INITIAL EMPIRICAL RESULTS FOR THE ENERGY PAYBACK TIME OF PHOTOVOLTAIC MODULES

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ABSTRACT: This research contributes to the growing literature on net benefits of renewable energy systems by conducting an empirical investigation of the energy requirements and net energy production of as-manufactured photovoltaic modules, evaluating both established and emerging products. Results are based on utility bills, measured energy use, and production records. Crystalline silicon modules achieve an energy break-even in a little over three years. The energy payback time for thin film copper indium diselenide 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 are presented for the major materials and process steps for both single-crystalline silicon and thin film copper indium diselenide.

Keywords: Module Manufacturing – 1: Sustainable – 2: Environmental Effect – 3

1. INTRODUCTION

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 materials. 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 requirements such as mounting structure, inverter, or batteries. The energy payback time is computed from

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

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).

2. 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 this report are indicated by horizontal lines.

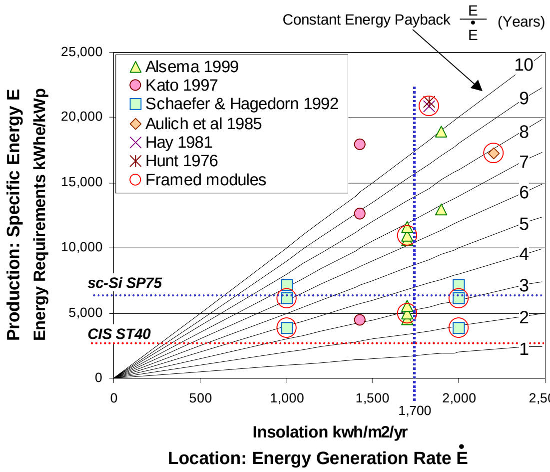

Figure 1: Specific Energy and Energy Generation Rate relationship to EPBT. Circled data are framed modules.

The earliest to publish in this arena are Hunt [8], and Hay [7]. Excellent literature reviews of previous work can be found in Alsema [2], Keolian & Lewis [11], von Meier [17], and Surek [16]. One of the key contributors to the energy payback field is Eric Alsema [1-4], 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). Palz & Zibetta [14] appear to include process energy only, thereby arriving at an understandably favorable payback time of less than two years for polycrystalline or multicrystalline modules. Keoleian & Lewis [11] focus on amorphous silicon thin films, providing some good data and a comprehensive approach. Aulich [5] provides useful data for raw materials use and alternate silicon production and wafering processes as well as potential module designs. Hynes [9] provides the only published energy analysis of CIS thin films.

3. METHODOLOGY AND ASSUMPTIONS

This investigation deviates from and complements this body of research. This is primarily an empirical endeavor, utilizing measured energy use, actual utility bills, production data and complete bills of materials to determine process energy and fully yielded raw materials requirements. The materials include both direct materials that are part of 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. 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. The process steps are illustrated in Figure 2.

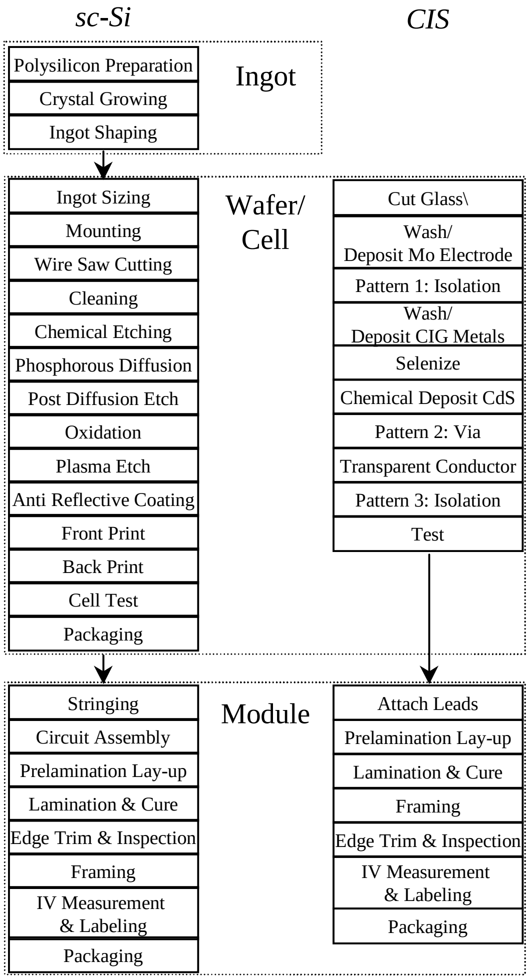

Figure 2: Siemens Solar manufacturing process sequences.

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 [6]. 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.

There is a general consensus among renewables advocates that the energy used in the first melt/crystal growth cycle of silicon intended for 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 production energy and the polysilicon purification energy as the measure of incoming raw polysilicon embodied energy, consistent with most of the recent work.

All energy forms are converted to their electrical energy equivalents, expressed in kilowatt-hours electric (kWhe). For natural gas and thermal energy, a conversion efficiency of 35% was assumed. Energy and materials requirements were tallied 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 (kWp) basis are easily computed from module area and power rating from the product datasheets. The resulting specific energy requirements are expressed in kWhe/kWp. 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 of natural gas. 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.

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.

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 3. The total materials energy contribution for production modules are not far from the process energy requirement: 2857 kWhe/kWp for sc-Si (about 85% due to direct materials) and 1,345 for CIS, (97% direct).

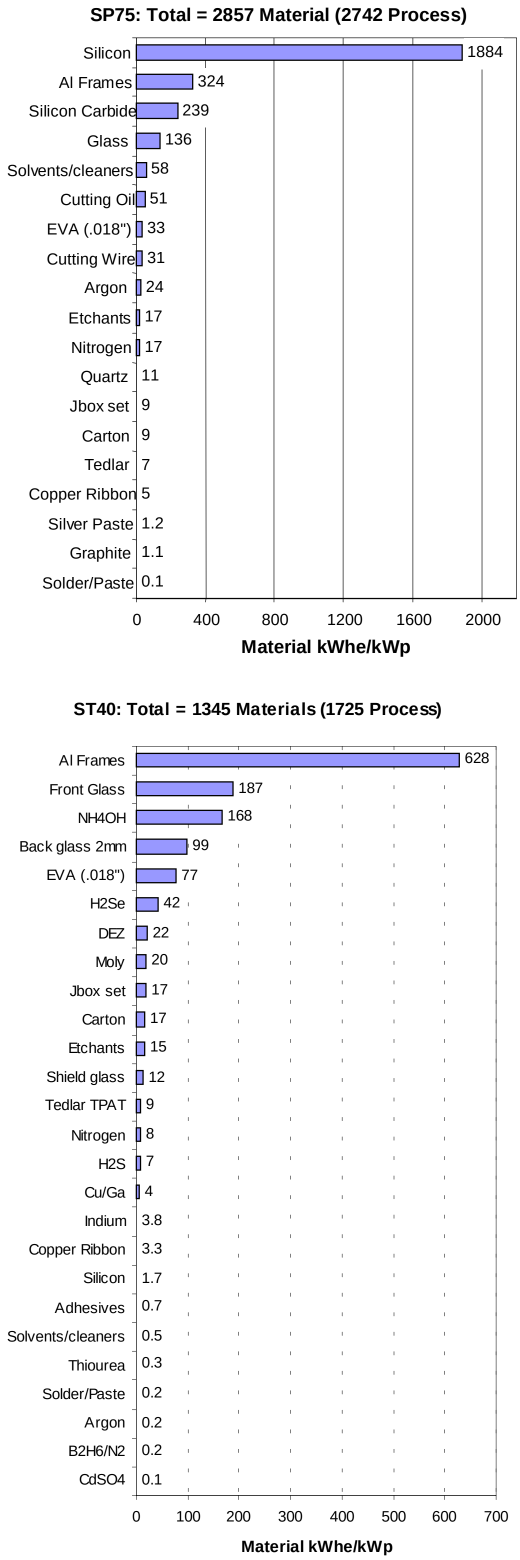

Figure 3: Materials energy content Pareto charts.

The gross energy requirement is the sum of the process and embodied materials energy, summarized by category and process step in Figure 4 and Table I. Payback time is 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 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, and 2.2 years, respectively. The final computations are very similar to Alsema's "low" silicon results [4] and Hynes' mid-range CIS results [9], even including all indirect materials.

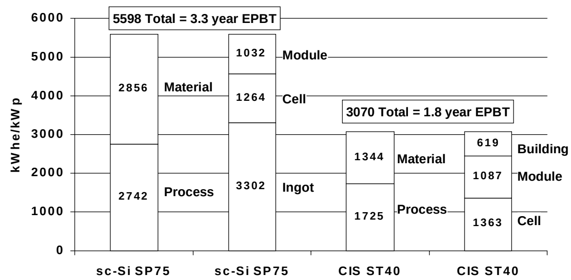

Figure 4: Energy requirements breakdown. EPBT computed at 1700 kWh/m^2/year.

Table I: Energy requirements breakdown by energy source category and process step. EPBT computed at 1700 kWh/m^2/year.

sc-Si SP75					(years)
kWhe/kWp	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 ST40					(years)
kWhe/kWp	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. CONCLUSION

These results indicate that payback times for today's sc-Si and CIS photovoltaic technologies 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 [12, 13]. 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 balance of systems design are necessary to claim sustainability.

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