An Empirical Perspective on the Energy Payback Time for Photovoltaic Modules

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ABSTRACT

Energy payback time is the energy analog to financial payback, defined as the time necessary for a photovoltaic panel to generate the energy equivalent to that used to produce it. This research contributes to the growing literature on net benefits of renewable energy systems by conducting an empirical investigation of as-manufactured photovoltaic modules, evaluating both established and emerging products.

Crystalline silicon modules achieve an energy break-even in a little over three years. At the current R&D pilot production rate (8% of capacity) the energy payback time for thin film copper indium diselenide modules is between nine and ten years, and 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. Energy content findings for the major materials and process steps are presented, and important implications for current research efforts and future prospects are discussed.

1. INTRODUCTION

A valid question raised in scrutinizing technologies regarded as environmentally friendly is whether they are truly “sustainable” or not. For alternative energy systems in particular, this query translates in one key sense to whether they represent a net gain – do they generate more energy than was used to create them in the first place and if so to what extent? The net gain concept extends as well to local pollutants (e.g. SO_x, NO_x, particulates) or global greenhouse gas emissions (e.g. CO_2). A truly sustainable technology should represent a net gain should the human race wish to continue its standard of living, historically correlated with energy use. This question is considered important enough to renewable energy analysts to recently convene a workshop devoted to this topic (20), and present several papers on the subject at a recent conference addressing several environmental issues for photovoltaics (9).

Energy payback time (“EPBT”) is one metric adopted by several analysts in characterizing the energy sustainability of various technologies. It is the energy analog to financial payback, defined as the time necessary for a photovoltaic panel to generate the energy equivalent to that used to produce it. This investigation focuses on the energy payback time for both single-crystalline silicon ("sc-Si") and thin film copper indium diselenide ("CIS") photovoltaic modules as manufactured by Siemens Solar Industries ("SSI").

Two parameters determine the EPBT: (1) how it is produced and (2) how it is implemented. 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. Implementation refers primarily to location, which determines the solar insolation and therefore the electrical output of the PV panel, but could extend to installation details (fixed tilt or tracking, grid-connected or stand-alone, etc.) or balance of system ("BOS") requirements such as mounting structure, inverter, or batteries. Figure 1 shows lines of constant payback times with the vertical axis being specific energy and the horizontal axis is energy generation rate (with some representative estimates found in the literature indicated). The energy payback time is computed from

(1) EPBT= (Specific Energy)/(Energy Generation Rate)

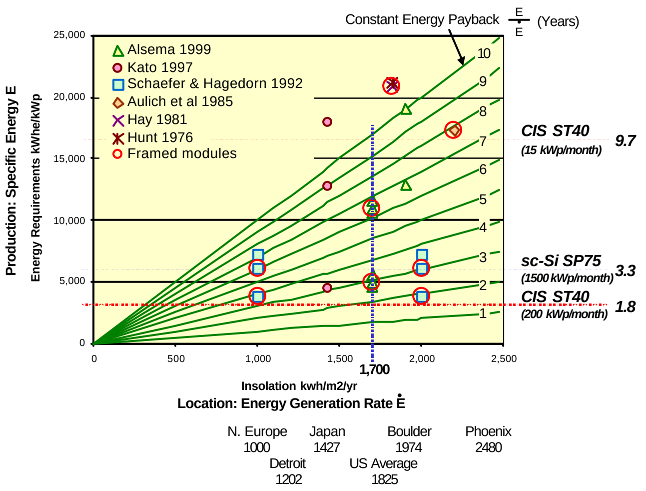

Fig. 1: Specific Energy and Energy Generation Rate relationship to EPBT. Circled data are framed modules.

2. PREVIOUS RESEARCH

Indicated in Figure 1 above are several reported results for a variety of technologies, system types, and installation locations and styles. The analyses range from solar cells to full systems. Results from this report are indicated, and circled datapoints correspond to framed modules, the emphasis in this analysis.

The earliest to publish in this arena are Hunt (13), who arrived at 11.6 years for just the cell (2” diameter with yields around 18%), and Hay (12) who calculated 11.4 years, and pushed early into investigating other techniques such as ribbon silicon, a-Si and CdS:Cu_2S, all of which looked more favorable at the time (7, 1.3 and 0.8 years respectively). Excellent literature reviews of previous work can be found in Alsema (3), Keolian & Lewis (17) and von Meier (24). The National Renewable Energy Laboratory ("NREL") has assembled a concise summary of recent work in this area in a two-page document released under the heading “PV FAQ’s”. One of the key contributors to the energy payback field is Eric Alsema (2-5), 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 1700 kWh/m^2/yr). Alsema expands the discussion for possible future paths for “solar silicon” production, comparing it to thin film estimates for energy payback. Thin films appear to be judged similar in nature to future advanced polycrystalline silicon modules (not single-crystal though) because the lower efficiency balances the lower energy input. Palz & Zibetta (21) appear to include process energy only, thereby arriving at an understandably favorable payback time of less than two years for polycrystalline or multicrystalline ("mc-Si") modules. Keoleian & Lewis (17) focus on amorphous silicon ("a-Si") thin films, providing some good data and a comprehensive approach, but appear to overstate the 2-7 year payback time (they combine primary energy input and electrical energy output), and seem to have an arithmetic error (“best available” total is less than the “low” estimate). Aulich (6) provides useful data for raw materials use and alternate silicon production and wafering processes as well as potential module designs, yielding energy payback of 8 years for the then-current technology, with estimates for all-plastic modules with various silicon sheet casting methods, all below 2 years.

Hynes (14) provides the only published energy analysis of CIS thin films, wherein he modeled five different deposition processes, with energy payback times ranging from 3 to 48 months, with process yield as the most important driver. Much relevant data was discovered in the life cycle analysis literature, particularly buildings literature that has been addressing embodied energy and energy payback for efficiency investment for many years (1, 8, 10) and the industrial energy analysis literature (7, 11).

3. METHODOLOGY AND ASSUMPTIONS

This investigation deviates from and complements these very excellent analyses. Modeling of the production process has been kept to a minimum. This is instead a chiefly empirical endeavor, utilizing measured energy use, actual utility bills, production data and complete bill of materials to determine process energy and fully yielded raw materials requirements. The materials include both direct materials that are part f the finished product such as silicon, glass and aluminum, and 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 which turn out to be significant. The best estimate for embodied energy content for these materials are combined with materials use to determine the total embodied and process energy requirements for each major step of the process as illustrated in Figure 2. Silicon has three major steps: (a) growth of the silicon crystalline ingot, (b) slicing the ingot into wafers and processing into solar cells, and (c) interconnecting the cells into circuits/ laminating to glass and completing the assembly of a complete framed and packaged module ready for shipment. CIS modules require fewer steps, fabricated directly as a coating on a glass substrate as a complete circuit.

Each process step is a mini-factory, inheriting the embodied energy in all of the previous processing steps and energy embodied in new raw materials, and adding the energy needed to process these inputs to make a product ready for the next step in the sequence. The energy content of raw materials and direct process energy used at the facility are included in the analysis, in line with the "second-order" analysis terminology of Bousted & Hancock (7). Energy used in heating, cooling and lighting, operating computers or even copiers and soda machines is included. Excluded from the analysis are (a) energy embodied in the equipment and the facility itself, (b) energy needed to transport goods to and from the facility, (c) energy used by employees in commuting to work, and (d) decommissioning and disposal or other end-of life energy requirements.

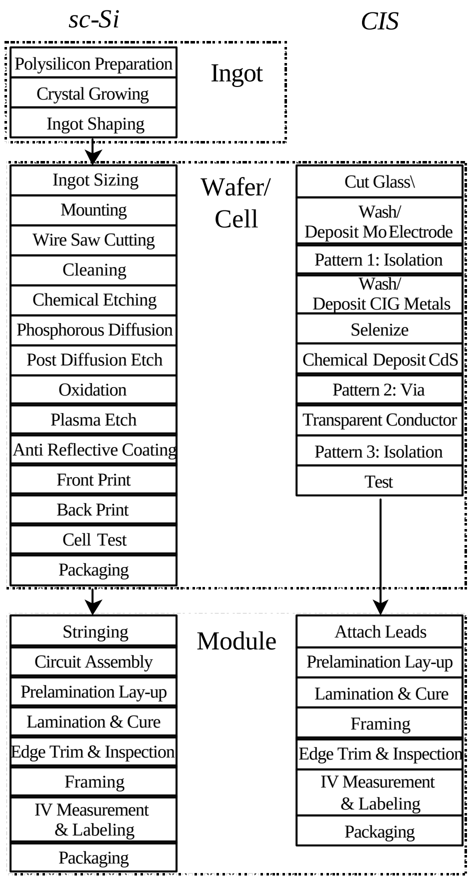

Fig. 2: Siemens Solar manufacturing process sequences.

Silicon used for photovoltaics is nearly universally scrap silicon from the semiconductor industry. There is a general consensus among renewables advocates that the energy used in the first melt/crystal growth cycle of silicon intended for in the semiconductor industry pessimistically overstates the true energy requirements for a photovoltaic product, although there is some debate as to the degree to which this energy should be included. This analysis uses the metallurgical grade ("MG- Si") production energy and the polysilicon purification energy as the measure of incoming raw polysilicon embodied energy, consistent with most of the recent work. Alternative methods of producing PV-grade silicon are discussed elsewhere (2, 16, 22). The scale of operations is beginning to approach the minimum size for silicon manufacturers to consider such an investment seriously.

All energy forms are converted to their electrical energy equivalents, expressed in kilowatt-hours electric (kWh_e). Where energy inputs are already electric, this is easy, which is the case for the bulk (>95%) of processing energy. For natural gas, a conversion efficiency of 35% was assumed. Energy and materials requirements were performed on a per-module basis for two representative products: the SP75 (sc-Si) and the 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, one need only divide by the average solar insolation, usually expressed in kWh/m^2/yr, and correct for any performance changes from the rating due to system losses or module operating temperature, which was not included in this analysis as it is site-specific. The U.S. average solar insolation is 1825 kWh/m^2/yr (5 full sun hours per day). A common mid-range number used in the literature is 1700 kWh/m^2/yr (4.7 full sun hours per day).

4. RESULTS

The process energy was derived from actual utility bills and monthly production data. From October 1998 through March 1999, SSI consumed a total of 20 million kWh of electricity and about 90,000 therms. During this time SSI produced 3.2 kilometers of silicon ingot (about 111 tons of incoming silicon), 8.6 MW of solar cells (about 5 million cells) and 5.5 MW of modules (the rest are produced at other facilities around the globe: India, Brazil, Portugal, & Munich). The crystal growing process is carried out in SSI's Vancouver, Washington facility. Consumption of the dominant energy component for each facility and process step is presented in Figure 3 as a function of production.

Crystal growth is electricity-intensive, and the variable process energy overwhelms any fixed overhead of operating the plant. The end result is an average total processing energy requirement of about 117 kWh/kg of incoming silicon. This translates to a yielded process energy requirement of 1,382 kWh_e/kW_p of finished product. In the Camarillo facility, about 90% of the electricity and 10% of

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[†] One full sun is defined as solar insolation at 1kW/m^2, thus one hour at one full sun under standard conditions will generate 1kWhe/kWp.

the natural gas is used for cell processing (diffusion tubes and firing furnaces), the balance used for module processing (lamination and curing). A large portion is used for maintaining the plant environment and various other overhead energy needs (indicated by a fairly high intercept at zero production level). This overhead energy is allocated proportionally to the process energy requirements. The result is a total yielded process energy requirement of 850 kWh_e/kW_p for the cell process and 510 kWh_e/kW_p for the module process. The total process energy requirement is 2,742 kWh_e/kW_p.

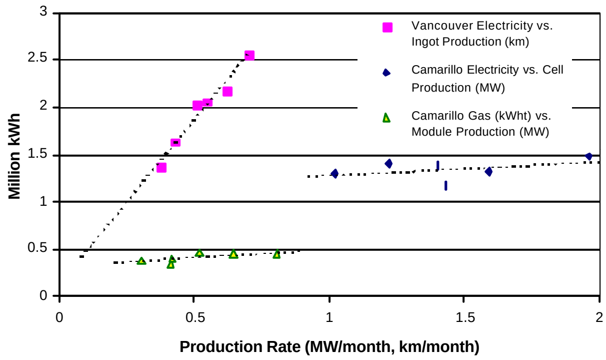

Fig. 3: Energy consumption vs. sc-Si production rates.

CIS is in the early stages of production scale-up, and therefore energy requirements were estimated using both empirical data and modeled performance. 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. At the current pre-pilot production rate of only 15 kW_p per month, the estimated process energy use is 7,554 kWh_e/day, which translates to a specific energy value of 15,107 kWh_e/kW_p ("Other" relates to building energy use). This high value stems from the fact that the plant is severely underutilized, operating at approximately 8% of its capacity, so that most of the energy is used for running idle equipment and building systems. To check the estimate, energy use was measured for one week by Southern California Edison for the power panels serving the CIS research and production facility, during which energy use averaged 7,549 kWh/day.

At a production rate of 200 kW_p/month, the process energy estimate fall significantly to 1,725 kWh_e/kW_p, because there is only a small increase in building energy use (about 30%) and equipment is more highly utilized (a balanced line based on the existing equipment set would require process energy of 1,100 kWh_e/kW_p). The remainder of the discussion focuses on the high production-rate values.
Yielded materials requirements and the resulting embodied energy contribution are based on production bills of materials and energy content coefficients cited in the literature. Materials are shown in decreasing order of their embodied energy contribution in Figure 4. The total materials energy contribution for production modules are not far from the process energy requirement: 2857 kWh_e/kW_p for sc-Si (about 85% due to direct materials) and 1,345 for CIS, (97% direct).

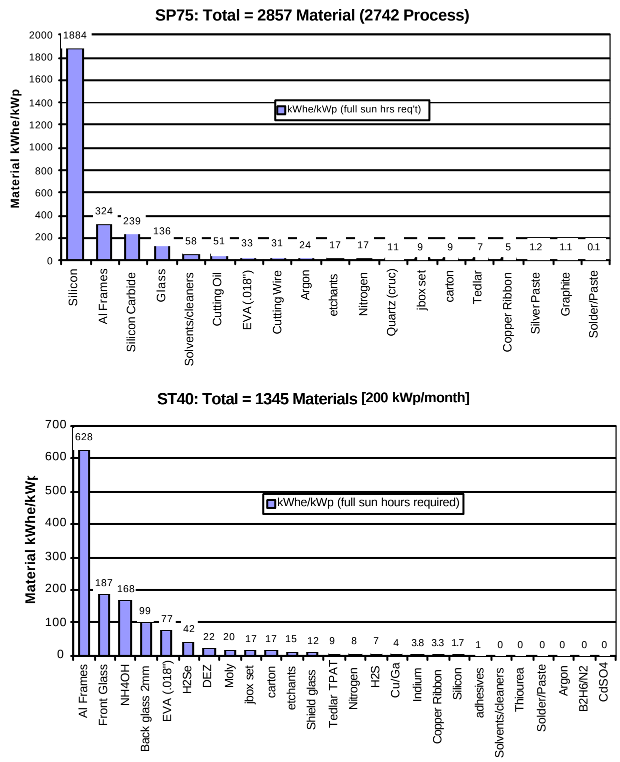

Fig. 4: Pareto charts of materials by energy content.

The gross energy requirement is the sum of the process and embodied materials energy, summarized by category and process step in Table 1. Payback time can now be computed as the ratio of the gross energy requirement to the solar insolation at the installation site. A typical value of 1700 kWh/m^2/yr yields 3.3 years for silicon, 9.7 years for pre-pilot CIS, 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 adjustment of about .80, the payback time jumps to about 4.1, 12.1, and 2.2 years, respectively. The final computations are very similar to Alsema's "low" silicon results (5) and Hynes' mid-range CIS results (14), even including all indirect materials.

These results indicate that payback times for today's sc-Si and CIS photovoltaic technology are substantially less than their expected lifetimes. With a module lifetime of 30 years, an SP75 will produce nine times the energy used in its production and an ST40 seventeen times, a measure referred to as the “energy return factor” in some of the relevant literature (18, 19).

TABLE 1: ENERGY REQUIREMENTS BREAKDOWN
Note: EPBT computed at 1700 kWh/m^2/year

sc-Si Production 2 MW_p/month					
kWh_e/kW_p	Ingot	Cell	Module	Total	EPBT
Process	1,382	850	510	2,742	1.6
Indirect Mat'l	36	412	-	448	0.3
Direct Mat'l	1,884	1	523	2,408	1.4
Total	3,302	1,264	1,032	5,598	3.3
EPBT (years)	1.9	.7	.6	3.3	

CIS Pre-Pilot 15 kW_p/month					
kWh_e/kW_p	Cell	Module	Other	Total	EPBT
Process	6,949	1,966	6,192	15,107	8.9
Indirect Mat'l	111	-	-	111	0.1
Direct Mat'l	369	940	-	1,308	0.8
Total	7,429	2,906	6,192	16,527	9.7
EPBT (years)	4.4	1.7	3.6	9.7	

CIS Production 200 kW_p/month					
kWh_e/kW_p	Cell	Module	Other	Total	EPBT
Process	958	147	619	1,725	1.0
Indirect Mat'l	36	-	-	36	0.02
Direct Mat'l	369	940	-	1,308	0.8
Total	1,363	1,087	619	3,070	1.8
EPBT (years)	0.80	0.64	0.36	1.8	

5. DISCUSSION

Balance of systems components can add significantly to EPBT when heavy support structures or batteries are involved (over 6 years in Alsema 1999). For example, a standard SSI 4-pole mount (holds 220 W) is 15 kg of aluminum, which works out to 1,360 kWh_e/kW_p, for a payback just for the structure of 0.8 years (220 days) at 1700 kW/m^2/yr. The 8-pole mount is slightly better at 920 kWh_e/kW_p (198 days). BOS energy contributions are small when grid-connected; inverters usually add only a few months (2, 15).

Using an embodied primary energy estimate for commercial and industrial style buildings of 5000 kWh_t/m^2 of building area (25), a facility of 200,000 ft^2 (18,580 m^2) would represent 93 million kWh_t, or about 32,000 MWh_e. If the building lasts 30 years that is 1068 MWh_e/year, which at a production rate of 20 MW_p/year reduces to an energy payback time of 53 full-sun hours, or about 11 days.

To get a handle on equipment, let’s look at a crystal grower. Assume it weighs 10,000 pounds, all steel (32 MJ/kg=3.5 kWh_e/kg), and lasts 10 years, yielding embodied energy of 1590 kWh_e/year, or 4.4 kWh_e/day. The grower processes about 40 kg of silicon per day, which at 12 kg/kW is about 3.3 kW_p/day. This yields an energy payback for the embodied energy of the crystal growers of about 1 hour.

Emerging photovoltaic technologies have demanded most of the attention for future trends. Single-crystal silicon, though, continues to make strides through reduced raw materials and process energy requirements. Reducing cost generally drives these improvements. An improved energy balance is usually a byproduct. SSI engineers recently completed a crystal grower redesign project together with the Northwest Energy Efficiency Alliance that has demonstrated a 40% decrease in energy consumption per kg of silicon, a 70% decrease in argon use per kg of silicon, and an increase in productivity of 20%. The reduced electricity and argon consumption translate to a 10% decrease in the total energy embodied in the module. New products featuring frameless mounting hardware could improve this metric by another 5%. Implementation of wire saws has been a net gain: about twice the energy is saved by decreased silicon and diamond blade use (750 kWh_e/kW_p) than is invested in use of silicon carbide, mineral oil, and cutting wire ~320 kWh_e/kW_p). Thin film technologies have the inherent advantage that they require very little material in the final module. Materials yields range widely for thin film processes and in practice involve tradeoffs between uniformity or some other film quality measure. As far as the authors are aware, this is the first empirical study of this kind.

6. CONCLUSION

The payback time for today’s production photovoltaic technology is substantially less than its expected lifetime. With a module lifetime of 30 years, the panels analyzed here will produce nine to seventeen times the energy used in its production. The effects of the other components of a photovoltaic system can be significant relative to the module payoff itself, most notably in systems requiring batteries. Including life-cycle energy balances in both module production and BOS design are necessary to claim sustainability.

Some determinants of the energy payback for alternative energy technologies are controllable by the manufacturers and some are not. They are not limited to working in their familiar domain, and several are pursuing improvements with suppliers and manufacturers in other industries with similar problems and interests. There is a long-term "sustainability ideal" that says we should work to reduce the energy burden imposed by new technologies. However, all of the improvements have been made in the interest of building a sustainable business. This strategy seems to be a good one, for without the cash flow, the electrons won't.

7. ACKNOWLEDGMENTS

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