PV Technology Characterization Review

The PV market continues its explosive growth. Simultaneously, a wide array of commercially available PV technology and application options are emerging. While still a minor percentage of the global generation portfolio, PV technology represents a potential transformation from the traditional centralized energy market. Investments and strategic planning, both short and long term, require a comparative understanding of the PV technologies along with pertinent metrics, from the manufacturing process through deployment in the field. This report characterizes the following topics:

- Manufacturing processes
- Feedstock and materials availability
- Current and future production scales
- Module physical and operating characteristics (conversion efficiencies, substrates, weight, area footprint, degradation, temperature and light response)
- Module economics
- Balance-of-system requirements
- Market applications
- Environmental characteristics

Source: Tucson Electric Power

For technology characterization, it is important to understand the historical evolution of the technologies and markets. Over the past two decades, the PV market has changed from mainly off-grid applications with 70 percent of the market in 1992, to grid connected applications with 95 percent of the market in 2008[1].

Until the early 1990's, PV energy, from mainly distributed applications, cost 10 times the price of grid energy, mainly produced from central fossil and nuclear powered plants. These early markets were focused on the high value attributes of PV, free renewable fuel available anywhere, no grid infrastructure required and minimal environmental impact.

In the early to mid 1990's grid energy supply costs had increased, many distributed generating technologies, even beyond renewable, were approaching competitive terms. The traditional energy businesses, which were regulated natural monopolies, and public power were facing deregulation and privatization respectively. With energy a prominent concern, policy makers realized additional value attributes of PV technologies such as fuel diversity, energy security, and economic development. A wide array of policies in Japan, Europe (mainly Germany) and the US emerged, which subsidized PV applications and jump started the grid-connected market enough to stimulate research and manufacturing investments, expanding PV technology diversity.

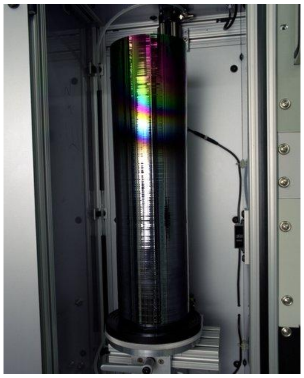
Flat-plate PV technology is subdivided into two main categories, crystalline silicon and thin-film. Crystalline technologies dominate the market and manufacturing capacity. However, thin films have emerged in the past decade, ramping up from 3 percent in 2002 to 14 percent in 2008. In addition, the largest PV module producer in

[1] IES-PVPS

2009 was no longer a crystalline silicon manufacturer, but a cadmium telluride thin-film producer, whose production grew from 25 megawatts (MW) in 2005 to more than 1100 MW in 2009. New producers of other thin-film technologies, such as amorphous silicon (a-Si) and copper indium gallium diselenide (CIGS), have successfully entered commercial production over the last year as well, and are beginning to see meaningful results in terms of commercial production. Simultaneously, a third wave of PV technologies such as organic PV and dye-sensitized cells are progressing in the research and development phases.

The report is focused on the PV technologies prominent in the market. PV technologies are primarily differentiated based on the nature of the absorber material that is responsible for converting light into electricity. The existing technology options can be classified into the following categories: (1) Crystalline silicon; (2) Thin films; and (3) Other PV technologies. Crystalline silicon technologies have three types, monocrystalline, multicrystalline, and ribbon silicon-based. Thin-film technologies include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium (gallium) diselenide (CIGS) PV. Other PV technologies include the less-commercialized and smaller-market segment technologies such as multijunction cells, concentrating PV, microcrystalline and tandem junction cells, “super” monocrystalline cells, dye-sensitized cells, and organic PV. Technology descriptions are provided for all technologies, but the main body of the report is focused on the market dominant thin-film and crystalline silicon technologies.

1. **Manufacturing Processes:** The main difference in the manufacturing of crystalline silicon and thin films is batch verses continuous, respectively. A continuous manufacturing process is typically easier to automate. However, most large-scale crystalline manufacturers use advanced robotics, diminishing the historically labor-intensive nature of crystalline technologies. Crystalline technologies begin with polysilicon, which is purified and grown or cast into an ingot. The ingot is then sliced into wafers that are used to produce photovoltaic cells. In the final step, the cells are assembled into modules. Thin-film modules are manufactured by depositing the absorber material directly onto a substrate which is then etched into cells and electrically connected. As the name implies, thin films use less absorber material.



Source: NREL, accessed 09/03/10.

2. **Long-Term Feedstock and Materials Constraints:** Silicon is the second most abundant element on earth and is virtually limitless in supply, such that polysilicon feedstock is not a material constraint in the long term. However, the PV market ramp of the last decade proved the crystalline silicon-based PV industry has not been immune to short-term supply constraints. The long lead times required to bring new polysilicon purification capacity online, led to feedstock price spikes and shortage between 2004 and 2008. Thin-film constituents such as tellurium and indium could be bottlenecks for terawatt-scale manufacturing of CdTe and CIGS respectively, given their evidently limited production potential. Global reserves for both elements are likely plentiful, however, and their recovery could be increased by the copper industry given sufficient economic incentive to do so. Commodity materials such as glass, plastic, steel, aluminum and copper are produced in large quantities and will not restrict the PV industry’s growth.

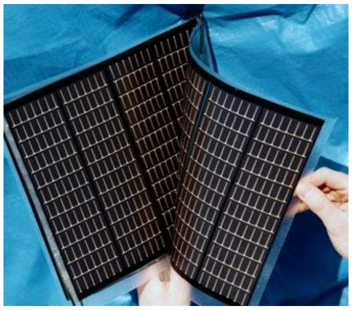
3. **Manufacturing Production and Capacities:** Crystalline silicon PV constituted the overwhelming majority of 2009 cell production, coming in at 8,020 MW, or 75 percent of all cells produced. At 1,019 MW, CdTe led thin-film production. Amorphous Si production came in at 796 MW. CIGS currently trails far behind with production at only 166 MW in 2009. While traditional crystalline silicon will constitute the majority of manufacturing capacity in the near term, its share of capacity is expected to decline from 80 percent in

2008 to 62 percent in 2012 due to significant gains for thin-film technologies. CdTe capacity is projected to stand at 2100 MW in 2012, from 733 MW at the end of 2008. 2012 CIGS and amorphous Si capacity could be as much as 2200 MW and 6000 MW respectively, compared to only 267 MW and 1,015 MW respectively at the end of 2008.

4. **Module Physical and Operating Characteristics:** There are two types of module characteristics, the physical and the operating characteristics. The physical characteristics of a module do not directly affect its energy production. Examples of physical characteristics include the substrate, weight and area footprint. The module efficiency, the photonic-to-electrical conversion, is an example of an operational attribute. Module efficiency directly affects a module's physical characteristics by determining a module's weight and space requirements. Additional operating characteristics of modules include efficiency degradation, temperature coefficient and spectral (light) response.

Efficiency is a key differentiator between technologies as it influences manufacturing costs, balance-of-system costs, and space requirements. There are five efficiency areas relating to PV technologies, starting from highest to lowest:

- Theoretical maximum cell efficiency is the analyzed, not measured, theoretical limit based on the cell's absorber material properties
- Research cell efficiency is generally measured on small "champion" cells individually made in a lab
- Commercial cell efficiencies are measured on small batches of unencapsulated, manufactured cells
- Commercial module efficiency is a market-ready measurement of commercial cells packaged together in a single, encapsulated module
- System efficiency, which includes packing-factor, thermal-degradation, module-mismatch, connection, wiring, inverter–efficiency, and other losses of the complete system.



Source: NREL, accessed 09/03/10.

This report details the ranges of all these efficiency measures across PV technologies. Traditional crystalline silicon technologies have significantly higher conversion efficiencies than thin films, with commercial monocrystalline silicon modules having higher efficiency (15-16 percent) than multicrystalline modules (13-15 percent). "Super" monocrystalline modules currently have the highest efficiency (as high as 19.3 percent). All three have increased 1-3.5 percent over the last five years due to continuing technological progress. Currently, commercially produced CdTe module efficiency stands at 11 percent, up from 7.6 percent five years ago, while CIGS modules have efficiencies in the 9-13 percent range, up from a maximum of 10 percent five years ago. Amorphous silicon efficiencies range from 6 percent for single-junction to 9 percent for tandem-junction technologies.

Module substrates are the encapsulants that provide the physical protection to the absorber materials. The brittle nature of crystalline silicon cells requires at least one side of the encapsulant to be glass and typically a glass-glass or glass-polymer packaging is used. Glass is also the dominant substrate used in thin-film manufacturing at present. However, materials such as stainless steel and plastic are being used to create flexible and lightweight thin-film PV modules.

The area footprint of a PV system is inversely proportional to module efficiency. Compared with traditional crystalline Si panels, thin-film PV panels generally have lower energy conversion efficiencies and thus require a larger area to generate the same amount of power. Higher efficiency modules are also generally lighter than lower efficiency ones for a given power output; however, the calculation can be complicated by the fact that different technologies have different substrate and framing designs, which can make non-trivial differences.

Module operating characteristics affect energy production, differ between technologies, and include long-term efficiency degradation, temperature coefficient and spectral sensitivity. Crystalline modules have minimal efficiency degradation. After a 20-year operating period, monocrystalline and polycrystalline modules seldom produce below 92 percent of their nominal capacity, which is well above the typical manufacturer's warranty of 80 percent, yielding an annualized degradation rate of around 0.5 percent per year. In the case of amorphous silicon cells, high degradation is observed in the first weeks to months of performance (anywhere from 10 percent to 50 percent) due to exposure to light. However, recent studies have shown that annual degradation rates of thin-film modules do not vary greatly from crystalline modules. CIGS technology does not exhibit meaningful long-term degradation, unless exposed to moisture, which necessitates robust and rigorous edge sealing and encapsulation methods.

All PV technologies exhibit some reduction in performance under high temperatures. Thin-film PV technologies generally have a lower temperature coefficient than standard Si modules, meaning they will not lose as much power in hot summer conditions. Overall, amorphous silicon performs the best under high heat, followed by CdTe, CIGS, monocrystalline silicon, and standard multicrystalline silicon[2]. Regarding sensitivity to lighting conditions, crystalline silicon cells are particularly sensitive to long-wavelength, amorphous silicon can absorb short-wavelength light optimally, and medium wavelengths are optimized for CdTe and CIGS. As a result, thin-film cells have higher performance under low light and cloudy conditions. Complete shading of one cell in a crystalline silicon module can reduce module output by a factor of 50 percent; by contrast, in a thin-film module, power loss is often proportional to the shaded area, though this depends on the circuit design and shading pattern.

5. **Module Economics:** Currently, CdTe is the lowest-cost PV module option on the market, with fully loaded costs under $0.90/W realized. Amorphous silicon and CIGS can be produced for roughly $1.20 – 1.80/W depending on manufacturing scale, although few CIGS manufacturers have reached this production level to achieve this cost. Crystalline silicon PV, depending on scale, degree of vertical integration and manufacturing location, can be produced for anywhere between $1.60/W and $2.30/W, while high-efficiency or "super" monocrystalline silicon PV is currently the most expensive at just under $2.50/W today, though it does have substantially higher efficiency. By 2015, manufacturing costs are expected to drop significantly across all technologies. "Super" monocrystalline silicon could be produced for just under $1.50/W. Multicrystalline silicon PV could be manufactured for as little as $1.10/W, while all three thin-film technologies are expected to have costs under $1.00/W. As opposed to costs, module prices are a function of efficiency differences and prevailing market conditions, and one cannot be assumed as a proxy for the other.
6. **Balance of System Requirements:** For traditional multicrystalline and monocrystalline silicon-based technologies, the decision as to whether or not to employ a tracking system generally depends on the insolation level and the price paid for solar energy production. A high percentage of high-efficiency monocrystalline systems are deployed with trackers. While lower concentration CPV systems may be deployed without the use of trackers, medium and high concentration systems will not work at all without tracking, so some form of tracking is mandatory; medium concentration systems (using silicon-based cells) tend to utilize single-axis tracking, while higher concentration systems (using multijunction technology) always employ double-axis trackers. The three commercially existing thin-film options typically use fixed mounts and do not employ trackers. The inverter is the electronic interface between the solar array and the electric grid or load being served. The main function of the inverter is to convert the DC PV power to AC grid power. Most system designs use centralized inverter architecture. Centralized inverters tend to be located away from heat and weather extremes, thus extending the inverter's lifetime. With the use of centralized large inverters, when conditions (lighting, shading, temperature, soiling, etc.) from panel to

[2] This report only examines widely used PV technologies. Multijunction cells perform best under high heat, but they are not discussed in detail in this report.

panel vary, the resulting power output can be dramatically and negatively impacted. However, recently micro-inverters, which are essentially an inverter on every module, have emerged on the market. Micro inverters optimize the conversion on each module, and when the inverter fails, only that module fails. Historically, inverters have been the least reliable component of the PV system and were associated with potential power quality problems. However, the high-growth market, research and standards work have diminished these inverter attributes and the inverter is seen as potential smart grid intelligence and reactive power supply in utility applications.

7. **Market Applications:** Crystalline silicon modules are most commonly utilized for residential installations because of their higher conversion efficiency and consequently smaller footprint. Both crystalline silicon and thin-film PV are equally utilized in commercial and utility-scale applications. Within the building-integrated photovoltaics (BIPV) realm, thin-film PV has an advantage over traditional crystalline silicon-based PV in that it can be deposited on flexible substrates and used as roofing material in residential and commercial applications.

Source: NREL, accessed 09/03/10.

8. **Environmental Characteristics:** During operation, PV systems have zero emissions. The environmental impacts of PV panels occur primarily as a result of conventional energy used during the manufacturing process for the cells, modules, mounting systems, and other BOS components. Additionally, the disposal of the panels after their end-of-use may have impacts. Life cycle analysis (LCA) is an assessment of raw materials and energy, operation, maintenance, and end-of-life disposal. This report focuses on the energy and emissions results from recent PV technology LCA studies. Energy payback time EPBT is an LCA measure for the time it takes a PV system to generate the same amount of energy required to manufacture the system. Since the electric generation is dependent on the location or solar resource available to the system, the EPBT will vary for different regions. However, in the same location, southern Europe, the EPBT for crystalline technologies is slightly higher compared to thin films. This is mainly due to the energy required during the ingot and cell phase of manufacturing.

   In addition to the greenhouse gases related to the energy required for manufacturing, there are chemicals used during manufacturing that may have environmental impacts if improperly handled. Silane, a pyrophoric and toxic gas, is used in crystalline and amorphous silicon manufacturing and CdTe is also a toxic substance.

   Some manufacturers also include end-of-life recycling as part of the system cost, similar to some appliance manufacturers to insure minimizing both material waste and environmental impacts.

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SEPA Research Report Summaries

Electric Utilities and Solar: A Market Review (2008)
This utility solar market report, which includes the solar integration rankings, discusses future solar market development issues that have arisen in 2007 and 2008, and their implications for utility involvement in solar.

Utility Solar Procurement (2009)
This report identified best practices for traditional utility solar procurement (RFPs/PPAs) and innovative new acquisition methods that may present cost or efficiency solutions for both utilities and the solar industry.

Utility Solar Tax Manual (2009)
In 2008, Congress extended the federal solar investment tax credit for eight years and removed the utility exemption, allowing regulated investor-owned utilities to utilize the credit. This manual provides detailed explanations of the tax provisions related to the bill, as well as exploring other tax issues such as Clean Renewable Energy Bonds, and unique business tax structures and issues.

Decoupling Utility Profits from Sales: Issues for the Photovoltaic Industry (2009)
The reduced sale of electricity creates an inherent problem for electric utilities in maintaining long-term operating revenue, especially as the solar industry expands. Decoupling is a regulatory policy option that can change the way utilities recover revenues to adjust this disincentive. This decoupling white paper introduces the concept into the solar community, explaining what decoupling is, and defining the different types. It includes a case study showing how solar market development in the future might affect utility rates under decoupling.

Distributed Photovoltaic Generation for Regulated Utilities (2009)
This analysis looks at both the regulatory and practical issues surrounding the installation of utility-owned distributed photovoltaics by investor-owned utilities.

Photovoltaic Incentive Programs Survey (2009)
In coordination with SEPA, an electronic survey was developed and distributed by U.S. utility and state PV incentive program managers to consumers who installed PV systems and received a rebate to offset the cost. The survey asked about the participants' satisfaction and experiences with the installation, incentive, interconnection, and ongoing maintenance of their systems. The resulting report analyzed the data across geographies to draw distinctions and parallels across the country

Top Ten Utility Solar Rankings 2009 (2010)
This report is the third of SEPA's annual survey of US utilities' grid connected solar. The results are top ten rankings of the most solar integrated utilities.

International Utility Survey: Utility Procurement Influences & Practices (2010)
Gartner and SEPA conducted a survey of 134 utilities in Europe and the United States to understand their requirements and objectives for implementing photovoltaic (PV) technologies in their energy generation portfolios. This telephone survey was complemented, in the U.S., by an online survey.