 KWH / m[2] / year.

Total raw materials requirements and the resulting embodied energy contribution are based on production bills of materials and the amount of energy needed to create the incoming materials (derived from existing literature and materials manufacturers). Materials are shown in decreasing order of their embodied energy contribution in Figure 3. The total materials energy contribution for production modules is not far from the process energy requirement: 2,857 KWH_e/KW_p for SC-Si (about 85% due to direct materials) and 1,345 for CIS (97% direct).

The gross energy requirement is the sum of the process and embodied materials energy. These are summarized by category and process step in Figure 4 and Table 1. Payback time is computed as the ratio of the gross energy requirement to the solar insolation at the installation site. A typical value of 1,700 KWH/m[2]/year yields 3.3 years for silicon and 1.8 years for production CIS.

System losses due to wires, inverters, cell operating temperatures, and so forth can be used as a direct multiplier for the specific location. For a typical generation rate adjustment of about 0.80, the payback time jumps to about 4.1, and 2.2 years, respectively. The final computations are similar to the most recent and thorough published results, obtained using very different methods.

Energy Requirements Breakdown by Energy Source Category & Process Step

SC-Si

	KWH_e / KW_p				*EPBT* (years)*
	Ingot	*Cell*	*Module*	*Total*	
Process	1,380	850	510	2,740	1.6
Indirect material	35	415	-	450	0.3
Direct material	1,885	-	525	2,410	1.4
Total	3,300	1,265	1,035	5,600	3.3
EPBT (yrs)*	1.9	0.7	0.6	3.3	

CIS ST40

	KWH_e / KW_p				*EPBT* (years)*
	Cell	*Module*	*Other*	*Total*	
Process	960	145	620	1,725	1.0
Indirect material	35	-	-	35	0.0
Direct material	370	940	-	1,310	0.8
Total	1,365	1,085	620	3,070	1.8
EPBT (yrs)*	0.8	0.6	0.4	1.8	

* Energy payback time, calculated at 1,700 KWH / m[2] / year insolation.
Some totals do not add up due to rounding.

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The Real Renewable Payback
Our study and analysis indicates that payback times for today's SC-Si and CIS photovoltaic technologies are substantially less than their expected lifetimes. With a module lifetime of thirty years, an SP75 will produce nine times the energy used in its production and an ST40 seventeen times.

The effects of the other components of a photovoltaic system can be significant compared to the module payoff, most notably in systems requiring batteries. You have to take into account all components of a PV system. The whole system needs to be a net gain to be truly sustainable.

Access

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For further reading:

Alsema, E.A., *Energy Requirements of Thin-Film Solar Modules, A Review,* Renewable and Sustainable Energy Reviews, v2, 387-415, 1998.

Fthenakis, V., K. Zweibel, and P. Moskowitz, ed., *Photovoltaics and the Environment* 1998, BNL/NREL, July 23–24, 1998, Keystone, CO, BNL-52557, Feb. 1999

K. Knapp and T. Jester, *An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules,* Solar 2000: ASES Annual Conference, June 16–21, 2000, Madison, Wisconsin, American Solar Energy Society
www.ecotopia.com/apollo2/knapp/PVEPBTPaper.pdf

K. Knapp, T. Jester, and G. Mihalik, *Energy Balances for Photovoltaic Modules: Status and Prospects,* 28th IEEE Photovoltaics Specialists Conference, September 17–22, 2000, Anchorage, Alaska
www.solarpv.com/paybackstudy.pdf

Additional references are available from the authors.