Integrated high-concentration PV
Near-term alternative for low-cost large-scale solar electric power

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Abstract

Large-scale photovoltaic electric power generation deployment and utilization is no longer dictated by limitations in technology, but rather by the economics of PV systems vs. other renewable or traditional options. This paper describes a near-term alternative option for cost-effective solar electric power generation based on a novel sunlight concentrating technology: integrated high-concentration PV (IHCPV). The advantages of high-concentration systems have been well analyzed, but development was constrained by the lack of solar cell capable of withstanding the rigors of concentrated sunlight. The development of a stable, high-concentration back-junction, point-contact cell, by Amonix, paved the way for high-concentration system development. System designers had to insure that the cost savings inherent in concentration systems through the reduction of costly solar cell content were not overshadowed by the ancillary costs of structure and tracking elements used in concentrating arrays. The IHCPV system has met these goals. Economic factors specific to the IHCPV system are presented including (1) low cost of entry, (2) enhanced energy production, (3) reduced land utilization, and (4) accelerated benefits of volume production.

Keywords: High-concentration PV

1. Background

Even though PV technologies have proven their maturity for large-scale applications, market penetration for Photovoltaic systems has been largely constrained by

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price. All PV manufacturers seek to reduce manufacturing expenses in order to bring the cost per watt of their systems below the “threshold” level needed for market acceptance. Each S/W reduction in PV prices opens up large market segments with great potential.

2. Cost reduction strategies

The principal strategy to reduce cost is to reduce the material and/or manufacturing expenditure for those system elements which contribute the most to total system pricing. In other words, reduce the “cost culprits”. The principal “cost culprit” in any Photovoltaic system is the high-priced solar cell; generally, 50% or more in typical systems. The solar cell is the economic key to any Photovoltaic system.

Crystalline silicon, the predominant material used for today's solar cells, represents a mature technology where labor costs have been minimized in comparison to material costs, and it is doubtful that any major technical breakthroughs can be achieved which will dramatically increase its performance or reduce its manufacturing expense. Performance for crystalline silicon solar cells is approaching its practical and technical limit. Despite its good performance and well-understood manufacturing processes, traditional crystalline silicon solar cell technology remains relegated to uses which can support its high price.

Reduction of high-priced silicon PV material is the primary focus of the majority of differing PV technologies. All approaches strive to reduce the silicon material content or move to lower-cost alternative materials.

The majority of the PV industry is pursuing the strategy of reducing the thickness of the cells themselves by using very thin films of silicon or alternate materials. Most of these approaches are relying on technical breakthroughs in performance coupled with extensive capitalization. The results expected are still several years away.

Sunlight concentrating concepts or concentrator systems use a highly cost-effective approach of reducing the area of expensive cell material required to generate a given amount of electricity. This technology, described below, is available today.

Ordinary, one-sun flat-plate solar modules have their entire sun-receiving surface covered with costly silicon solar cells and operate at a fixed tilt to the Sun. Concentrating system designs fall into two major categories: low-concentration (10X–50X) and high-concentration (> 100X). Maximum performance and associated cost benefits can only be achieved at high concentration. High-concentration Fresnel lens concentrating systems offer significant cost savings by using inexpensive flat, plastic Fresnel lenses as an intermediary between the Sun and the cell (see Fig. 1). These magnifying lenses concentrate sunlight 250 – 500 times on a relatively small cell area. The concentrating system’s unique mode of operation reduces the silicon cell area required by an amount approximating its concentration ratio.

Although the high-concentration photovoltaic concept had been theoretically studied for many years, it was not considered commercially practical because of the lack of solar cell capable of withstanding the punishing environment generated by highly concentrated sunlight.
In ordinary "ONE-SUN" solar panels as seen on rooftops, etc., the entire surface being illuminated with sunlight is covered with expensive solar cells. Intermediary (magnifying) lens, called "Fresnel" between the sunlight collected on a small cell area, reducing cell usage by 250 times, effectively substituting expensive areas of silicon solar cells with inexpensive plastic lenses.

Fig. 1. Graphical representation of operation of flat-plate vs. concentration solar systems.

3. High-concentration solar cells

Amonix developed its back-junction, point-contact silicon solar cell with many superior attributes for high-concentration system applications [1].

- High efficiency - The Amonix high-concentration silicon solar cell holds the world's record for performance for cells manufactured in a commercial environment (>26% efficiency at \(\approx\) 300X concentration, 25°C).
- Ultraviolet light stability - No degradation in performance through system life.
- High power capability - Allows wide concentration application range (200X - 500X) without significant loss in efficiency.
- Both electrodes on the same side - Allows for highly automated surface mount assembly methods.
- Industry standard manufacturing processes - Allows high-volume cell production specifically adaptable to large-volume computer chip foundries for low-cost manufacturing.

4. The integrated high-concentration PV (IHCPV) system

The development of the Amonix HCPV solar cell paved the way to commercial deployment of HCPV systems [2]. High-Concentration PV systems offer several distinct advantages for low-cost power generation: (a) cost reduction through
reduction in silicon area – a traditional silicon 10 cm diameter one-sun wafer with 75 cm² of active area produces ≈ 1 W while the same wafer produces the equivalent of 700 W at 500X concentration; (b) higher conversion cell efficiency at concentration vs. one-sun; and (c) inherently higher capacity factor compared to fixed-tilt, flat-plate systems in high direct normal insolation (DNI) areas because of its built-in tracking. Despite these intrinsic cost-reducing elements, high-concentration PV systems have not previously emerged for large-scale utility use because of (a) the earlier lack of a stable, high-performance, commercially available high-concentration solar cell, and (b) the high costs associated with PV modules, structure, tracking system, and ancillary equipment.

With the arrival of the Amonix solar cell, HCPV systems can now be realized. However, to reduce costs, considerable effort has been applied so that all of the savings resulting from greatly reduced silicon usage does not get lost in the cost for the structure, tracker, and ancillary equipment required in the concentrating system. The result is the integrated high-concentration PV (IHCPV) array. This new, innovative (patented) system concept eliminates much of the costly hardware used in earlier high-concentration designs. This has been accomplished by the simplification of the array structure which (1) eliminated earlier separate “box”-type modules mounted on structure assemblies, and substitutes an integrated design which combines both the load-bearing structure and the Fresnel lens/receiver plate elements, thus eliminating the need for separate modules, and (2) a novel, manufacture-worthy receiver plate which makes use of “circuit-board” construction techniques, with surface mount cell technology, eliminates costly and labor intensive cell packaging and interconnects.

Fig. 2. Schematic of IHCPV system.
A schematic illustration of the IHCPV system is shown in Fig. 2. Fig. 3 shows a picture of a 18 kW IHCPV system installation at a large utility site: Arizona Public Service Company's Solar Test and Research (STAR) facility.

Amonix has installed five full-scale 18 kW utility demonstration IHCPV systems which have demonstrated the maturity of the technology as a provider of cost-competitive utility-scale (multi-megawatt) electric power. These systems have demonstrated 18% conversion efficiency at PVUSA conditions (more than twice the performance of other technologies). Now that the basic technology has been validated, attention can shift to economics of IHCPV as a low-cost near-term alternative PV system for large-scale solar electric power generation.

5. Economics of IHCPV

There are several factors, specific to IHCPV systems, which offer a near-term opportunity for low cost PV installations on a large scale:

- low cost of entry,
- enhanced energy production,
- reduced land utilization,
- accelerated benefits of volume production.

5.1. Low cost of entry

Billions of dollars have been spent on R&D and hundreds of millions on facilities for other PV technologies. It is estimated that each 10 MW increase in production
capacity requires $20–25 million in capitalization. In contrast, Amonix has used a unique approach in order to adapt its complex solar technology (both cell and system) to commonly existing manufacturing infrastructures (e.g. high-volume semiconductor computer chip manufacturing facilities called foundries) rather than developing and capitalizing custom facilities around a specialized technology. Both the Amonix HCPV solar cell and the IHCPV system have been designed to standard industry manufacturing methods and processes. This enables IHCPV immediate high-volume market entry. This strategy has resulted in major benefits:

1. **‘Fast-Track’ high-volume production capability.** An enormous underutilized manufacturing capacity, equaling gigawatts of IHCPV, exists in the US alone. By using this semiconductor and other manufacturing capacity, IHCPV can achieve production levels of 50 MW per year within 18 months at one-third the capital cost of other PVs. No other PV technology has this capability or capacity.

2. **Price/cost predictability.** By using industry-standard high-volume manufacturing methods, Amonix can project costs with considerable authority and confidence.

High-volume production costs for semiconductor chips similar in complexity to the Amonix HCPV solar cell have been well established. Based on this, Amonix projects HCPV cell costs to be < 20¢/W at the 50 MW/yr production level. Fresnel lens and structure cost projections are based on equally accurate information and analysis derived from existing manufacturing infrastructure. A conservative projected comparison of IHCPV vs. generic flat-plate system components in dollars per watt is shown in Table 1. The figures are for installed costs at the DC level because DC to AC conversion costs are the same for both technologies. The projection is for the year 1999 at 50 MW/DC production rates per annum at a single factory.

### Table 1
IHCPV/Flat-plate comparison

<table>
<thead>
<tr>
<th></th>
<th>IHCPV</th>
<th>Flat-plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell</td>
<td>$0.20</td>
<td>$1.20</td>
</tr>
<tr>
<td>Fresnel lens</td>
<td>$0.20</td>
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</tr>
<tr>
<td>Receiver plate</td>
<td>$0.44</td>
<td>N/A</td>
</tr>
<tr>
<td>Modularization</td>
<td>N/A</td>
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<tr>
<td>Subtotal</td>
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<tr>
<td>Structure</td>
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<tr>
<td>Tracker</td>
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<td>N/A</td>
</tr>
<tr>
<td>Installation</td>
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<td>$0.15</td>
</tr>
<tr>
<td>Total</td>
<td>$1.68</td>
<td>$2.80</td>
</tr>
</tbody>
</table>

Source: available literature

5.2. **Enhanced energy production**

Sophisticated PV systems such as concentrators actively track the sun maximizing energy production. At almost any installation site, tracking enhances energy production although the expenditure associated with tracking must always remain cost...
effective. Note that the cost comparison shown in Table 1 does not take increased energy production into consideration. Realistically, IHCPV produces up to 30\% more electricity than competing technologies. A simple methodology for determining the benefits of enhanced energy production from HCPV systems has been reported [3]. By “normalizing” the dollar per watt comparisons between differing technologies using an energy production factor (EPF), a greater accuracy can be obtained relative to the value of competing PV concepts. The energy production factor is defined as

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EPF = \frac{\text{Site & tech. specific avg. daily solar radiation/Reference solar irradiance}}{\text{Fixed flat - plate site specific avg. daily radiation/1000 W/m}^2}
\]

Typical data taken for a side-by-side comparison of 20 kW peak systems graphically demonstrates that the IHCPV system produces considerably more electricity than a similarly sized fixed flat-plate system as shown in Fig. 4.

5.3. Reduced land utilization

Because of its high efficiency and performance, IHCPV systems utilize a proportionately smaller land area to produce equivalent amounts of electrical energy. This is an attractive benefit, especially in urban areas where real-estate costs can play a determining factor in power-plant location. With a system efficiency approaching 20\%, the IHCPV system consumes one-fourth the area required by less efficient technologies such as thin-film. In addition to the obvious benefits, this implies for multi-megawatt installations, the small “footprint” of the IHCPV system is advantageous for distributed networking and adjunct installations.

5.4. Accelerated benefits of volume production

Perhaps the most significant aspect of IHCPV's advantages is its enhanced potential for meeting the cost thresholds needed for large-scale deployment and utilization.

![Graph showing comparison of output power between fixed flat-plate and IHCPV systems.]

Fig. 4. Comparison of similarly sized fixed flat-plate and IHCPV systems showing greatly enhanced energy production.
No other PV technology is positioned to reap the benefits of volume production levels in an accelerated fashion as is IHCPV. By utilizing industry standard manufacturing facilities and methods as described above, IHCPV is capable of being produced today at large-volume levels without the multi-year “ramp-up” required by other technologies. And, because all of the elements of the IHCPV system (solar cell, lens, structure) were designed for volume manufacturing at the onset, IHCPV will transit to volume production much faster (Fig. 5).

6. Summary

A near-term, cost-effective alternative PV technology is available for large-scale deployment: integrated high-concentration PV (IHCPV). This system combines world record performance with low cost of market entry, enhanced energy production, reduced land utilization, and accelerated benefits of volume production.

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References

