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TECHNOLOGY CHOICES FOR THE PV INDUSTRY:
A Comparative Life Cycle Assessment

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ABSTRACT

In contrast to widely-used electricity generation technologies, photovoltaic (PV) systems produce little or no environmental pollution at the point of use, contributing to their market status as an environmentally-preferable product. However, there are numerous materials and energy inputs that go into the fabrication of the components of PV systems that may carry significant environmental burdens. A life-cycle perspective helps to compare the net environmental benefits of a particular generation. In this effort, we systematically examine design options from feedstock to integration in order to identify current and future opportunities for minimizing the environmental impact of PV systems.

We use a combination of process-based and economic input-output life cycle assessment (EIOLCA) to capture both a breadth and depth of information. We decompose a PV system into a set of design and manufacturing choices at each step of the process: 1) feedstock – electronic and solar grade silicon, 2) diffusion – conventional furnace (CFP) and rapid thermal processing (RTP), 3) silicon growth – multicrystaline silicon using electromagnetic casting (EMC) or directional solidification, single crystalline silicon using Czochralski or float zone crystal growth, and amorphous silicon, 4) cell encapsulation and covering – standard ethylene vinyl acetate (EVA) versus mixtures containing additives for adhesion strength and standard low-iron glass versus cerium-doped glass 5) module construction – traditional framed module and building integrated frameless glass laminates, 6) integration – sloped roof, flat roof, Building Integrated PV (BIPV), ground mounted, 7) construction – new or retrofit, 8) heat recovery, 9) insolation maximization – tracking or flat plate, and 10) energy storage – grid connected, electrochemical battery, or micro-hydro using a pre-existing agricultural infrastructure.

We find that 1) carbon intensities for best case systems are an order of magnitude lower than coal; 2) carbon intensities for best case and conventionally designed systems are still higher than wind or hydro; 3) significant opportunities exist in further development of solar-grade silicon feedstock, float zone crystal growth rapid thermal processing, and high durability encapsulants; 4) there are significant drawbacks in employing ground-based installations, including 30-50% increases in air pollutant emissions; 5) in many cases, the efficiency gains realized by using tracking devices do not translate into financial or environmental benefits; 6) the emissions from the manufacturing of batteries for stand alone systems are significant, increasing toxic material releases by 100 fold.

When the best choices are made throughout the system's life cycle, environmental burden reduction of 25% can be achieved for carbon intensity, while increasing economic value.

Keywords: Photovoltaics, Hybrid LCA, Life Cycle Assessment.

OBJECTIVES

The objectives of this study are to take a full life cycle view of the environmental impacts of photovoltaic (PV) energy production, and to compare these with the effects of conventional energy sources as well as other renewable sources. In addition, the report investigates the positive and negative environmental implications of design and installation choices, and presents a set of most preferable PV manufacturing decisions.

METHODS

Life Cycle Assessment Methodology

Our study uses a hybrid life-cycle assessment methodology consisting of a combination of SETAC methods and Economic Input-Output methods. Where aggregation problems were identified in the cell manufacturing stage, the EIOLCA method was supplemented with process based data.

System Size [kWp output]	Avg. Peak Sunlight per Day [hours]	System Life [years]	Wholesale Energy price [cents/kWh]	Retail Energy Price [cents/kWh]
2.5	5	30	6.5	12.5

TABLE 1. SOME FUNDAMENTAL ASSUMPTIONS USED IN THE ANALYSIS.

The semiconductor sector of the economy is used as the representative sector for PV manufacturing in the US economy. However, this sector is dominated by the IC industry, which has similar inputs and processing steps, but much lower energy use per dollar of output. Therefore, the emissions due to energy use in the semiconductor were replaced with detailed process-based analysis of energy use for different PV manufacturing scenarios. For all purposes of this analysis, the functional unit used to normalize all inputs was a 2.5 kWp system, the typical installation size that would be implemented in a single family solar home. All Balance of System components are sized for a 2.5 kWp installation, along with maintenance and end of life considerations. Therefore, the conclusions are valid primarily for single-family residential installations. The insolation and efficiency assumptions are valid primarily for the

Northern California/Bay Area region. The main assumptions used in this analysis are shown in Table 1.

Data Sources

For cell manufacturing, industry data was largely unavailable, so publicly and academically available data has been aggregated to describe environmental impacts as thoroughly as possible. In analysis of the feedstock, wafer, and cell models for equipment-based process choices were built from data on energy and material use culled from trade journals, academic literature (Alsema, 1995), conference papers, government documents, patents (United States and European), and books. Analysis of energy use from mining to cell production and testing was established. The final inputs for energy use are shown in Table 2.

Device Production Step, in kWh/m²	sc-si (FZ)	sc-si (CZ)	mc-si (DS) RTP	mc-si (DS) CFP	mc-si (DS) glass lam (CFP)	mc-si (EMC)	SoG-si	a-si
Mining and refining of silica	.1	.1	.1	.1	.1	.1	.1	~0
Reduction of silica to silicon	11.7	11.7	11.7	11.7	11.7	11.7	11.7	~0
Production of high purity silicon	256.8	256.8	256.8	256.8	256.8	256.8	97.5	0.09
Casting	36	34.5	13	13	13	19	13	0
sawing / wafering	66	66	66	66	66	66	66	0
Cell processing	94	94	68.9	94	94	94	94	108
Module encapsulation	3.8	3.8	3.8	3.8	0	3.8	3.8	53
capital goods	39	39	39	39	39	39	39	63
TOTAL	506	504.5	457.9	483	479.2	489	323.7	224.09

TABLE 2. ENERGY REQUIREMENTS FOR DIFFERENT DEVICE MANUFACTURING OPTIONS.

For all installation and integration life-cycle stages, EIO-LCA data was used to represent the proportional inputs from appropriate industrial sectors. Data was taken primarily from actual installations based on a series of case studies from a local Northern California Installer. Other inputs were estimated from hypothetical system design and components from manufacturer and distributor catalogues. Efficiency estimates were adapted from CEC system design guidelines (Anon, 2001). Materials data was based on weight and average market prices for the material under consideration.

RESULTS

Societal Benefits of PV: Climate Change, Jobs, and Externalities

The results of this study are similar to results of larger studies comparing societal options for energy generation. For example, Pacca and

Horvath (2002) found global warming emission intensities for a PV power plant of 91 g CO_2 equivalent per kWh output for a system's lifetime. The most significantly similar option considered by this study was that of the ground-based installation, which yielded emissions of 141 g CO_2 equivalent per kWh output. Figure 1 shows that both of these options are approximately an order of magnitude higher than hydro or wind power, but an order of magnitude lower than coal. These results highlight the need for the PV industry to focus on reducing its carbon intensity through the design changes suggested in this paper. This can and must be achieved in two ways. First, using currently available technology choices, energy use can be reduced by 25%. Second, with proper energy chain management it is possible to reduce the carbon content of the remaining 75% by 40% or more. At this level of carbon intensity, PV systems become competitive with wind and hydropower from a carbon mitigation perspective. As environmental equals, the technologies can compete directly based on their other strategic merits.

Our analysis indicates that PV offers other significant societal benefits in addition to global warming mitigation. Displacing conventional generation with PV creates 3-5 times more jobs. The jobs created are not only more local to the community installing the PV capacity, but also involve arguably more rewarding labor.
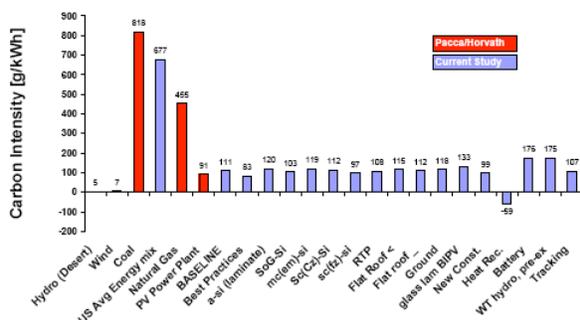

FIGURE 1. GLOBAL WARMING POTENTIAL [CO_2 EQUIVALENT] PER KWH, FOR DIFFERENT ENERGY PRODUCTION TECHNOLOGIES.

The creation of jobs is one step towards a more healthy and efficient economy. Another important step is moving towards full cost accounting. When the active parties of an economic transaction do not pay for the full cost of a good

or service they are exchanging, the rest of the cost must be paid by uninvolved parties. This additional cost is called the externality of the economic transaction and is a very real, actual cost that must be paid. Despite the fact that externalities are real costs that must be paid, they are very difficult to measure or estimate accurately. The presence of this externality leads to economic inefficiency, as the transaction will be oversubscribed due to its artificially low price, in addition to unfairness, as those who bear the externality are not the ones who get the benefit.

Estimates of the externality associated with conventional power generation are shown alongside estimates of different design options for PV power generation in Figure 2. Due to the difficulty of measuring externalities, the high and low estimates vary over an order of magnitude, depending on the assumptions underlying the estimation. Despite this, the message is clear at every level of estimation: conventional generation externalizes 10 times more cost than PV technology, leading to a drastically under-costed, overused energy source.
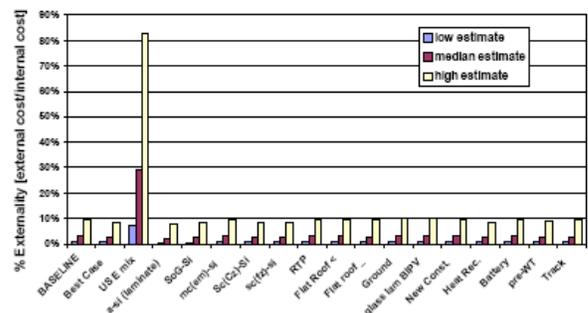

FIGURE 2. HIGH, MEDIAN, AND LOW ESTIMATES OF ECONOMIC EXTERNALITIES FOR A VARIETY OF PV DESIGN OPTIONS AND FOR THE CURRENT US ENERGY PRODUCTION MIX.

PV devices: Feedstock, Growth, and Processing

Conclusions from our analysis show that rapid thermal processing (RTP), float zone crystal growth, and solar grade feedstock are beneficial design choices. Float zone growth is a clear winner, in that the toxic emissions are reduced considerably. This processing choice also results in the largest reduction in energy payback time and global warming impacts. RTP is an

improvement in almost all areas of environmental pollution, but only by a modest amount due to the fact that conventional processing represents only a small fraction of total manufacturing energy requirements. The use of solar grade silicon trims the energy payback time slightly and reduces SO_2 and NO_2 emissions, but causes larger releases of other toxics, due to the lower expected efficiency numbers and consequential need for a larger cell area to produce a 2.5kWp installation. These tradeoffs are shown in Figure 3.
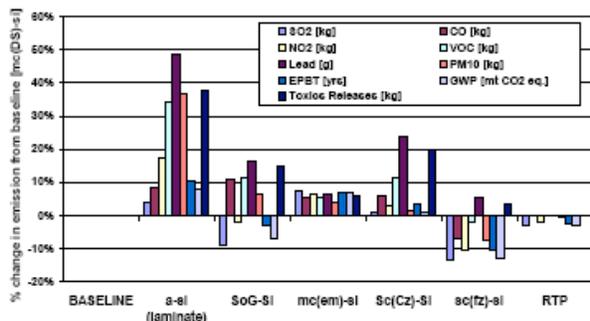

FIGURE 3. VARIOUS ENVIRONMENTAL METRICS ARE SHOWN COMPARING FEEDSTOCK OPTIONS, WAFER MATERIALS, AND PROCESSING CHOICES.

Modules: Encapsulation and Framing

Investigation into the limitations on cell life show that cell lifetimes are most often limited by failure of the encapsulant material, through optical degradation (UV browning), and then failure through corrosion or delamination from the superstrate glass. The "energy life" (Ewan, 2003), the total energy produced by the cell, may be increased with encapsulant and superstrate materials that allow the cell to sustain higher power production with age and extend the productive life of the cell. UV-filtering Ce-doped glass has been shown to reduce browning of the ethylene vinyl acetate (EVA) encapsulant (King, 1998), and additives and alterations to the encapsulant formula allow for a more durable seal with the glass. Economic Input-Output LCA techniques show that the impact of total encapsulant material on the energy payback time is only 16.7 - 25.5 kWht/m2 cell. Energy required for additional processing to dope the glass surface material or to manufacture encapsulant material additives are expected to be small in comparison to the energy gains provided by the

longer lifetime of a cell. Environmental cycling has shown a range in efficiency losses of 2.3% to 61.5% from the original performance over a simulated cell lifetime (Watson, 2001). Assuming a lifetime of 25 years, and approximating the degradation as linear, the relative Energy Life of a cell may be 1,140 to 35,359 kWh lower than ideal, and a up to 21,671.5kWh lower than a baseline case (123,187.5kWh), which assumes efficiency degradation within the limits of an average manufacturer's warrantee (25 years at or above 80% rated power.) Investigation into the toxic impacts of cerium-doped glass and encapsulation material additives prove that the design improvements have a potential for harm in terms of occupational health, but do not create a significant environmental impact. Cerium in the form of the cerium oxide is used in the making of UV-filter glass and cerium oxide is non-soluble and non-toxic (Venugopal, 1978). There is currently no encapsulant test method that has been shown to predict fatigue life (King, 1998). However, strong adhesion strength of the encapsulant is a positive indicator for a longer-lasting bond with the superstrate. Tests of the adhesion strength of various encapsulants show that variation of the vinyl acetate (VA) to EVA ratio influence performance, as well as addition of cross-linking agents to the material and application of coupling agent to the bond (Pern, 2003). EVA cross-linking agents are commonly peroxides, such as dicumyl peroxide. Dicumyl peroxide is a respiratory toxicant which could pose occupational hazard, and shows conflicting behavior as a carcinogen (Gimenez-Conti, 1991, 1998). The coupling agent used in the study is gamma-methacryloxy-propyltrimethoxysilane.

The silane used to produce the agent is an occupational risk, being highly flammable and toxic in large concentrations. Liquid methacrylates are also dermal and (when volatilized) respiratory irritants (Kirk-Othmer, 1984). Other improvements to the environmental durability of solar cells may have a more significant toxic risk. Flame-retardant EVA fillers are typically composed of a mixture of antimony trioxide, zinc borate, and aluminum or magnesium hydroxide (Tucker, 2003). Antimony trioxide is considered a likely human carcinogen (IARC, 1989), and chronic exposure to aluminum hydroxide may cause neurological, bone, lung or kidney disorders. Zinc borate and magnesium hydroxide are, however, benign. Modifications to encapsulant formulation and glass type, while posing some potential occupational health

hazards, would have positive impact on the energy payback time and energy life of the cell.

Integration: Mounting, Construction, Energy Storage, and Tracking

As can be seen in Figure 4, the environmental tradeoffs between integration options are complex, although there are some straightforward conclusions that can be made. Integration is often dominated by the practical considerations of each application; thus, these conclusions should be taken in context with all other design factors. The significant results of these tradeoff studies are:

1. The tradeoffs between mounting structure, orientation, and ease of installation are generally small and unclear between sloped roof and different types of flat roof installations. However, mounting PV to preexisting building structures when possible shows clear benefits compared to ground mounting.

2. Direct building integration appears environmentally beneficial, especially with increased experience, standardization, and integration into early phases of architectural consideration.

3. Integrating PV into the new construction phase is clearly beneficial, with decreases in environmental impact from 7%-30%. This should provide good justification for incentive programs such as the one currently in place in San Diego, CA where new construction using PV receives "fast-track" permit status, often saving contractors months of time, and increasing project value.

4. Hybrid solar photovoltaic/solar thermal systems, while theoretically appealing, may be too difficult to effectively integrate in all but a few optimally designed cases. This conclusion does not preclude the use of solar thermal collectors; in fact the benefits shown in Figure 4 suggest that solar thermal is a natural complement to photovoltaics, with questionable benefits going from separate to combined systems.

5. Tracking systems do not show general benefits, especially as modules increase in efficiency and decrease in environmental burden per unit area.
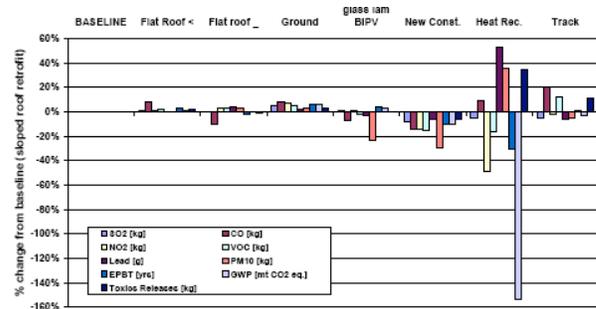

FIGURE 4. VARIOUS ENVIRONMENTAL IMPACT METRICS ARE SHOWN FOR A VARIETY OF MOUNTING AND INTEGRATION OPTIONS.

Overall, the most effective energy storage system is the grid. When a grid interactive system is not possible, batteries are overwhelmingly chosen to store energy. Unfortunately, the results of this study agree with that of Alsema (2000) in his study of stand-alone solar home systems: namely, that batteries can dominate certain aspects of the environmental performance of the system. As can be seen in Figure 5, batteries contribute to 55%-435% increases in the environmental burdens of the PV system over its lifetime. This highlights a few important points: 1) the need to consider manufacturing impacts, 2) the need to consider impacts other than global warming potential, 3) the industry need to develop alternate energy storage strategies. One interesting and potentially beneficial alternative for remote applications is to convert preexisting water storage infrastructure into micro-hydro powered energy storage. Although there is still an environmental penalty of 35%-65% over a grid tied system, a hydro-powered energy storage system outperforms batteries in terms of cost, longevity, and environmental performance when employed in an appropriate situation.
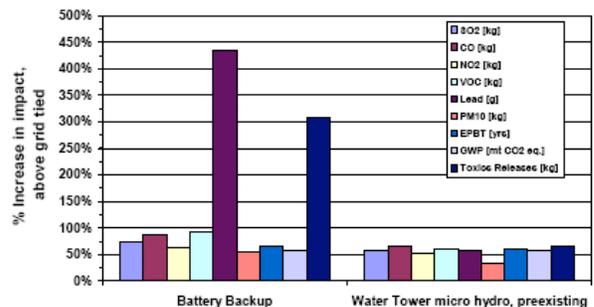

FIGURE 5. ENVIRONMENTAL METRICS FOR TWO ENERGY STORAGE OPTIONS.

Supply Chain and Energy Chain Management

The value of EIOLCA becomes apparent when the economy wide supply chain is revealed, stretching through 480 sectors of the economy. Examining the 2 cases of supply chain impacts, we find that 70%-90% of the environmental burden comes from industrial sectors not directly considered in our EIOLCA inputs. This indicates that the semiconductor sector itself (the recipient of the majority of the direct economic input) is admirably environmentally benign. However, the economic sectors that it purchases materials from are not. Consider Figure 6; 85% of the toxic releases to the environment come from three sectors of the economy. If the suppliers of these key commodities were selected based on their environmental performance, the burden of the entire PV system could easily be reduced by 50%, without any changes in the semiconductor sector itself.
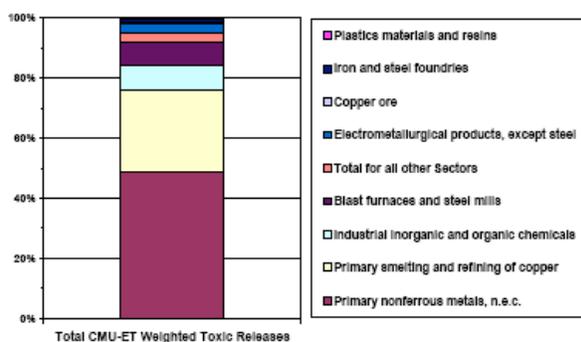

FIGURE 6. CONTRIBUTIONS OF VARIOUS ECONOMIC SECTORS TO THE RELEASES OF TOXIC MATERIALS TO THE ENVIRONMENT.

If this mode of thinking is extended further, it becomes even more compelling. Consider the supply chain contributions to life cycle global warming potential. As would be expected, the majority of emissions come from the electricity used provided by the utility grid. However, the PV industry is in a perfect position to eliminate utility sector from its supply chain – a PV powered PV manufacturing facility. In addition to discounted access to solar hardware, aligning business practices with values, publicity value and a low-cost supply of power, it would give the PV facility a gut sense of energy pay back time.

UNCERTAINTIES AND DATA QUALITY ASSESSMENT

Using the methods presented by Weidema (1996), and further described by Junnila (2003), we use a method of subjective data quality assessment. This method consists of rating the quality of data based on number of categories. In each of these categories, criteria are presented dictating the numerical value from 1-5 (1 is the highest) of the quality of the data. We can apply these criteria to each category of the present analysis as shown in Table 3 to get a general sense of the quality of the data used and opportunities for data quality improvement. From the results of this assessment, a few salient feature of the data quality of this study are apparent: 1. The weakest phase of the analysis is for pumped hydro energy storage. This is to be expected, since this technology choice is not prevalent, and data questionable. 2. Strongest phase of the analysis is for power conditioning. This is mainly due to the fact that this technology is well documented and publicly available cost data is easy to obtain. In addition, there is a good match between this technology and the EIOLCA economic sectors. 3. Data age and geographical correlation data quality are controlled by EIOLCA. All EIOLCA data is nationwide and comes from 1997.

	Acquisition Method	Independence of Data Supplier	Represent-ativeness	Data Age	Geographical Correlation	Technological Correlation	Average
Feedstock	3	1	3	2	2	3	2.3
Processing	3	2	3	2	2	3	2.5
Module Assy	3	1	2	2	2	3	2.2
Heat Recovery	3	1	2	2	2	3	2.2
Mounting	1	1	3	2	2	1	1.7
Batteries	1	1	3	2	2	2	1.8
Pumped Storage	3	3	4	2	2	4	3.0
Maintenance	1	1	3	2	2	1	1.7
Transportation	2	1	3	2	2	1	1.8
Power Conditioning	1	1	1	2	2	1	1.3
Building Integration	3	3	3	2	2	2	2.5
	2.2	1.5	2.7	2.0	2.0	2.2	2.1

TABLE 3. DATA QUALITY ASSESSMENT.

CONCLUSIONS

Taken in full, synergies among process choices illustrated the potential for a life cycle analysis to increase the environmental performance of the overall system. That is, benefits gained at the manufacturing stage can be multiplied through proper installation and system design. Engineers and contractors interested in maximizing environmental and economic performance of the installed system can augment balance of system efficiencies with targeted procurement from

manufacturers employing more resource efficient techniques such as Rapid Thermal Processing or employing solar grade feedstock. The photovoltaic industry exemplifies rapid change and innovation, and every effort should be made to extend this capacity to environmental performance and comparative assessment techniques.

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