PN. ABN-558 8/3

U.S. AGENCY FOR
INTERNATIONAL
DEVELOPMENT

A Report of the

Office of Energy and Infrastructure

Technical and Commercial Assessment of Amorphous Silicon and Energy Conversion Devices, Inc., Photovoltaic Technology

Bureau for Research and Development
Agency for International Development
Washington, D.C. 20523-1810

Report No. 92-04

A Report of the

Office of Energy and Infrastructure
Bureau for Research and Development
United States Agency for International Development

TECHNICAL AND COMMERCIAL ASSESSMENT OF AMORPHOUS SILICON AND ENERGY CONVERSION DEVICES, INC. PHOTOVOLTAIC TECHNOLOGY

Prepared by:

International Development and Energy Associates, Inc.
1111 14th Street, N.W., Suite 500
Washington, D.C. 20005

Renewable Energy Applications and
Training Project, 936-5730
DHR-5728-C-00-9074-00

December 1992

DISCLAIMER

The information contained in this report is largely a compilation of publicly available information. The author attempted to report information that is pertinent to the subject treated and objective in its content. The information contained in this report can not be attributed to the United States Agency for International Development.

ACKNOWLEDGEMENTS

The author of this report is Paul Hesse of IDEA, Inc. He would like to thank the following individuals for their various contributions to this report: Nancy Bacon, Energy Conversion Devices, Inc. (ECD); Cubhendu Guha, ECD; Carl Hocevar, IDEA, Inc.; Paul Maycock, PV Energy Systems, Inc.; Byron Stafford, Amorphous Silicon Photovoltaics Program, National Renewable Energy Laboratory; Jerome Weingart, IDEA, Inc.; and John Wiles, Southwest Technology Development Institute.

TABLE OF CONTENTS

Background and Purpose I

Key Issues I

Executive Summary E1

Issue 1: Status and Related Issues of A-Si Development 1
Commercial Status 1
Key Technical Issues 2
Research and Development 5
Prognosis for Future Commercial Development 6

Issue 2: The Status of ECD A-Si Technology 9
Corporate History 9
Commercial Activity - Joint Ventures 9
Commercial Product Performance 10
Recent R&D Efforts 14
Issues and Requirements for Continued Commercial Expansion 14

Issue 3: Status and Prospects for Other PV Technologies and A-Si Competitiveness By Application 17
Competing Technologies 17
Single and Poly Crystalline Silicon Cells 17
Concentrator Cells 17
Ribbon Silicon 18
Other PV Technologies 18
Environmental, Health, and Safety Considerations 20
Applications 21
Large Power Demands 22
Medium Power Demands 22
Low Power Demands 23
PV Market Expansion 23

Issue 4: Issues and Requirements for and In-Depth Assessment of ECD Technology Scale-Up 27

References 29

TECHNICAL AND COMMERCIAL ASSESSMENT OF AMORPHOUS SILICON AND ENERGY CONVERSION DEVICES PHOTOVOLTAIC TECHNOLOGY

BACKGROUND AND PURPOSE

The Office of Energy and Infrastructure of the U.S. Agency for International Development (USAID) and the Rockefeller Foundation are providing support to a U.S./Indian joint venture (Energy Conversion Devices/Suryovonics) effort to assess the market potential for a large-scale facility for the manufacture of amorphous silicon (a-Si) photovoltaic (PV) modules in India. An assessment of a-Si PV technology, in general, and of the Energy Conversion Devices (ECD) technology, in particular, is necessary to provide the Office of Energyand Infrastructure, the Rockefeller Foundation, and other potential donors with a basis for supporting investment decisions for the ECD/Suryovonics joint venture manufacturing and market development efforts. The purpose of this assessment is to identify and discuss the key issues related to the current and future commercial potential of the ECD a-Si technology. A detailed technical description of the technology is beyond the scope of this report. The reader requiring more detailed information should refer to the references for this report and to the PV literature.

KEY ISSUES

The key issues addressed in this assessment are:

1. The status of a-Si technology in general including commercial products and market share, technology research and development (R&D), and current costs and projections for module costs per peak Watt (Wp) and per kWh of power produced under various assumptions;

2. The status of ECD and its proprietary a-Si alloy technology including the corporate history and commercial activities of the company, the commercial status and performance of its technology and the status of its manufacturing process and product research and development, and the requirements for the company and its joint venture partners to compete in targeted markets;

3. The commercial status, likely R&D and manufacturing developments, and projected costs per Wp of the major competing PV technologies, the comparative advantages of a-Si other than cost in large, medium, and low power demand applications, and the potential world-wide market growth for PV and the implications for ECD and its joint venture partners; and

4. The scale-up of the ECD manufacturing process to a level that will achieve module production costs of less than $1/Watt peak (Wp) and the requirements for conducting an in-depth assessment of the technical feasibility of such a facility.

EXECUTIVE SUMMARY

Issue 1: Technology Status

In 1990, a-Si based PV cells/modules comprised approximately 35% (17 MW) of total worldwide and 15% (2.1 MW) of U.S. PV cell and module shipments. The majority of these a-Si cells and modules were used in low-power, "consumer products" applications with power loads of less than 50 Watts peak.

Various qualities of a-Si will ensure the continued commercial development and expansion of the technology. The major qualities are:

- a-Si cells can be produced in very small to large sizes of any shape;
- the a-Si material can be deposited on low cost, lightweight, flexible substrate; and
- cell and module manufacturing can be highly automated with a large throughput, therefore achieving economies of scale production.

The principal technical issues facing a-Si technology development are:

- a low sunlight to electricity conversion efficiency (relative to other PV cell technologies);
- a significant and permanent degradation of conversion efficiency on initial exposure to sunlight; and
- the stabilization of this degradation over time and therefore the useful operating life of a-Si cells and modules.

Results of field performance monitoring programs in the U.S. on various brands of a-Si modules and arrays demonstrate that:

- module power output efficiencies degrade 10 to 40 percent from initial efficiencies within six months of exposure to sunlight;
- the rate of efficiency degradation levels off or "stabilizes" after this period to about 1/5th to 1/10th the initial rate; longer term monitoring results are necessary to assess long-term degradation rates and cell operation life;
- "stabilized" efficiencies among commercially available modules range from 3.5 to 6.5 percent (at Standard Test Conditions; see Section 2);
- cell/module efficiencies increase slightly with increases in ambient and module temperatures;
- early module design and fabrication among some manufacturers was poor, but has improved substantially in the past five years; and
- newer modules perform reliably.

Over half of all U.S. based PV technology R&D is targeted on a-Si technology development to improve efficiencies and manufacturing techniques. This R&D ranges from basic material and cell technology to module design and manufacturing. Efficiencies approaching 14% have been achieved for triple-junction a-Si cells and 8% for modules in research laboratories. However, these laboratory successes have not been fully transferred to commercially available modules.

According to some industry experts, there is a high probability that manufacturers of a-Si cells/modules will achieve module production costs close to $1/Wp by 2000 if:

- laboratory advances in cell/module design and performance (large area, multi-junction devices with at least an 8% stable efficiency) are commercialized; and
- manufacturing process are improved and scaled-up so that high continuous yields of 90% or more are achieved in plants on the order of at least 10 MWp annual production capacity.

Costs of PV generated electricity on a life-cycle, kWh basis are the major determinants of PV competitiveness with other electricity generation technologies and among PV technologies themselves. These costs are system design- and site-specific since they are a function of many factors including: the costs and operating lives of the modules and all other system components (less any tax credits and depreciation allowances); costs of shipment, installation, insurance, financing, land, and maintenance, and the amount of power produced as determined by module efficiency; and site-specific solar insolation regime and environmental conditions.

However, cell/module efficiency and long-term reliability or operating life are and will continue to be the major factors determining PV system kWh costs and the continued commercial expansion and competitiveness of a-Si technology with other PV technologies particularly in the larger power module markets. Unless higher, stable efficiencies and module operating lives of at least 20 years are attained, the installed cost of power per kWh on a life-cycle basis may be uncompetitive. Commercial modules need to be backed by at least a 10 year warranty to provide customers with confidence in the technology. Some a-Si manufacturers are offering this level of warranty.

Approximately six companies in the U.S. are producing or are planning to produce commercial a-Si modules, most of which are 10-20 Wp nominal capacity for low-power applications. Several firms are developing larger modules (40-60 Wp nominal) for higher power demand or utility scale applications. Advanced Photovoltaic Products (APS) is constructing a 10 MW annual production capacity plant in California.

Issue 2: Overview of Energy Conversion Devices

Energy Conversion Devices (ECD) is one of the oldest U.S. a-Si technology developers. The company has received considerable government and private industry support which has resulted in significant progress in the development of low-cost a-Si manufacturing techniques and equipment and improved cell/module design and performance. ECD's proprietary process can produce single and multi-junction cells deposited on 1 foot by 2500 foot rolls of flexible stainless steel sheets.

ECD has recently formed joint manufacturing ventures with Japanese, Russian, and Indian companies. The ECD/Canon joint venture, United Solar Systems Corporation (USSC), has scaled-up the former Sovonics plant in Troy, Michigan to a capacity of 2 MW/year and is marketing modules for a range of power demand applications. ECD is in the process of transferring a 2 MW/year triple-junction cell/module manufacturing plant to its Russian joint venture partner (KVANT). ECD is investigating the possibility of a scaled-up 4 MW annual capacity plant for installation in India and Russia.

ECD commercial module quality improved significantly during the period between initial production and when the Sovonics line became United Solar Systems Corporation (USSC) in 1990. Average DC conversion efficiencies for Sovonics arrays in field performance monitoring programs by Detroit Edison in 1987, and PVUSA in 1989, have "stabilized" at 3.5% to 4%. This is 1/3 to 1/2 the efficiency of arrays of flat-plate crystal silicon PV based arrays commercially available. The arrays exhibit seasonal fluctuations in efficiencies -- efficiencies increased in summer months (correlated to higher ambient and module temperatures and possibly caused by annealing of the a-Si material) and decreased in winter months (correlated to a higher ratio of infrared radiation which a-Si does not respond to). These fluctuations are the opposite of those recorded for crystal silicon modules. Despite low efficiencies, the modules and arrays have performed reliably.

Laboratory research conducted by ECD under contract to the U.S. government has achieved cell efficiencies of 13.7% for a triple-junction device which is the highest for an a-Si device. After 240 hours of one-sun exposure, 13% efficient cells degraded approximately 13% to 11.3% efficiency. ECD is undertaking research and development to produce multi-junction modules with a target stable efficiency of 12%.

Transferring these laboratory achievements to commercial products and producing a consistently reliable, high quality module are the crucial issues facing ECD in competition with other PV companies, especially in the larger power demand markets. ECD has just recently been awarded an $8 million cost-share contract with the National Renewable Energy Laboratory under the PVMAT program (see section 1) to improve module manufacturing processes and achieve lower costs on a Watt peak output basis.

The trend in improvements in its commercial product, and in the focus and pace of technology R&D, suggests that ECD and its various joint venture manufacturing partners have the potential to produce competitive modules for larger power applications. Field trials of the triple-junction modules produced by the machine built for Sovlux would provide important data on the performance of this technology.

Manufacturing process scale-up, and therefore economy-of-scale production, will also be a significant factor in ECD's ability to significantly reduce module costs per Wp. Current manufacturing plant sizes with annual production capacities of 2 MW may require a significant scale-up to at least 10 MW/year or more to achieve module production costs below $2/Wp. The ability of ECD to realize a scale-up of this magnitude and maintain or increase module efficiency and stability should be addressed in a detailed engineering study (Issue 4).

Issue 3: Competing Technologies, Applications, and Market Forecasts

The leading PV technology competitors of a-Si are single- and poly-crystalline silicon, ribbon/sheet, and concentrator cell technologies. Other technologies which have yet to be commercially demonstrated on any scale are various non-silicon alloy thin-films and the Texas Instrument spherical cell technology.

There is a high potential for achieving a-Si module manufacturing costs below $1/Wp by 2010 assuming technical R&D achievements are transferred to commercial modules and significant scale-up in manufacturing occurs.

Environmental, health, and safety considerations associated with PV cell/module manufacturing and system installation or construction apply equally to all PV technologies. The principal area of environmental concern is in manufacturing where many hazardous and toxic substances are used. Correct in-plant procedures and controls should adequately protect workers and contain these potential hazards to the manufacturing site. Use of toxic compounds in some non-silicon alloys may pose a problem at module decommissioning and disposal.

The application in which PV technologies are employed is an important determinant of the relative competitiveness between PV technologies. The broad categories of applications used in this report are large power demand (utility or central station scale); medium power demand (remote, stand-alone, decentralized applications); and low power demand (consumer products and appliances).

A-Si technology will most likely maintain its dominance in low-power consumer products applications due to inherent characteristics (see Issue 1) which provide a-Si cells and modules with a competitive edge over crystalline cells. This market should continue to expand as new applications are developed and cell/module prices decrease. The ECD technology may have a comparative advantage in these applications due to the light-weight, ruggedness, and flexibility of the modules.

A-Si technology faces significant competition in medium and large power markets with other PV technologies. The principal determinant of a-Si competitiveness in these markets will be life-cycle costs per kWh which in turn will be largely determined by module prices per Wp and module operating life (all other factors such as balance of systems and installation costs and the site specific solar insolation regime and environmental conditions being equal). At present the ECD module technology does not hold any comparative advantage over other PV technologies in these applications except where low weight and ruggedness may be advantageous.

World-wide market expansion for photovoltaics is very promising. Even if market conditions do not improve substantially over those existing now, and technical improvements continue as they have in the past, annual sales of PV modules could increase from a current level of 50 MWp to 100 MWp in the next four years and approach 200 MWp by 2000. By 2010, the market could be on the order of 800 MWp. The majority of this market growth will be in medium power demand applications. The implications for ECD and its joint venture partners are positive; there should be ample opportunity to continue further commercial expansion especially in the low power applications market.

Issue 4: Scaling-Up ECD Manufacturing Technology

A detailed engineering and production cost analysis would be required to determine the feasibility of scaling-up the current ECD manufacturing technology capable of 1-2 MW annual production capacity to one that will achieve module production costs of $1.00/Wp and with guaranteed operating lives of at least 20 years. Such an analysis is beyond the scope of this report; however, key issues that must be addressed in the analysis are:

- the realistic and achievable stable efficiencies and operating lives for the single and triple-junction modules currently under development;

- the level of production required to achieve these costs;

- the technical challenges involved in scaling-up and whether it is likely that they can be addressed economically;

- the effects of scale-up on cell/module performance and reliability;

- the site and country specific issues and conditions that will affect the technical feasibility of the construction and operation of such a facility including raw material and power supply, plant siting, quality and environmental controls, operator skill levels and training requirements, etc.;

- the likely time frame for the design, planning, construction, and commissioning of such a facility; and

- the capital cost and financing requirements for such a plant.

An assessment of this nature will require a specialized team of individuals with in-depth experience in PV technology and process scale-up. This team would require access to confidential and proprietary information on the ECD technology in order to provide a realistic determination of the feasibility of a scale-up of the magnitude envisioned. The confidentiality of their investigative activities would have to be guaranteed.

ISSUE 1: STATUS AND RELATED ISSUES OF A-Si DEVELOPMENT

Commercial Status

The commercial development of a-Si technology has progressed significantly over the past decade increasing from a very small share of the total PV market in the early '80s to around 35% by 1989 (PVIP, 2/91). Most of the a-Si market has been in "consumer products" applications which include solar-charged battery-powered calculators, watches, radios, outdoor lighting, etc, with cell/module outputs less than 20 Wp. Japanese corporations produced at least 65% of the total a-Si sold in 1990.

A-Si cell/modules held about 15% of the total U.S. 1990 PV market share (PV News, 2/91) with the majority used in consumer products. Table 1 presents the U.S. market share of the leading PV technologies and the distribution of module shipments for major categories of applications according to the amount of modules shipped in MW.

Table 1
1990 U.S. PV Module Shipments
By:

Technology	MWs	%	Application	MWs	%
Single crystal silicon	7.2	48.6	Grid-Connected	4	2.7
Poly-crystal silicon	5.4	36.6	Central Station > 1 MW	--	NA
Amorphous silicon	2.1	14.8	Exports	6.4	43.2
Concentrator crystal silicon	.03	.002	Off-grid Resid.	2.8	18.9
Ribbon si.	.05	.003	Gov. Projects	.5	3.4
			Off-grid Indust. and Commercial	2.5	16.9
			Consumer Prod.s	2.2	14.9
TOTAL	14.8	100		14.8	100

The use of a-Si in consumer products reflects several advantageous characteristics of the technology. Principally these are the ability to be produced in any shape and in very small cell sizes, and a better response to low-light levels and fluorescent light relative to other PV cell technologies thus allowing their use indoors for calculators, watches, etc.

The expansion of a-Si technology into the total PV market lost ground in the past three years for various reasons -- the relative share of the consumer products market within the total has declined; a-Si manufacturers have not delivered a competitive module for large and medium power demand applications (which are growing strongly); and several Japanese corporations have aggressively pursued the development of low cost crystalline power modules. As a result, a-Si market share slipped to approximately 32% of the world-wide total in 1990. To date, a-Si based modules make up a very small number of the larger power modules (40 - 60 Wp nominal) sold which are used in applications ranging from off-grid and grid-connected residential and commercial power supply to central station power generation.

There are currently six U.S. a-Si module producers: Energy Conversion Devices/United Solar Systems Corporation (USSC); Advanced Photovoltaic Systems (APS); Iowa Thin Film Technologies (ITFT); Solarex; Utility Power Group (UPG); and Energy Photovoltaics (EPV). Besides ECD/USSC, which is discussed in Section 2, APS, Solarex, and UPG are moving ahead in developing 30 Wp and larger modules.

APS is producing 50 Wp modules targeted for utility applications at its Trenton, New Jersey plant, and is constructing a 10 MW/year production capacity plant in California. APS plans to provide 400 kW of modules to the PVUSA facility in Davis, CA, and then sell modules on the general market. ITFT plans to build a 1 MW capacity pilot plant which will produce single-junction a-Si cells on a flexible plastic substrate for low power applications. Cells produced to date stabilize at about 4% efficiency. Solarex is one of the oldest U.S. producers of a-Si products and one of the earliest producers of a reliable and stable commercial module. Solarex has a highly regarded and productive a-Si research team that has received several SERI (now NREL) R&D contracts totalling some $13 million. At the same time, the company has a heavy investment in poly-crystal production. Solarex a-Si production is currently focused on consumer products, but is reported to be developing a 10 MW/year capacity multi-junction production line for larger modules.

Key Technical Issues

In principal, the concept of amorphous silicon cell technology has important implications for achieving low-cost solar electricity due to its low material intensity (1/50th to 1/100th that of thick-film cells) and adaptability to thin-film, continuous deposition techniques onto low-cost, light-weight, and flexible substrates. Thus low manufacturing costs may be realized from low material input - large throughput automated production.

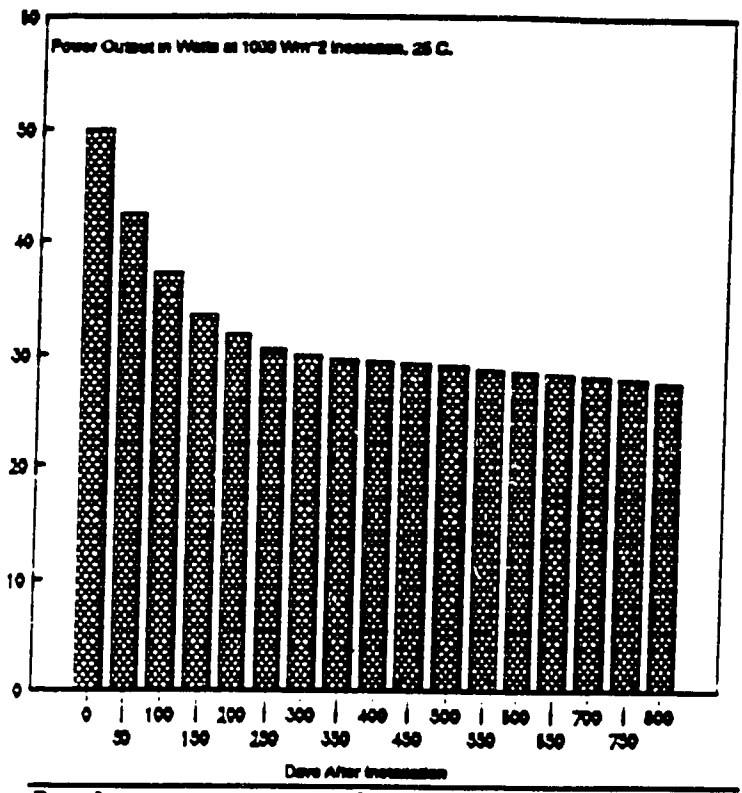
Despite these characteristics, three important technical issues have constrained the application of a-Si technologies in meeting medium to large power loads. These are:

- a low sunlight to electricity conversion efficiency (relative to other PV cell technologies);
- a significant and permanent degradation of conversion efficiency on initial exposure to sunlight; and
- the stabilization of this degradation over time and therefore the useful operating life of a-Si cells and modules.

Low energy conversion efficiency has plagued a-Si technology ever since it was developed. Although improvements have been made through laboratory research and development efforts, a-Si module manufacturers have yet to deliver a commercial module capable of an initial 10% conversion efficiency. (See Figure 3)

Coupled with low initial efficiencies of a-Si technologies is the troublesome characteristic of degradation in efficiency over time. This effect, named after Staebler and Wronksi who are credited with its discovery, begins with an initial, marked decline in power output or conversion efficiency of between 10% to 45% of initial ratings (depending on the type of device) within the first month of exposure to sunlight. This degradation levels off over several months to a rate 1/5th to 1/10th of the initial rate of degradation. Figure 1 depicts this effect from a plot of power output measured at Standard Test Conditions (STC) of 1000 W/m^2 insolation and 25°C module temperature, and 1.5 Atmospheres.

Figure 1: Degradation in Power Output Over Time For a 'Typical' A-Si Module



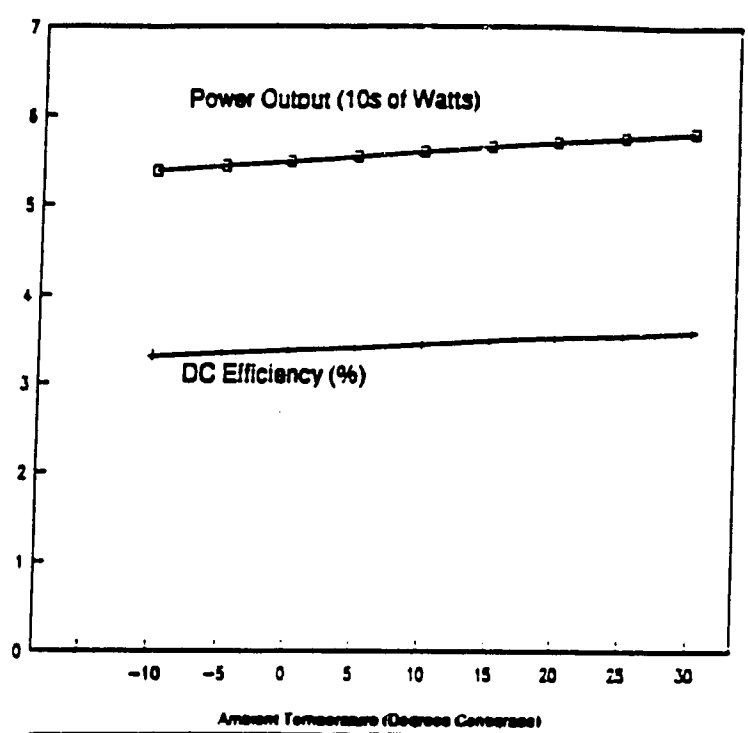
Data Source: Interpreted from Sandia & STDI, 1/90.

Performance monitoring of commercially available a-Si modules and arrays over periods ranging from 2 to 5 years at the Photovoltaics in Utility Scale Applications (PVUSA) facilities in Maui, Hawaii and Davis, California, at a Detroit Edison facility, and by Sandia National Labs and the Southwest Technology Development Institute (STDI) report "stabilized" average DC operating efficiencies of 3.5% to 4.1%. NREL is testing production modules but no results have been reported to date.

For comparison, average module efficiencies for single-crystal modules are around 12-13%, and 10-11% for DC efficiencies. Although results of these field performance monitoring programs indicate that a-Si module efficiencies level off, longer-term results are needed to determine at what level efficiencies stabilize in actual field conditions.

Another characteristic of some a-Si cells/modules which is important in comparison with other silicon based PV technologies (single- and poly-crystal) in terms of applications is the effect of temperature on system performance. Average a-Si cell performance under increasing ambient and module temperature is different from that displayed by crystal silicon devices. Crystal silicon cell devices experience a .3% to .5% decrease in power output per degree Centigrade increase in module temperature due to a temperature induced voltage drop. Many single and poly-crystal manufacturers produce a higher voltage module for hot-climate applications to compensate for this effect. Some a-Si devices on the other hand experience a slight *increase* in conversion efficiency and power output with an increase in module and ambient temperatures. This effect is depicted in Figure 2.

Figure 2: Temperature Affects on Power Output and Efficiency for a "Typical" A-Si Module



Data Source: Sandia/SWRES, 1/1990

The reasons for this effect are not fully understood as changes in air mass and the solar radiation spectrum may play a role and because a-Si material changes, or anneals, in response to increases in temperature. This characteristic may be beneficial in hot climates and in building applications since an a-Si module will not require cooling to maintain performance and thus can be "flush" mounted or incorporated into building architecture, for example as roofing tiles. Thus a-Si may have a comparative advantage with other PV technologies in these applications (if Wp costs are comparable and longterm efficiencies are stable).

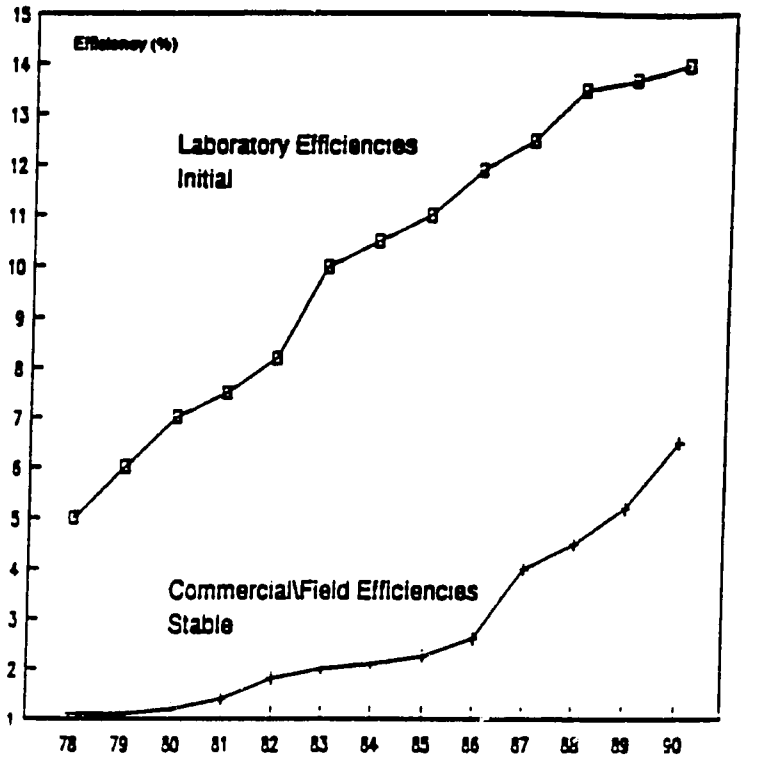
A-Si manufacturers were historically relatively unsuccessful in marketing their modules for applications other than consumer products due to the problems of low and degradable efficiencies and an early track record of poor module quality -- fabrication and assembly (lamination, sealing, encapsulation) and junction box designs were sub-standard. However, significant improvements have been made in the past few years, and manufacturers now produce modules of the quality and design required for multi-module array assemblies in extreme environmental conditions and constant exposure to the elements. Commercially available modules are also very rugged and able to withstand rough handling. The results of system field performance monitoring programs indicate that module/array performances are reliable (PVUSA, 1990).

Research and Development

U.S. government, utility, and industry R&D has focused on addressing efficiency and stability issues with some encouraging success. A significant percentage of total PV industry R&D is targeted on a-Si with an estimated $80 to $100 million in U.S. dollars being spent annually. The focus of U.S. government sponsored a-Si research is undertaken by the U.S. Department Of Energy (DOE) Amorphous Silicon Research Project managed by the National Renewable Energy Laboratory (NREL) (formally the Solar Energy Research Institute - SERI). Under this program, government, university, and government-industry cooperative research is being conducted on cell and module design, material alloys, new deposition techniques, and plasma diagnosis. This project constitutes about 25% of NREL's FY88 to FY92 PV R&D budget, which is indicative of the importance that NREL places in the potential for a-Si technology to achieve low cost power.

One result of the program is the highest laboratory scale a-Si cell efficiencies achieved to date which approach 14% for small area, triple-junction devices, and 6-7% for commercial and prototype modules (Stafford, NREL, 1991). Importantly, these laboratory efforts have led to improvements in the performance of commercial modules. Figure 3 illustrates the progress in improvements of a-Si conversion efficiencies in laboratory and commercial systems from 1978 to 1990.

Figure 3: Progress in A-Si Device Efficiency Improvements for Laboratory and Commercial Modules



Source: Sandia Nat. Lab. 1/90 and NREL. 1991.

NREL has recently initiated a new "A-Si Utility/Industry Power Project" with a goal of developing a-Si power systems with improved stability and performance, and is also sponsoring industry R&D in targeted efforts to improve module manufacturing techniques and quality and thus reduce manufacturing costs through the PVMaT project. Several a-Si manufacturers are involved in this project. NREL believes that a-Si modules with 8% stable efficiencies are attainable by the mid-to-late 1990s.

The Electric Power Research Institute (EPRI) also sponsors a-Si technology research and development at various universities and cooperates with DOE in various PV projects which include a-Si technologies.

Prognosis for Future Commercial Development

The key issues facing the future commercial development of a-Si technology (see Issue 3 discussion below) are: whether or not the success of laboratory developments can be transferred to commercial products; if the low material intensity and automated manufacturing cost advantages of a-Si will compensate for low power output; and at what rate can low cost technological improvements in manufacturing be achieved. Addressing these issues is largely a matter of making educated judgements based on the realized and projected R&D developments and the ability of a-Si producers to transfer these laboratory results to commercial products.

According to a recent analysis by PV Energy Systems, Inc. (PVES): "Amorphous silicon thin-films (single and multi-junction) will gain an increasing share of the world PV market by 1995 (including consumer products) and will result in direct competition between Japan and the U.S. Module efficiencies will increase 6% to 10% by 1995. Profitable module prices below $2 per Watt are likely by 1995 and certain by 2000. Stacked cells of amorphous silicon, a-Si/germanium, and copper indium desalinate may be marketed in 1992-93 and could be the principal product by 2000 with prices less than $2/Wp and module efficiencies of 14%. Relative to other PV technologies "thin film a-Si cells and high efficiency concentrator modules have the highest probability of reaching module 'prices' below $2,000 per kW." Table 2 depicts the PVES forecast for a-Si technology over the next 18 years. This forecast is depends upon:

- obtaining commercial module efficiencies (stable) of at least 8%;
- commercializing multi-junction cells;
- developing large area cells of one square meter or larger;
- achieving continuous high yields of 90% of in-line manufacturing processes; and
- building production facilities with 10 MW per year capacity.

Table 2: Amorphous Silicon Technology Forecast: 1990 -2010

Factor	1990	1995	2000	2010
Cell Efficiency (%)	5-7	8 -10	10	12
Module Efficiency (%)	5	7-9	9	11
Area Yield (%)	70	90	90	95
Warranty (Years)	5	5	10	10
Manufactured Cost ($/Wp)	3.00	2.00	1.20	.90
Price ($/Wp, 40% GPM)	5.00	3.33	2.00	1.50

Source: PV Energy Systems, 6/91

Stabilized module efficiency and long-term reliability or operating life will continue to be the major factors affecting the commercial expansion and competitiveness of a-Si technologies, especially in the larger power module markets. Lower manufacturing costs may offset lower relative efficiencies of a-Si modules to produce competitive module prices on a Wp basis. However, even if a-Si module purchase prices on Wp basis are competitive with other PV technologies, unless stable efficiencies and comparable module operating lives are ensured, costs of power per kWh on a life-cycle basis will be higher. Therefore, a 20 year a-Si performance life must be guaranteed and manufacturers should back their modules with at least a 10 year warranty to provide customer confidence in the technology.

ISSUE 2: THE STATUS OF ECD AMORPHOUS SILICON TECHNOLOGY

Corporate History

Energy Conversion Devices (ECD) has been developing a-Si technologies since the mid-1970s with considerable technical and financial support from both private and governmental sources. An early investor was ARCO Solar which contracted ECD in 1978 for $9 million to develop an a-Si device on a steel substrate. In 1980, Standard Oil of Ohio (SOHIO) initiated a $50 million program with ECD to work on all aspects of a-Si technology including device design, material deposition, and substrate cleaning in a state-of-the-art laboratory. When British Petroleum (BP) took over SOHIO in 1986 this arrangement terminated, and ECD continued R&D and production under the name of Scvonics until 1990. This early support and subsequent cooperation with and funding from Sharp, SERI, and lately Canon, has enabled ECD to acquire an extremely well equipped R&D facility, and to develop a proprietary 1 foot by 2000 foot a-Si roll-to-roll continuous deposition process which produces "coated web" rolls. These rolls can be cut into any shape and size for cell and module fabrication and can be shipped for fabrication into modules in downstream or off-shore facilities. This equipment has been adapted to produce multi-junction devices. ECD and its affiliates have produced multi-junction devices since 1986.

Commercial Activity - Joint Ventures

ECD/Sovonics produced the equivalent of approximately 600 kWp of module capacity in 1990. In 1990 ECD formed the joint venture United Solar Systems Corporation (USSC) with Canon of Japan which assumed ownership of the Sovonics production facilities in Troy, Michigan. Module production halted temporarily in 1991 while USSC upgraded the Troy plant for expanded production at 2 MW per year. Production has recently resumed. The cells produced in the plant are a same-band-gap, tandem (multi-junction) structure device with a rated initial efficiency of 7.5 to 8%. USSC is marketing three modules rated at 5.5, 11, and 22 Wp and a 15.6 V - 22 Wp power module with a 10 year warranty. These flexible, light-weight, shatter- and water-proof modules will be sold under the brand name of "Uni-Solar," and are targeted towards applications with relatively small electrical loads. Several modules are being tested by NREL at this writing with some encouraging results for initial efficiencies. Light soaking tests have not yet begun, and official results of the testing have not been reported.

ECD has also formed a joint venture, Sovlux, with the Russian firm KVANT, which was the former USSR's principal PV producer, to produce ECD's triple-junction device technology (see the Research and Development section) in the Republic of Russia. The equipment for a 2 MW equivalent annual capacity module production plant is being tested and optimized in Michigan and will be shipped to Sovlux in 1992. Additionally, ECD has formed another joint venture in India called Suryovonics, which has been making modules from the Sovonics cell stock. ECD is investigating the possibility of building a 4 MW annual production capacity facility in India. This plant will be a scaled-up version of the triple-junction cell equipment built for Sovlux.

Previous Page Blank

Another important development for ECD, and for the solar field in general, is the development of a nickel-metal-hydride rechargeable battery through its subsidiary Ovonic Battery Company (OBC). This battery has significant benefits over nickel cadmium (ni-cad) and standard lead-acid batteries in that it does not contain hazardous compounds, has two times the energy density of ni-cads, and has no memory effect. At mass production they should be cost competitive with ni-cads since the manufacturing process can utilize approximately 80% of a typical ni-cad production line. OBC has signed license agreements with Hitachi-Maxell Ltd. of Japan, and with Gates Energy Products of the U.S. to produce the batteries. Sovlux also has an exclusive license to produce the batteries in the U.S.S.R., and a non-exclusive right for export.

Although a detailed assessment of the financial viability of ECD is not within the scope of this assessment, the financial status of ECD should be noted. ECD lost some $8.36 million on revenues of $14.07 million in 1990, and another $2.24 million on revenues of $25.57 million in 1989. The 1990 loss was compensated by an $8 million payment from Cannon to form the USSC joint venture.

Commercial Product Performance

At present, information on the field performance of the ECD technology is only available for Sovonics modules produced during 1987 to 1990. This information is valuable in that it is indicative of the advances that ECD has made in product development and as a base-line from which to gauge how ECD's recent research and development efforts may increase module performance further. It should be kept in mind that *this data does not define how currently available and future modules produced by ECD's technology will perform.*

ECD/Sovonics modules improved greatly in quality and performance during Sovonics operational history. Early modules had fabrication quality problems resulting in delamination of the cover material, corrosion of the cell material, and electrical leakage. The latest modules produced were of higher quality. As with other a-Si manufacturers, Sovonics modules have low conversion efficiencies relative to crystalline silicon modules. The results from field installation monitoring programs for several years at a 4 kW facility operated by Detroit Edison near Detroit and by the PVUSA project test bed facilities in Davis, CA and Maui, Hawaii demonstrate module performance, efficiency degradation, and temperature effects on efficiency. The following discussion and graphs present the results recorded from these programs as they apply to the Sovonics modules installed.

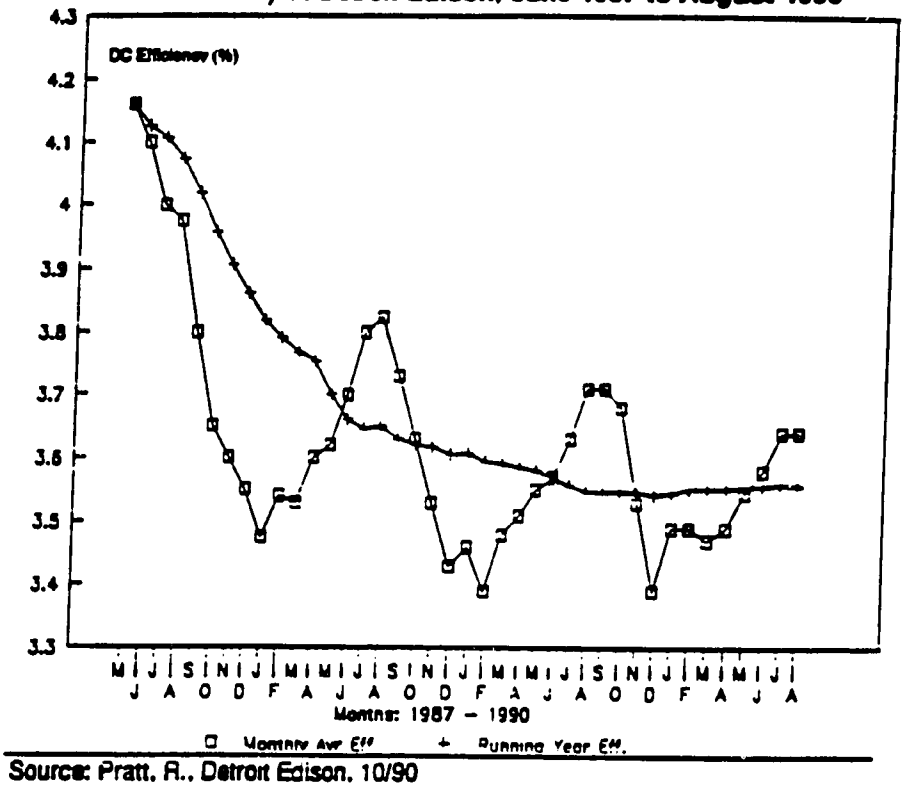
Detroit Edison Facility: Information Source: Pratt, 10/90. Description: A 4 kW flat plate, fixed array composed of 144 Sovonics R100 modules comprised of dual-tandem cells, 420 cells per module, 30 Wp nominal per module; installed April 1987, energized in May 1987.

Results: DC array efficiency (direct current module output in Watts relative to the power level of solar radiation striking the module surface) recorded during the monitoring period varied on a monthly basis according to a seasonal pattern -- efficiency decreased in the winter and increased in the summer on a delayed basis most likely due to annealing of the amorphous material from warmer temperatures. A measured Staebler-Wronski degradation of 12.5% (relative, from initial value) occurred over an initial

17 month period and resulted in a stabilized average annual DC array efficiency of 3.6%. Figure 4 depicts this efficiency degradation by comparing the average monthly and the running year DC efficiencies (calculated as the average of efficiencies recorded for the preceding 12 month period) for the system.

The system was highly reliable, resulting in a total power availability from the array (positive net AC energy production when insolation was greater than or equal to 100 W/m^2) of 95.9% over the 39 month monitoring period. The array capacity factor fluctuated on a seasonal basis, correlated to insolation, from lows of 4% in December to highs of 22% in summer; the average was 14.5%.

Figure 4: Monthly Average And Running Year DC Efficiencies For Sovonics Array at Detroit Edison, June 1987 to August 1990



Source: Pratt, R., Detroit Edison, 10/90

PVUSA Facility: Information source: PVUSA Progress Report, 1990. Description: Davis, CA: Sovonics, tandem-junction a-Si cells on stainless steel substrate; 1,200 modules at .414 m^2 each with nominal power rating of 16.5 Wp; total array area 497 m^2 with nominal power rating of 20 kW and typical operating voltage at 300 VDC. Maui, Hawaii array is essentially identical. Davis array installed in February 1989, operational in 6/1989; Maui array fully operational in 10/1989.

Results: Table 3 presents the average array DC and system efficiencies, system efficiency (AC) and capacity factors for the Davis and Maui installations. For comparison, data on the performance of the Siemens crystal silicon array at Davis is included.

Table 3: Annual System Performance Summary for PV Arrays at PVUSA (at PVUSA Test Conditions, Values are averages for period.)

	1989 Results			1990 Results		
	Sovonics		Siemens	Sovonics		Siemens
Factor	Davis	Maui	Davis	Davis	Maui	Davis
DC Efficiency	3.3	3.7	10.7	3.1	3.7	10.6
System Efficiency	2.9	3.5	10.0	2.7	3.3	9.5
Capacity Factor	21.8	21.4	21.7	20.9	19.1	21.7

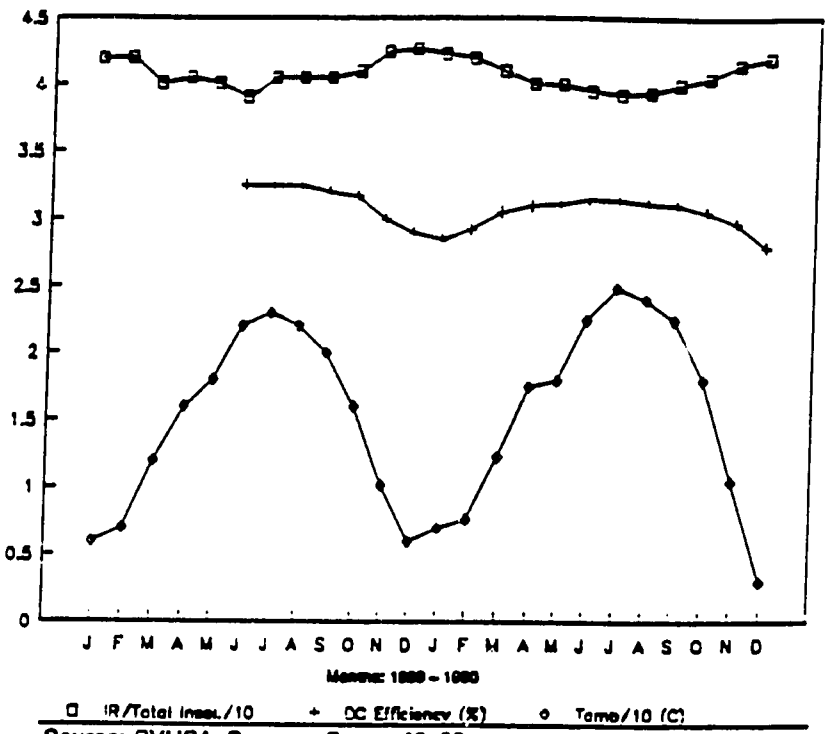
Source: PVUSA Progress Report, 1990

Relative average efficiency improved slightly during summer months (the opposite of that recorded for crystal silicon arrays). During 1989, the Davis array experienced an efficiency degradation of about 20% from its initial June rating. However, by May 1990, this loss was reversed and the system moved to 93% of initial efficiency. Figure 5 presents the plot of average monthly efficiencies recorded for the Davis array. The seasonal variations in measured efficiency are attributed to the a-Si material's low-response to infrared radiation (there was an approximate 18% increase in winter in the ratio of infrared radiation to total insolation (IR/Total) at the Davis site) and/or by a time- and temperature-related a-Si annealing process.

The average values for IR/Total Insolation and ambient temperature are also plotted in Figure 5. Problems encountered included lower than expected power ratings, some initial ground fault problems (which were repaired), and various module cover material delamination and contact grid shorts which required 71 modules to be replaced at Davis (1.5% of total installed). At Maui, 18 modules had to be replaced due to junction box failures.

The overall results from the above monitoring programs are positive in the sense that the arrays provided reliable power after the problems with the modules were corrected and had capacity factors comparable to the other PV technologies being monitored. The average degradation in efficiency recorded over the period was about 10% and appeared to have stabilized.

Figure 5: Monthly Average DC Efficiencies, Ambient Temperatures, and Ratio of Infrared Radiation to Total Insolation for Sovonics Modules at PVUSA - Davis, CA.



Source: PVUSA, Progress Report,89-90.

Recent Research and Development Efforts

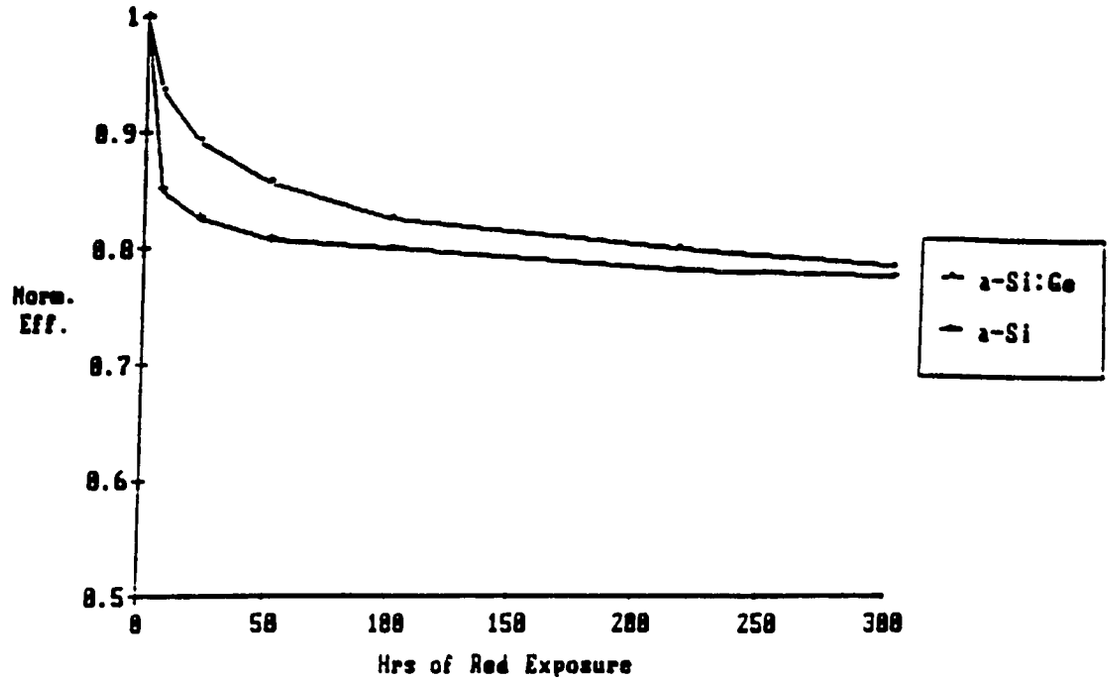
ECD has achieved notable success in its a-Si R&D efforts. Under a 1987-90, $8.8 million cost-share research contract with SERI, triple-junction cells were fabricated with an active-area efficiency of 13.7% and a total area efficiency of 12.4% (under global AM 1.5, at 25°C). (ECD, 2/1990) This is the highest efficiency recorded for an a-Si thin-film cell. Cells with initial efficiencies of 11% to 12% degraded to about 10% (12% to 17% degradation overall) after 300 hours of illumination. A triple-junction cell, with an initial efficiency of 13%, degraded to 11.3% after 240 hours of illumination. These degradation rates are significantly less than rates of 25% to 40% measured for single-junction cells of comparable initial efficiencies. Figures 6 and 7 depict some of the results of this research effort.

ECD has also fabricated the most efficient triple-junction a-Si modules with aperture-area laboratory efficiencies of 8.4% (PVIR, 6/90), and is in the process of commercializing this technology through its various joint venture partnerships. USSC is now operating under a $6.5 million contract with NREL to develop multi-junction power modules with a 12% stable efficiency. ECD has also recently been awarded an $8 million dollar three year contract with NREL under the PVMAT program to improve module manufacturing and achieve lower module costs on a Wp basis.

Issues and Requirements for Continued Commercial Expansion

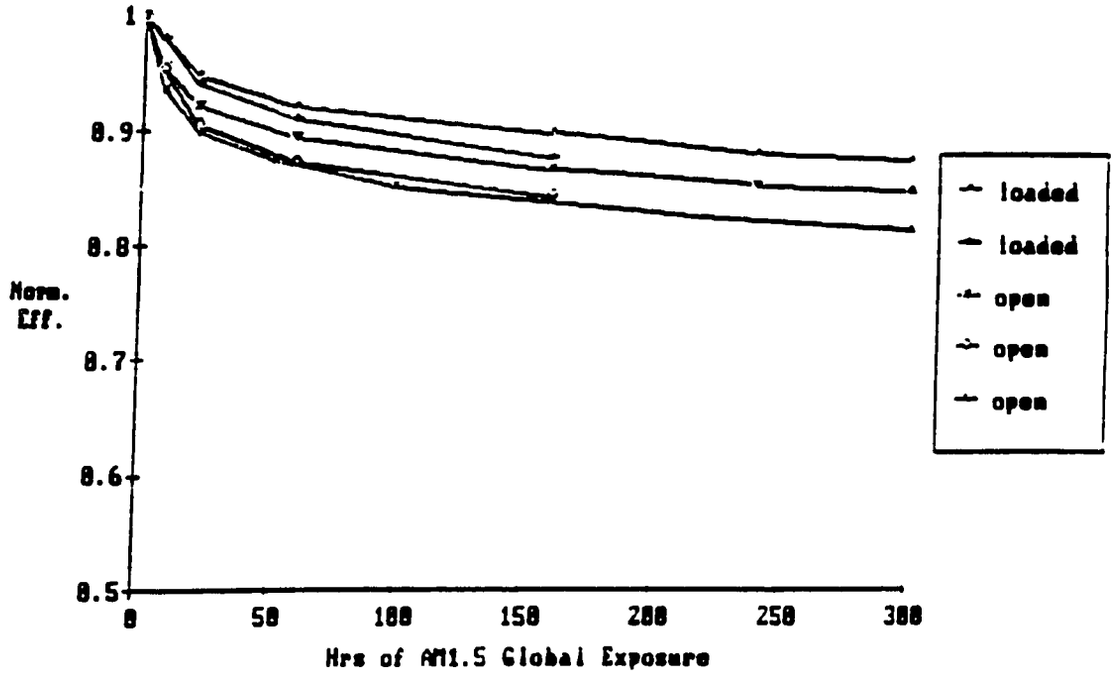
For ECD to continue its progress in commercializing its technology, and to be a major player in the world market, several issues must be addressed. Most importantly, ECD must demonstrate that laboratory R&D achievements can be transferred to commercial modules. Secondly, it may be necessary to scale-up annual production capacities to at least 10 MW or more to achieve module manufacturing costs below $2/Wp. Third, the application or market niche at which ECD and its joint venture partners (USSC, Sovlux, and Suryovonics) will target their modules will have important implications for corporate success. The latter two issues are discussed in more detail in the next sections of this report.

Figure 6: Normalized Conversion Efficiency Versus Time of Red-light Exposure for ECD A-Si Alloy Single-Junction Device and an A-Si:Ge Alloy Single-Junction Device.



Source: ECD, 2/90

Figure 7: Normalized Conversion Efficiency Versus Time of AM1.5 Global Exposure for Five Similar ECD Triple-Junction Devices at Maximum Power Point and in Open Circuit.



Source: ECD, 2/90

ISSUE 3: STATUS AND PROSPECTS FOR OTHER PV TECHNOLOGIES AND A-Si COMPETITIVENESS BY APPLICATION

A key issue in the commercial expansion of a-Si is the relative competitiveness of the technology, specifically the ECD product, with other existing and emerging PV cell technologies in specific applications. The primary PV competitors are single and poly crystal silicon, concentrator cell technologies, and ribbon silicon. Other potential competitors include non-silicon based thin-films and the Texas Instrument spherical silicon cell technology.

Photovoltaic Energy Systems Inc., has recently produced a comprehensive in-depth assessment of the status and future prospects of these technologies. (PVES, 6/91) Below are the highlights of the assessment technology.

Competing PV Technologies

Single and Poly Crystal Silicon Cells

The industry standards for flat plate power modules (30 to 60 Wp nominal) are those using single and poly-crystal silicon cells. These cells have the highest conversion efficiencies and a reputation for stable and reliable performance for up to 20 years. Efficiencies in commercially available cells are on the order of 15% and 14% respectively for single and poly crystal cells. Single crystal modules now on the market are slightly more expensive per Watt than poly-crystal. The prospects for future module cost reductions for both cell types are positive. Increased efficiencies to 18% for single crystal and 17% for poly crystal through improved cell design, improved cell growth and more efficient slicing techniques, development of thin-film cast ingot poly crystal cells, and reduced cell and module fabrication costs from large-scale production (10 MW or more) should reduce module costs to under $2/Wp by 2000.

Concentrator Cells, Modules, and Arrays

Concentrator cell technologies presently deliver the highest efficiencies (17%) of any other PV technology. However, because of the high cost of system engineering, components, and array operation and maintenance, electricity costs from concentrator modules are higher than from flat-plate module arrays of comparable capacity. To date, these technologies have only been applied in experimental or pilot facilities and in aerospace and military research. The commercial potential of concentrator cells is fairly limited for the immediate future but should grow as progress is achieved in increasing cell and module efficiency; in reducing costs of module, array, balance-of-system (BOS) components, and operation and maintenance; and in improving system performance and reliability. Module costs within the range of $1.20/Wp are forecast for 2000, which would make concentrator systems the most competitive technology for large power block (100 kW or more) applications where climate conditions are optimal, ie consistent, high, specular insolation. The U.S. Electric Power Research Institute (EPRI) has defined concentrators as the "preferred" option for central station PV electricity generation. U.S. corporations lead in the development of this technology.

Ribbon Silicon

Although ribbon silicon technology has a good potential for achieving low cell and module Wp costs through reduced cell thickness, relatively high conversion efficiencies, and automated production, today's ribbon cell based module sales are almost insignificant. However, if cell formation processes improve and cell efficiencies increase, very low cell/module costs may be achieved by 2000. To date there has been a relatively low level of interest on the part of industry to develop and commercialize this technology. Only about four U.S. firms -- Mobil Solar, SolarWeb (using the Westinghouse dendritic web technology), AstroPower, and Arthur D. Little -- are involved in process, cell, module development and manufacturing.

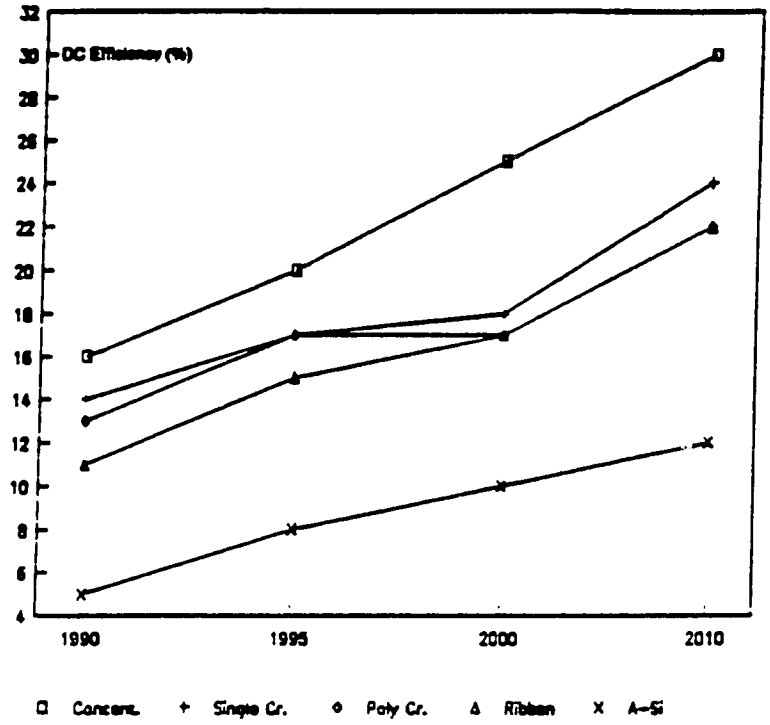
Other Photovoltaic Technologies

Researchers have also been investigating other promising photovoltaic materials such as copper indium desalinate, cadmium tellurate, and gallium arsenide. These materials have characteristics that have great potential for producing high efficiency thin-film cells in automated production. However, technical problems and the costs of the materials has constrained their use in all but experimental applications. The commercial potential of these materials is not promising for several years. It should also be noted that these materials may be toxic, and therefore disposal of the modules at the end of their useful operating life could be an issue of environmental concern.

Texas Instruments (TI), in cooperation with Southern Cal Edison, has recently announced plans for the commercial development of its unique micro-sphere PV technology which utilizes low-grade silicon globules embedded on flexible sheets of aluminum foil. TI claims that this technology will produce electricity at $.14/kWh and that a commercial product will be available in 1993. The ability of TI to deliver on this claim is a matter of conjecture but, if successful, will have significant impacts on the PV industry. Some industry experts believe that the TI target is extremely optimistic.

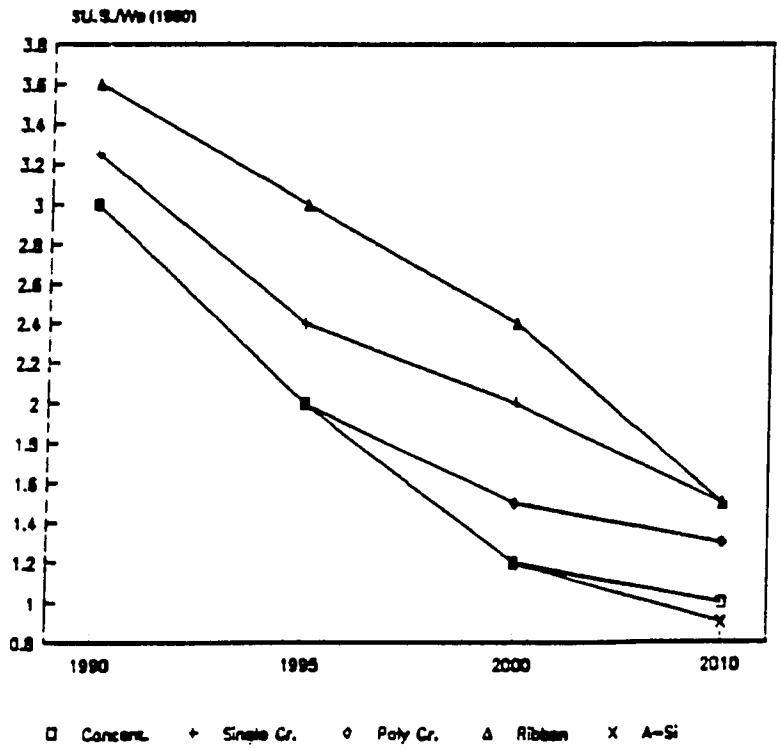
Figures 8a and 8b present forecasts by PVES, Inc., for module efficiencies and manufacturing costs for concentrator, single crystal, poly crystal, ribbon, and a-Si technologies from plants with 10 MW/year production capacity.

Figure 8a: Projected Module Efficiencies For Major PV Technologies From Manufacturing Plants with 10 MW/yr Production Capacity



Forecast By PV Energy Systems Inc.

Figure 8b: Projected Module Costs for Major PV Technologies From Manufacturing Plants with 10 MW/yr Production Capacity



Forecast By PV Energy Systems Inc.

Environmental, Health, and Safety Considerations

Photovoltaic technologies are considered to be environmentally benign because they do not produce pollutants when operating. However, there are key environmental, health, and safety issues associated with PV which should be recognized. These are:

- the use of toxic compounds in or as the photovoltaic material (e.g. copper indium desalinate, cadmium tellurate, and gallium arsenide);

- the use of toxic and hazardous gaseous, liquid, and solid compounds in the manufacture of PV cells and modules;

- the use of potentially hazardous processes in cell/module manufacture;

- the high material intensity and large area/land requirements in large-power block applications;

- the use of batteries in many PV applications;

- the inherent electrical hazards associated with PV system operation; and

- the aesthetic impacts of arrays and large power blocks on the landscape and building architecture.

Numerous toxic and hazardous chemicals and compounds are used in the manufacture of PV cells and modules. Some silicon alloy and non-silicon alloy cells may themselves be composed of toxic materials. (Moskowitz and Fthenakis, et al, 86, 85, 83; and USDOE, 1988.) Proportionally more hazardous materials are used in thin-film manufacturing, including a-Si, than in single and poly-crystal processes.

The types and amounts of these compounds is technology and process specific. In all cases, proper in-plant processes and technologies will control and mitigate any potential environmental hazards, and these issues are of greatest concern for plant employees and to people in the immediate vicinity of the plant if uncontrolled releases of liquid and gaseous compounds occur. Cells made of toxic materials may require controlled disposal when their operational life has ended. The ECD technology does not contain any such compounds.

The last four issues apply to any type of PV technology equally. Aesthetic impacts may be addressed through screening of the array and/or incorporating modules into building architecture. Electrical hazards are serious and must be addressed through proper design and installation of systems by trained and qualified technicians and by instruction and education of the user. Batteries are perhaps the most important health and safety issue facing decentralized and consumer product applications where they are used.

Batteries are potentially hazardous when stored and in use, and when their operational life is completed (depending on their composition). The wide-spread use of lead-acid and ni-cad batteries throughout the world and the cumulative impact of their improper disposable could pose a significant health problem for present and future generations. Therefore, the advent of low-cost, non-toxic, rechargeable batteries is critical for PV technologies to guarantee their "green" image.

Material intensity and land area requirements are important when considering the total energy and environmental "fuel cycle" impacts of PV technologies relative to alternatives. Specifically, these are the energy and material inputs and resulting pollutants produced in their production and delivery to the PV manufacturing facility and in the construction of large PV power stations relative to those impacts associated with the construction, operation, waste treatment and disposal, decommissioning, and associated fuel cycles of alternatives. These issues are complex and beyond the scope of this assessment. The reader is referred to the Pace University report (Ottinger, et al., 1990) which provides a comprehensive review of the subject.

Applications

Although module cost is obviously important, it is not the only consideration for PV market development; the application to which the technology is employed is also a major factor since other characteristics provide a comparative advantage in specific applications. This section is therefore focused on addressing the comparative limitations and advantages of a-Si with its primary competitors in these applications. Three broad categories of applications, or market niches, are used here delineated on the basis of the size of power demand -- large power demands of greater than 1000 kW generated by or for utilities or central stations; medium power demands of 50 W to 1000 kW for decentralized, stand-alone, and/or remote applications; and low power demands of less than 50 Wp for point-of-use, consumer products or appliances.

Large Power Demand Applications - Utility/Central Station Scale

In order for PV to make major contributions to global energy supply it has to compete in the utility and captive power market with other electricity generation technologies. The principal determinants of this competitiveness will be the levelized kWh cost, reliability, and availability of generated power.

Numerous factors will determine the busbar cost of PV generated power. These include the costs and operating lives of the modules, array supports, BOS components and power storage (if required), and costs for shipment and installation, operation and maintenance, insurance, decommissioning, salvage value, land costs, plant financing, tax incentives, amortization, rebates or credits, and environmental credits or restrictions. However, the single most important factors will be module costs/Wp and operating life. For PV generated power to be price competitive with fossil fueled power, module costs of less than $1/Wp and a levelized-life-cycle electricity price of at least $.06/kWh need to be achieved. If these price levels are achieved, this would entail a huge market for PV technologies. At present, a-Si does not have any comparative advantage over other PV technologies within this niche and it will not until the technical and cost issues discussed above have been addressed.

A sub-category of this and the medium power category is the installation of modules on houses or buildings to supply all or part of a load center's power requirements. These may be grid connected and supply excess generation capacity to the utility (in the place of on-site storage). Several utilities in the U.S., Europa, and Japan are investigating this application to supply peaking power requirements, such as air conditioning loads, as a demand management option (PVIR, 4/92). Low cost, innovative module design that can be incorporated into building architecture and low cost power conditioner and inverter technologies will be major factors in the market for PV in this application. A-Si modules may have a comparative advantage in this application due to an enhanced performance at higher temperatures (therefore allowing flush mounting) and greater flexibility in module size and shape.

Medium Power Demand Applications - Remote, Stand-alone, and Decentralized

This category includes power demands on the order of 100 W to 1000 kW met by arrays with module sizes between 20-60 Wp nominal. This encompasses practically any power requirement where the levelized life-cycle cost per kWh for PV are equal to or less than alternative power generation, grid and power line extension, and/or where fuel supply and system maintenance are physically difficult and expensive. Applications include village and commercial mini-grids; single dwelling-domestic and institutional electrification (6, 12, 24 Volt battery charging for lighting, refrigeration, television, etc.); street lighting; water pumping and purification; highway, railway and marine navigational sign and signal lighting; cathodic protection; air circulation fans; and remote telecommunication and environmental data gathering installations. PV/other renewable/diesel hybrid systems are included in this category. PV systems are already cost competitive with fossil fuel and line extension in these applications and there are tens of thousands of such installations in the U.S. -- the U.S. Coast Guard alone has installed approximately 15,000 systems for communication and signal buoys. There is a huge potential market on the order of thousands of MWs for these types of applications throughout the world.

Aside from than the issues of cost and long-term performance, flexible, light-weight a-Si modules such as the ECD technology may have a comparative advantage in these applications where these qualities are advantageous.

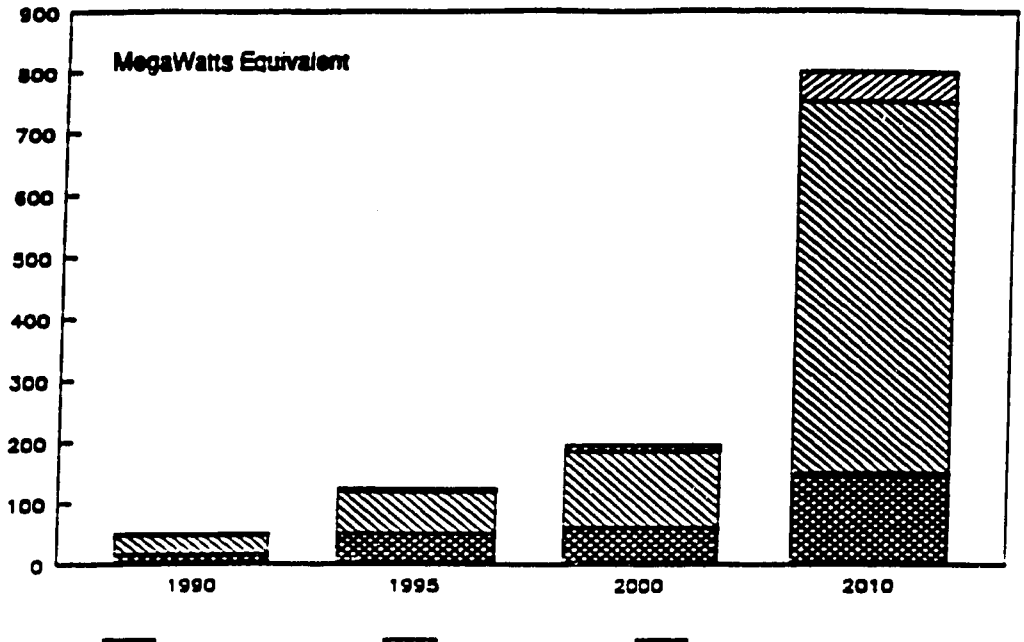
Low Power Demand Applications - Consumer and Specialty Products

This category includes power demands of less than 100 W using cells/modules of under 20 Wp for battery charging in watches, clocks, calculators, radios (receiver and transmitter), portable computers, hand tools, portable lanterns, and numerous other devices where power demands are low and/or intermittent. The market for such applications will continue to expand for consumer products, especially for appliance battery charging in the developing countries. A-Si technologies will most likely continue to dominate this application and, as cell/module prices decline, new applications will develop. The use of batteries in this application is an area of environmental concern and the fact that ECD/Ovonics is an early developer of the nickel-hydride technology will provide them with a potentially important market edge.

PV Market Expansion

From 1985 to 1990, annual world-wide PV cell/module sales more than doubled from 22.8 MW to 46.8 MW, with an average annual increase of 15%. U.S. industry shipments followed this trend with 7.7 MW shipped in 1985 (34% of the world market) and 14.8 MW in 1990 (32% of the world market). The PV Energy Systems' PV cost and market forecast provides a detailed assessment of the potential growth of seven sectors or applications of PV technologies under two basic scenarios -- business as usual and accelerated. The conclusions of these forecasts are provided in Figures 9 and 10. The realization of these forecasts is highly dependent on whether or not the assumptions used to develop the scenarios hold.

Figure 9: Business as Usual Forecast For PV Market Growth By Application in MegaWatts Equivalent Annual Module Shipments (PV Energy Systems Inc.)



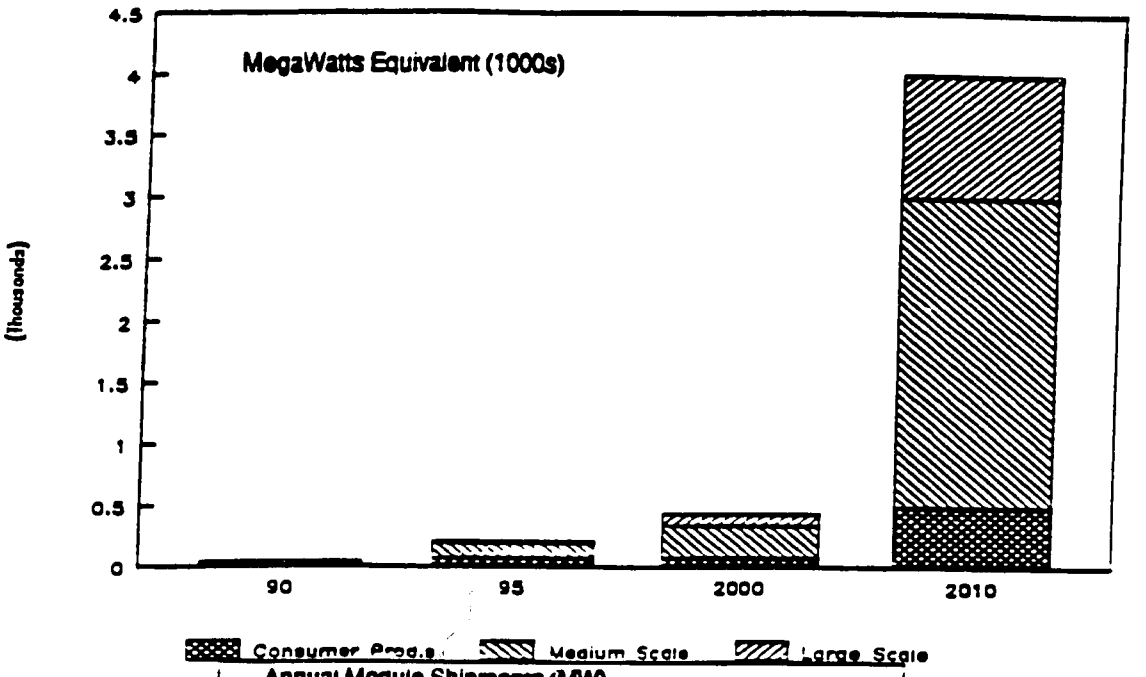
Application	Annual Module Shipments (MW) 1990	1995	2000	2010
Consumer	16	50	60	150
Medium	31	69	125	600
Large	1	5	10	50
Total:	48	124	195	800

BAU Scenario Assumptions:

- Oil prices remain at $15 - $20 per barrel.
- Natural gas prices are $1.50 - $3.00 per MBtu.
- No tax incentives provided for small PV systems.
- Technical progress is linear with no major discontinuities.
- No 50 MW annual capacity production plant built by private sector.
- Module prices do not drop below $3/Wp by 1995.

Even at the BAU scenario, the market for PV technologies promises to expand fairly significantly, and the implications for ECD and its joint venture partners are positive. The projected growths in the low and medium power demand market should provide ECD the opportunity to continue further commercial expansion as its modules are well suited to these applications. The ability of ECD to compete in the large power demand market is highly dependant on the development of cost and performance competitive power modules. While ECD is pursuing technical improvements in its technology, a much larger scale of production will be required to reduce module costs down to the level of $2 to $1/Wp. The issues involved in such a scale-up are outlined in section 4.

Figure 10: Accelerated Forcast For PV Market Growth By Application in MegaWatts Equivalent Annual Module Shipments (PV Energy Systems Inc.)



Annual Module Shipments (MW)

Application	1990	1995	2000	2010
Consumer	16	70	80	500
Medium	31	130	260	2500
Large	1	10	100	1000
Total:	48	210	440	4000

Accelerated Scenario Assumptions:

- Oil prices escalate at 3%/yr.
- U.S. energy policy gives high attention to renewables.
- Japanese initiate serious residential (national) programs.
- Europe continues high R&D budget, demonstrations, subsidized markets, and internalized social/environmental costs for fossil and nuclear fuel/power technologies.
- Accelerated progress in moving R&D results into manufacturing commercial products to achieve module costs at or below $1/Wp.

ISSUE 4: ISSUES AND REQUIREMENTS FOR AN IN-DEPTH TECHNICAL ASSESSMENT OF ECD TECHNOLOGY SCALE-UP

A detailed engineering and production cost analysis would be required to determine the feasibility of scaling-up the current ECD manufacturing technology capable of 1-2 MW annual production capacity to one that will achieve module production costs of $1.00/Wp and with guaranteed operating lives of at least 20 years. Such an analysis is beyond the scope of this report; however, key issues that must be addressed in the analysis are:

- the realistic and achievable stable efficiencies and operating lives for the single and triple-junction modules currently under development;

- the level of production required to achieve these costs;

- the technical challenges involved in scaling-up and whether it is likely that they can be addressed economically;

- the effects of scale-up on cell/module performance and reliability;

- the site and country specific issues and conditions that will affect the technical feasibility of the construction and operation of such a facility including raw material and power supply, plant siting, quality and environmental controls, operator skill levels and training requirements, etc.;

- the likely time frame for the design, planning, construction, and commissioning of such a facility; and

- the capital cost and financing requirements for such a plant.

An assessment of this nature will require a specialized team of individuals with in-depth experience in PV technology and process scale-up. This team would require access to confidential and proprietary information on the ECD technology in order to provide a realistic determination of the feasibility of a scale-up of the magnitude envisioned. The confidentiality of their investigative activities would have to be guaranteed.

REFERENCES

Energy Conversion Devices, Inc., 2/90, "Research on High-Efficiency, Multiple-Gap, Multi-Junction Amorphous Silicon-Based Alloy Thin-Film Solar Cells," Final Subcontract Progress Report, Subcontract No. ZB-7-06003-4, Solar Energy Research Institute, limited distribution.

Energy Conversion Devices, Inc., and Suryovonics, Ltd., 3/91, "Proposal for Market Seeding Program and Development of Business Plan Feasibility Study To Provide Low Cost Photovoltaics To Developing Countries", submitted to USAID Office of Energy, limited distribution.

Fifth International Photovoltaic Science and Engineering Conference, 11/90, "Technical Digest" of conference, PVSEC Committee, Kyoto, Japan.

Fthenakis, V.M. and Moskowitz, P.D., 1985, "Characterization of Gas Hazards in the Manufacture of a-Si Photovoltaic Cells", BNL 51854, Brookhaven National Laboratory, Upton, New York.

Ottinger, R., et al., 1990, "Environmental Costs of Electricity," Pace University Center for Environmental Legal Studies, Oceana Publications, NY.

Moskowitz, P.D., et al, 1983, "Health and Environmental Effects Document for Photovoltaic Energy Systems", BNL 51676, Brookhaven National Laboratory, Upton, New York.

Moskowitz, P.D., et al, 1986, "An Environmental Source Book on the Photovoltaics Industry", BNL 52052, Brookhaven National Laboratory, Upton, New York.

Photovoltaic Energy Systems, Inc.,(PVES)/Paul Maycock, 6/91, "Photovoltaic Technology, Performance, Cost, and Market Forecast to 2010: A Strategic Technology and Market Analysis," PVES, Cassanova, VA.

Pratt, R., 10/90, "Three Year Performance and Reliability Analysis of a 4 KW Amorphous-Silicon Photovoltaic System in Michigan," Detroit Edison Company, Detroit, MI.

PV Insiders Report (PVIR), Richard Curry, ed., all editions from 1/1990 to present, Dallas, Texas.

PV News, Paul Maycock ed., all editions from 1/1990 to present, PVES, Casanova, VA.

PVUSA, 1990, "1989 - 1990 PVUSA Progress Report," Photovoltaics for Utility Scale Applications project, USDOE, USEPRI, PG&E, CEC, Davis, CA.

Previous Page Blank

Sandia Photovoltaic Design Assistance Center, Sandia National Laboratory, and Southwest Technology Development Institute - Southwest Regional Experimental Station, 1/90, "Performance of Amorphous Silicon Photovoltaic Systems: 1985 - 1989," Sandia Report No. SAND-90-0612, NTIS, Springfield, VA.

Schaefer, J., et al., 1990, "Experiences With U.S. Line-Connected Amorphous Silicon Systems," by EPRI, Alabama Power & Light, Wisconsin Power & Light Co., Philadelphia Electric Co., and Detroit Edison Co.

Stafford, Byron, editor, 1991, "Amorphous Silicon Materials and Solar Cells," AIP Conference Proceedings 234, American Institute of Physics, New York.

Stafford, B.L, et al., 10/1991, "The U.S.DOE/NREL Amorphous Silicon Photovoltaics Program," paper presented at the 22nd IEEE PV Specialists Conference, Las Vegas, NV.

Solar Energy Industries Association (SEIA), 1990, "Federal Programs for Research and Development of Solar Energy: Industry Analysis and Recommendations for Funding for FY 1991," SEIA, Washington, D.C.

Solar Energy Research Institute (now National Renewable Energy Laboratory), 8/88, "Photovoltaics Technical Information Guide," 2nd ed., Golden, Colorado.

Southwest Technology Development Institute, 1/90, "Photovoltaic System Performance Assessment for 1988," Electric Power Research Institute, Report No. EPRI GS-6696, Palo Alto, CA.

USDOE, 10/88, "Energy Technologies and the Environment, Environmental Information Handbook", DOE/EH-0077, U.S. Department of Energy, Washington. D.C.

USDOE, Technical Information Program, 1990, "Programs In Renewable Energy: Fiscal Year 1989," U.S. Depart. Of Energy, Washington, D.C.

USDOE, Technical Information Program, 1990, "Photovoltaics - Entering the 1990s," U.S. Depart. Of Energy, Washington, D.C.

UNITAR/UNDP and Massachusetts PV Center, 1990, "Photovoltaic Resources: Applications, Utilization and Assessment Guidebook for Policy Planners," United Nations Development Programme, Rome, Italy.

Personal correspondence and interviews with officials from ECD, PVES, Maycock, PVUSA, PG&E, Texas Instruments, 1991.

The Office of Energy and Infrastructure

The Agency for International Development's Office of Energy and Infrastructure plays an increasingly important role in providing innovative approaches to solving the continuing energy crisis in developing countries. Three problems drive the Office's assistance programs: high rates of energy use and economic growth accompanied by a lack of energy, especially power in rural areas; severe financial problems, including a lack of investment capital, especially in the electricity sector; and growing energy-related environmental threats, including global climate change, acid rain, and urban air pollution.

To address these problems, the Office of Energy and Infrastructure leverages financial resources of multilateral development banks such as The World Bank and the InterAmerican Development Bank, the private sector, and bilateral donors to increase energy efficiency and expand energy supplies, enhance the role of private power, and implement novel approaches through research, adaption, and innovation. These approaches include improving power sector investment planning ("least-cost" planning) and encouraging the application of cleaner technologies that use both conventional fossil fuels and renewable energy sources. Promotion of greater private sector participation in the power sector and a wide-ranging training program also help to build the institutional infrastructure necessary to sustain cost-effective, reliable, and environmentally-sound energy systems integral to broad-based economic growth.

Much of the Office's strategic focus has anticipated and supports recently-enacted congressional legislation directing the Office and A.I.D. to undertake a "Global Warming Initiative" to mitigate the increasing contribution of key developing countries to greenhouse gas emissions. This strategy includes expanding least-cost planning activities to incorporate additional countries and environmental concerns, increasing support for feasibility studies in renewable and cleaner fossil energy technologies that focus on site-specific commercial applications, launching a multilateral global energy efficiency initiative, and improving the training of host country nationals and overseas A.I.D. staff in areas of energy that can help to reduce expected global warming and other environmental problems.

To pursue these activities, the Office of Energy and Infrastructure implements the following six projects: (1) The Energy Policy Development and Conservation Project (EPDAC); (2) The Biomass Energy Systems and Technology Project (BEST); (3) The Renewable Energy Applications and Training Project (REAT); (4) The Private Sector Energy Development Project (PSED); (5) The Energy Training Project (ETP); and (6) The Energy Technology Innovation Project (ETIP).

The Office of Energy and Infrastructure helps set energy policy direction for the Agency, making its projects available to meet generic needs (such as training), and responding to short-term needs of A.I.D.'s field offices in assisted countries.

Further information regarding the Office of Energy and Infrastructure projects and activities is available in our Program Plan, which can be requested by contacting:

Office of Energy and Infrastructure
Bureau for Research and Development
U.S. Agency for International Development
Room 508, SA-18
Washington, D.C. 20523-1810
Tel: (703) 875-4052