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EMPIRICAL INVESTIGATION OF 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 3 to 4 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 9 and 12 years, and in full production is ~2 years. Over their lifetime, these solar panels generate 7 to 14 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 can also be applied 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 convene a workshop devoted to this topic (Nieuwlaar and Alsema, 1997), and present several papers on the subject at a recent conference addressing several environmental issues for photovoltaics (Fthenakis *et al.*, 1999).

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’).

EPBT is determined by (1) how it is produced, (2) its power rating or efficiency, and (3) how it is implemented. The gross energy required to manufacture a product includes both the energy consumed directly by the manufacturer during processing and the energy embodied in the incoming raw materials — energy consumed ‘upstream’ in producing glass, aluminum rails, or purified polysilicon for example. The module efficiency determines the rate at which incoming sunshine is converted to electrical energy. Overall system efficiency includes correction for module operating temperature and system losses. When expressed on a per-module or per-system basis this is simply the power rating. When expressed on a per-area basis it denotes efficiency. ‘Implementation’ refers primarily to location, which determines the solar insolation and therefore the electrical output of the PV panel, but also extends to issues such as installation style (fixed tilt or tracking, grid-connected or stand-alone, etc.) or possibly the energy requirements of components

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such as mounting structure, inverter, or batteries. The energy payback time is computed from these three terms as follows:

$$\text{EPBT} = [\text{production energy requirements}]/[(\text{power rating}) \times (\text{insolation})]. \quad (1)$$

Some of the scatter in reported payback time for photovoltaic modules is due to energy calculations (the numerator) and the rest is due to implementation assumptions (the denominator). Several reported results for a variety of technologies, system types, and installation locations and styles are indicated in Fig. 1, as a function of assumed insolation level. The analyses range from solar cells to full systems. Circled datapoints correspond to framed modules, the emphasis in this analysis. Results from this investigation are indicated by horizontal lines.

The earliest to publish in this arena are Hunt (1976), who arrived at EPBT of 11.6 years for just the cell (2″ diameter with yields around 18%), and Hay *et al.* (1981) who calculated 11.4 years, and pushed early into investigating other techniques such as ribbon silicon, amorphous silicon, 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 (1998), Keoleian and Lewis (1997) and von Meier (1994). The National Renewable Energy Laboratory has assembled a concise summary of recent work in this area in a two-page document released under the heading 'PV FAQs' (Surek and Cameron, 1999). One of the key contributors to the energy payback field is Alsema (1997, 1998, 1999). 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 $kWh/m^2/year$ insolation). Alsema also explores potential alternative raw silicon production processes. His thin film estimates were similar to those for future advanced polycrystalline silicon modules, as the lower efficiency offsets the lower energy input. Palz and Zibetta (1991) arrive at a favorable payback time of less than 2 years for polycrystalline or multicrystalline ('mc-Si') modules, but it is not clear whether they include much in the way of materials energy. Keoleian and Lewis (1997) 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 *et al.* (1985) provides

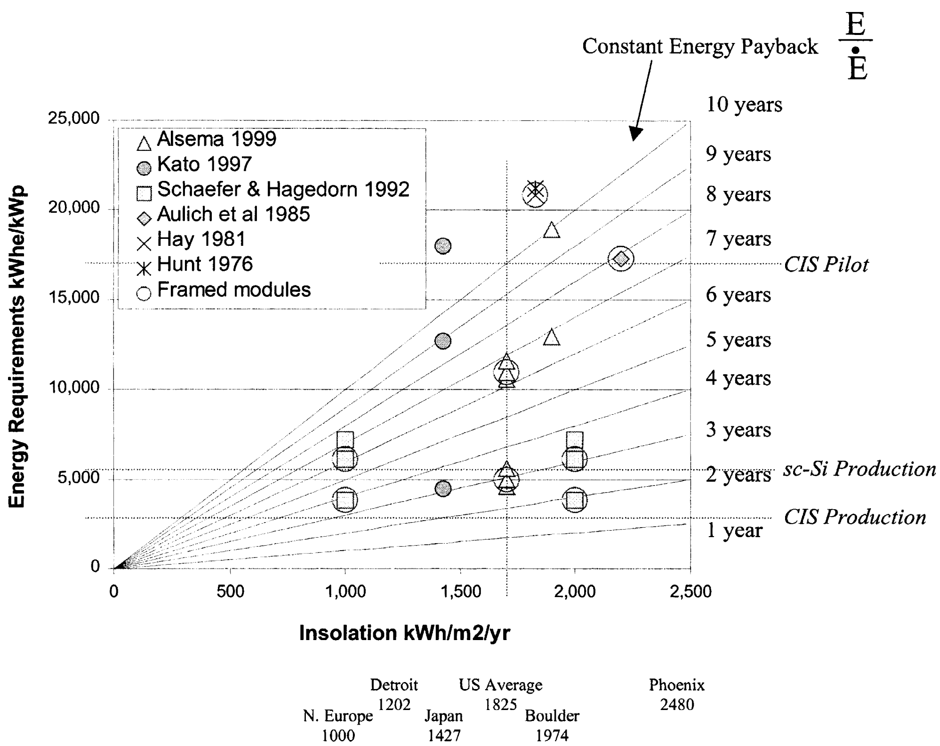

Fig. 1. Reported specific energy, insolation, and energy payback results. Circled data are framed modules. Diagonal lines represent constant energy payback with no system losses. Horizontal lines indicate results of this analysis.

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 with EPBT less than 2 years.

Hynes *et al*. (1992) provides the only published energy analysis of CIS thin films to date, 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 the buildings literature that has been addressing embodied energy and energy payback for efficiency investment for many years (Alcorn and Baird, 1996; Frankl and Gamberale, 1999; Griffiths *et al*., 1996) and the industrial energy analysis literature (Boustead and Hancock, 1979; Hancock, 1984).

2. 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 raw materials requirements. The materials include both direct materials, which are part of the finished product such as silicon, glass and aluminum, and indirect materials, which 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. All data are based on gross inputs, fully accounting for all yield losses without requiring any yield assumptions. The best available estimates 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. The process sequence for each technology is illustrated in Fig. 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 Boustead and Hancock (1979). 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.

Silicon used for photovoltaics has dominantly been 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 use 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 (150 kWhe/kg). Alternative methods of producing PV-grade silicon are discussed elsewhere (Alsema, 1999; Kato *et al*., 1997; Rogers, 1990). 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 (kWhe). The bulk ($>$95%) of the processing energy is electricity. For natural gas, a conversion efficiency of 35% was assumed. Energy and materials requirements were performed on a per-module basis for two representative products: the SP75 (sc-Si) and the ST40 (CIS). Conversions to module area (m^2) and rated peak power (kWp) are easily computed from module area and power rating from the product datasheets. The SP75 is rated at 75 W and measures 527$\times$1200 mm, and the ST40 is rated at 38 W and measures 329$\times$1293 mm. The resulting specific energy requirements are expressed in equivalent electric kilowatt-hours per rated peak watt (kWhe/kWp). This choice of units is convenient and intuitive because it represents some-

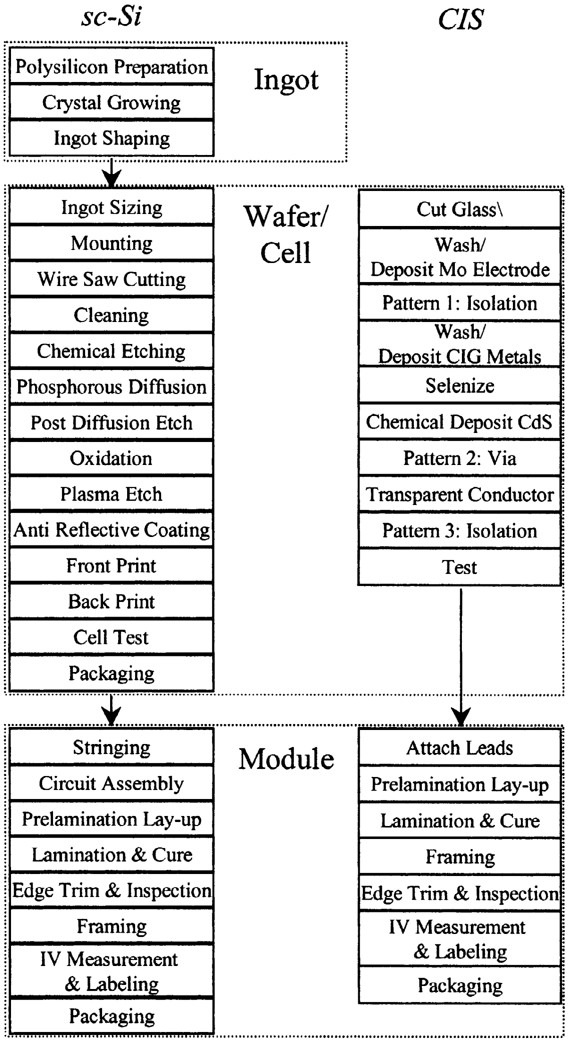

Fig. 2. Siemens solar manufacturing process sequences.

thing physical: the number of full-sun hours[1] 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/year, and correct for any performance changes from the rating due to system losses or module operating temperature. The US average solar insolation is ~1825 kWh/m^2/year (5 full sun hours per day). A common mid-range number used in the literature is 1700 kWh/m^2/year (4.7 full sun hours per day).

3. 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 9500 GJ (90,000 therms) of natural gas. During this time SSI produced 3.2 km 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, and Munich). The crystal growing process is carried out in SSI's facility in Vancouver, Washington. Consumption of the dominant energy component for each facility and major process step is presented in Fig. 3 as a function of the monthly production rate.

Crystal growth is electricity-intensive, and the variable process energy overwhelms any fixed overhead associated with operating the plant. The end result is an average total processing energy requirement of about 117 kWhe/kg of incoming

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

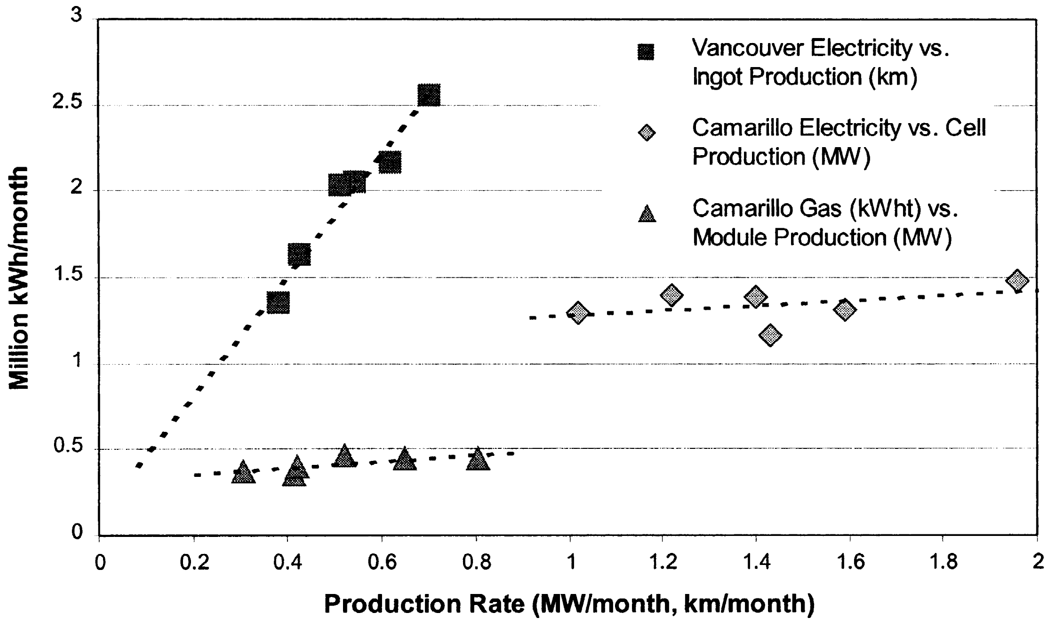

Fig. 3. Energy consumption vs. sc-Si production rates.

silicon. This translates to a yielded process energy requirement of 1382 kWhe/kWp of finished product. In the Camarillo facility, about 90% of the electricity and 10% of the natural gas is used for cell processing (diffusion tubes and firing furnaces), and the balance used for module processing (lamination and curing). A large portion appears to be used for maintaining the plant environment and various other overhead energy needs, indicated by a fairly high implied intercept at zero production level. This overhead energy could not be measured directly, and is allocated to the different process steps in proportion to their average process energy requirements. The result is a process energy requirement of 850 kWhe/kWp for the cell process and 510 kWhe/kWp for the module process. The total sc-Si process energy requirement is 2742 kWhe/kWp.

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 kWp per month, the estimated process energy use is 7554 kWhe/day, which translates to a specific energy value of 15,107 kWhe/kWp. This high value stems from the fact that the plant is severely underutilized, operating at ~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 1 week by Southern California Edison for the power panels serving the CIS research and production facility, during which energy use averaged 7549 kWh/day.

At a production rate of 200 kWp/month, the process energy estimate fell significantly to 1725 kWhe/kWp, 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 1100 kWhe/kWp). The remainder of the discussion focuses on the high production-rate values.

Materials requirements and the resulting embodied energy contribution are based on production bills of materials and energy content coefficients cited in the literature. No assumptions were required about cell thickness, cutting losses, or production yields that are required for production modeling analysis.[2] Materials are shown in decreasing order of their embodied energy contribution in Fig. 4. 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 1345 for CIS (97% direct).

The gross energy requirement is the sum of the process and embodied materials energy, summa-

[2] For reference, the SP75 cells are 380 microns thick, and about 150 microns are lost during wafer slicing.

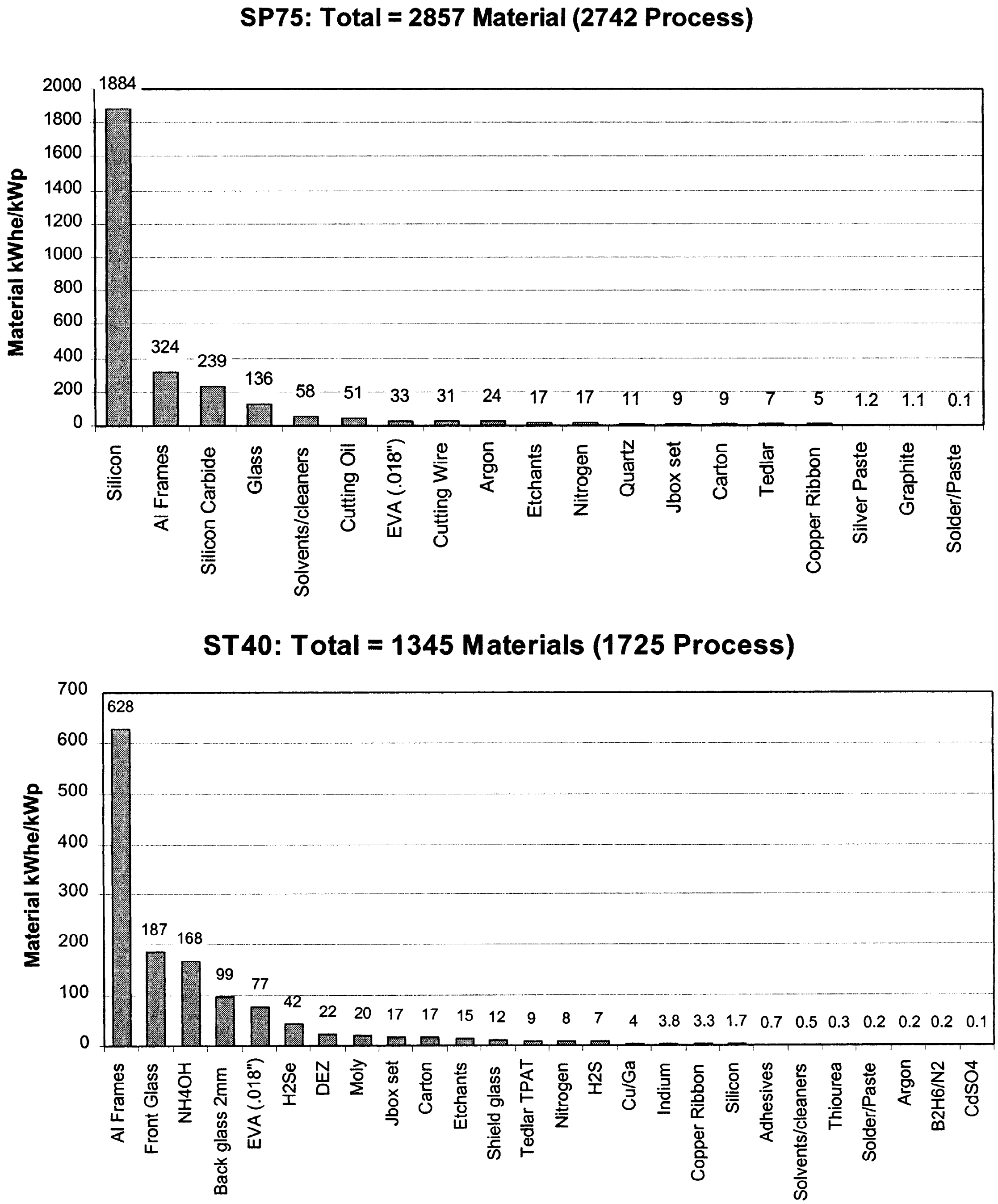

Fig. 4. Pareto charts of materials by energy content.

rized 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/year 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 0.80 (the 'performance ratio' or 'PR'), 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 (Alsema, 1997) and mid-range CIS results from Hynes *et al.* (1992), even having included 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.

Table 1. Energy requirements breakdown (kWhe/kWp)[a]

sc-Si production 2 MWp/month	Ingot	Cell	Module	Total
Process	1382	850	510	2742
Indirect materials	36	412	–	448
Direct materials	1884	1	523	2408
Total	3302	1264	1032	5598
CIS pre-pilot 15 kWp/month	**Cell**	**Module**	**Other**	**Total**
Process	6949	1966	6192	15,107
Indirect materials	111	–	–	111
Direct materials	369	940	–	1308
Total	7429	2906	6192	16,527
CIS production 200 kWp/month	**Cell**	**Module**	**Other**	**Total**
Process	958	147	619	1725
Indirect materials	36	–	–	36
Direct materials	369	940	–	1308
Total	1363	1087	619	3070

[a] Indirect materials are not part of the final product. 'Other' is building use not easily allocated to a specific process.

With a module lifetime of 30 years and a performance ratio of 80% at a moderate insolation level, an SP75 will produce seven times the energy used in its production and an ST40 14 times, a measure referred to as the 'energy return factor' in some of the relevant literature (Nieuwlaar, 1997; Nieuwlaar and Alsema, 1998).

4. DISCUSSION

Balance of systems ('BOS') 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 made of 15 kg of aluminum, which works out to 1360 kWhe/kWp, for a payback just for the structure of 0.8 years (220 days) at 1700 kW/m^2/year. The 8-pole mount is slightly better at 920 kWhe/kWp (198 days). BOS energy contributions are small when grid-connected; inverters usually add only a few months (Alsema, 1999; Johnson *et al*., 1997).

Using an embodied primary energy estimate for commercial and industrial style buildings of 5000 kWht/m^2 of building area (Wilson and Young, 1996: kWht is the equivalent primary energy requirement in kilowatt-hour units), a facility of 18,580 m^2 (200,000 ft^2) would represent 93 million kWht, or about 32,000 MWhe. If the building lasts 30 years, this yields 1068 MWhe/year, which at a production rate of 20 MWp/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 4545 kg (10,000 pounds), all steel (32 MJ/kg = 3.5 kWhe/kg), and lasts 10 years, which yields embodied energy of 1590 kWhe/year, or 4.4 kWhe/day. The grower processes about 40 kg of silicon per day, which at 12 kg/kW is about 3.3 kWp/day. This yields an energy payback for the embodied energy of the crystal growers of about 1 h. Even if there is significantly more energy content in the equipment than is reflected in its material embodied energy, the equipment energy content appears to be dwarfed by the process and materials energy requirements.

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 by-product. 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 (750 kWhe/kWp) by decreased silicon and diamond blade use than is invested in use of silicon carbide, mineral oil, and cutting wire (320 kWhe/kWp). Thin film technologies have the inherent advantage that they require very little material in the final module. Ongoing efforts to reduce costs and energy use have the potential to cut these energy requirements by about half (Knapp *et al*., 2000). As far as the authors are aware, this investigation is the first empirical study of this kind.

5. CONCLUSION

The energy 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 7 to 14 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.

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