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The Role of Research and Development in the Worldwide Deployment of Photovoltaics

J. Stone
D. Ritchie
S. Deb
T. Surek

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Solar Energy Research Institute
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1617 Cole Boulevard
Golden, Colorado 80401

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NOTICE

The Role of Research and Development in the Worldwide Deployment of Photovoltaics

J. Stone, D. Ritchie, S. Deb, T. Surek

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO, USA

The dream of significant electrical energy production for all mankind may well be fulfilled by photovoltaics. The attainment of this objective will be determined primarily by the cost and performance of future technologies. The role of research and development will be significant. Advanced thin films materials and very high efficiency concepts are being pursued as potentially viable technologies for worldwide deployment in energy significant quantities. R&D opportunities are discussed with emphasis on progress to date, significant technical barriers to be overcome, and future R&D direction.

1. INTRODUCTION

A dichotomy exists in the world community as lesser developed countries attempt to improve their lot, competing with the industrialized minority for available energy resources necessary for economic development. Figure 1 dramatically shows this competition in terms of projected primary energy consumption. Solar energy may well offer a solution. As shown in Figure 2, the largest predicted population growth, and hence, energy demand, will occur in the equatorial, sun-belt regions of the world. However, those most needing the technology may be the least able to afford it, hence the dichotomy. Realistically, perhaps the best that can be hoped for is that the developed countries will shift their future energy mix away from fossil based fuels in favor of renewables, thus lessening the competition for the depletable resources.

Photovoltaics - the direct conversion of sunlight to electrical energy - offers distinct advantages as an energy supply option. Photovoltaics is based on modular solid state devices which are capable of being mass-produced at low cost. Photovoltaic systems are suitable for a broad range of applications and, regardless of scale, require short lead times for design, installation, and start-up. Systems can be designed to minimize land use and environmental impacts and to provide simple and inexpensive operation. However, present day photovoltaic systems do not produce low cost electrical energy and high technology research and development is required to improve the electrical conversion efficiency and long-term stability of those photovoltaic concepts having the potential for greatly reduced cost.

In this paper, we will examine the role that photovoltaics can play as a viable electrical energy supply option, and the importance of a realistic, but bold, research and development strategy to fulfill this end.

2. CHOICE OF RESEARCH PATHS

Within approximately the last ten years a large number of PV applications have been fielded throughout the world, ranging from water pumping in the remotest parts of Africa to the central power stations of California. All have common attractive features including modularity, established reliability, and low maintenance. The key factor is that for specific applications, current systems can be cost effective. For pumping water in remote regions, the competition is high priced, delivered diesel fuel, while the availability of domestic tax credits allows the economic deployment of large PV farms in the United States. In order to achieve further progress for the technology, one may follow one of two paths which, fortunately, are not mutually exclusive. On one hand one could simply pursue incremental improvements in the current technology, being satisfied with minimal impacts on the needs of the developing countries, realizing that massive aid programs may be necessary for large scale deployment. Or one may choose to take a higher risk path toward substantive improvements. Success in the latter approach naturally encompasses the first, but goes well beyond. The price to be paid for the second option is in the risk involved. Government programs have been built around assumptions of risk, particularly by governments of the industrialized countries. The current United States National Energy Policy has as its goal, "an adequate supply of energy at a reasonable price". One of the strategies towards this end is to promote a balanced and mixed energy resource base. Contained within this strategy is an appropriate federal role for assuming research risks which private enterprise is unable or unwilling to assume by itself.

3. THE STRATEGY

The recently adopted Five Year Research Plan of the National Photovoltaics Program establishes aggressive R&D goals which focus the Department of Energy's resources on developing the photovoltaic technology to a point where it can eventually become an energy significant option. Working closely with the PV industry and the electric utilities, a goal of providing electrical energy at a levelized constant dollar cost of 6.5 cents/kWh was established. This translates into the cost and performance combinations (shown in Figure 3) required for flat plate and concentrator modules. Current studies show that achieving this goal would place PV in a favorable competitive position with electricity generated from oil and natural gas fired plants and would be marginally competitive with coal.

DOE's research and development efforts are focused primarily on applied research for the development of promising new photovoltaic approaches, such as thin film and multijunction concepts. Whereas basic research is directed toward gaining scientific knowledge primarily for its own sake, applied research is directed toward gaining scientific knowledge in an effort to meet a recognized need. Further development of photovoltaic technology directs that knowledge towards the production of useful materials, devices, and systems. Despite the potentially high payoff of these research and development activities, they are costly, risky, and lengthy, and private enterprise is unlikely to pursue them for these reasons. The purpose of SERI's Photovoltaic Program is to conduct high risk, potentially high payoff research and development which will result in a scientific and technical knowledge base which private enterprise can use for further concept and product development and, ultimately, competitive application in electrical energy markets.

Two primary R&D paths have been identified which hold good promise for meeting the Program goals. Since it is evident from Figure 3 that cost and efficiency can be traded off (i.e., low efficiency, low cost versus high efficiency, high cost), the two rather different research approaches merge to the same cost goal if successful. The probability of success can be enhanced by a multi-path approach and by multiple options within each path. Research scenarios addressing these approaches will be discussed individually in the following sections.

4. THE TECHNOLOGIES

The Solar Energy Research Institute (SERI) under contract to the Department of Energy, is charged with the responsibility of managing the Advanced Research and Development Project within the National Photovoltaics Program. Work is carried out in three broad categories, namely materials research, collector research, and systems research with SERI's primary emphasis being in the first area. The National Photovoltaics Program Five Year Research Plan further subdivides the research into ten tasks, as shown below.

- Materials Research
  - Single Junction Thin Films
  - High Efficiency Multi-Junction Concepts
  - Innovative Concepts
  - Silicon Materials
  - Advanced Silicon Sheet
- Collector Research
  - Flat Plate Collectors
  - Concentrator Collectors
- Systems Research
  - Module Reliability
  - Array and BOS Development
  - System Experiments

In FY1984 (October 1, 1983 - September 30, 1984) and projected for FY1985 (October 1, 1984 - September 30, 1985), the total DOE Program funds were divided as follows:

	FY1984 $K	FY1985 (Projected) $K
Materials Research	$25,782	$30,900
Collector Research	9,300	10,400
Systems Research	13,600	3,900

For the Advanced Research and Development Programs only, SERI was funded at $21,800,000 in FY84 and is projected at the same level in FY85. SERI's primary responsibilities lie in thin films and high efficiency multi-junction research. Internally, SERI has two principal R&D activities in photovoltaics. First, the Photovoltaic Devices and Measurements Branch develops and provides state-of-the-art measurement and device research and support including cell performance evaluation, materials characterization, electro-optical measurements, device research and fabrication, and solar cell modeling, for the improvement and advancement of current R&D devices and materials. These activities are conducted for and in cooperation with internal SERI photovoltaic research, DOE contract research activities, and the photovoltaics industry. Second, SERI's Solid State Research Branch conducts photovoltaic research complementary to subcontract research on several advanced photovoltaic materials and technologies. Other internal R&D activities include advanced PV systems research and insolation research. Finally, SERI's external research activities are a significant portion of the photovoltaic program; about half of SERI's photovoltaic budget is allocated to subcontracted research and development conducted by the nation's universities, industries, and research institutes.

4.1 Low Cost, Medium Performance, Thin Films

One path of the multi-path research options concentrates effort on low cost ($<\$50/m^2$) and medium performance (η = 10-15%) approaches. Thin films which are material conservative, potentially scaleable to large areas, and which can be deposited at rates which make them commercially feasible are being pursued. In order of priority, single junction, hydrogenated amorphous silicon, polycrystalline thin film heterojunctions of CdS with $CuInSe_2$ (with sulphur and/or gallium substitutions), and cadmium telluride are being given significant research attention.

In 1984, a major initiative in amorphous silicon was put in place with research contracts awarded to Solarex Corporation, Chronar Corporation, and 3M Corporation. The program was established with aggressive three year goals of achieving 8%, 1000 cm^2 submodules, resolving the light induced stability effect(s), demonstrating a 12%, 1 cm^2 laboratory cell, and achieving 10%, 1 cm^2 cells at deposition rates of 20 angstroms/second or greater. It is felt that achievement of these milestones will represent significant progress towards the eventual commercial success of this technology. During the early stages of this program, 6%, 100 cm^2 and 4%, 1000 cm^2 submodules from Chronar have been verified at SERI. Alternate deposition techniques, such as chemical vapor deposition (CVD) are being investigated for higher deposition rates, including alternate silicon precursors such as disilane.

The polycrystalline thin films heterojunction device area has shown promise, particularly with the demonstration of a 10.3% $(Cd,Zn)S/CuInSe_2$ cell from Boeing, and an 8.2% ITO/CVD-CdTe device from Southern Methodist University. Both devices exhibit excellent stability and are prime contenders for achieving the long term goals of the PV Program. The $CuInSe_2$ device exhibits excellent stability over long term, accelerated testing. However, there are concerns regarding scaleability of the present three source evaporation deposition approach. Various approaches to deposition such as Knudsen cell evaporation, CVD, electroplating and RF sputtering are being investigated. CdTe continues to be of interest because of its promising bandgap match to the solar spectrum. Here the emphasis is on fabricating heterojunction and homojunction thin film devices.The polycrystalline thin film area is responsible for the following Five Years Plan Milestones: (1) 12.5%, 1cm^2 in FY84 (2) 15%, 100cm^2 in FY87.

4.2 Low Cost, High Performance Thin Films

Included in this task are materials and device structures with the potential of achieving $<\$50$ m^2 cost with an operating efficiency of 15-25%. Two approaches are being researched. In the first, thin film multi-junctions which utilize two or three junctions connected optically in series are able to convert portions of the solar spectrum which would otherwise be lost in a conventional single junction device. In the second approach, peeled thin films (CLEFT) of GaAs or III-V alloys are utilized. In 1984, as part of the amorphous silicon initiative mentioned earlier, Spire Corporation was selected to work on multi-junction concepts. Various alloys of amorphous silicon (e.g. a-Si:H/Sn, a-Si:H/Ge, etc.) whose bandgaps can be adjusted and, thus, optimized for stacked cell operation, will be used to achieve agressive milestones of 18%, 1cm^2 and 13%, 100 cm^2 devices in the next three years. Stacked cells involving polycrystalline thin films are also being pursued. In particular, the combination involving $CuInSe_2$ and CdTe are two absorbing materials being investigated.

Using the CLEFT process, peeled crystalline films from a reuseable GaAs substrate, 5 microns in thickness have been fabricated into 13.8% solar cells by MIT/Lincoln Lab, very close to the milestone of 20%, 1cm^2 in FY86.

4.3 High Cost, High Performance Multijunction Concepts

Devices capable of reaching efficiencies greater than 35% under extremely high concentration ratios (> 1000X) represent another research path towards achieving competitive electricity costs. Utilizing ternary and quaternary III-V materials, a variety of multi-terminal device structures have been proposed. To date, Chevron has reported a 22%, GaAsP/GaAsSb, two-color, three terminal, 120 X concentrator cell, Varian has achieved 21.5% for GaInAs under 200 X concentration, and 16.6% and 15%, one sun efficiencies are reported for GaAlAs and GaAsP respectively by MIT/Lincoln Lab. The high efficiency, multijunction cells are planned to meet a 35% milestone in FY88.

5. Conclusion

Research paths have been identified offering parallel photovoltaic options, which if successful, can lead to electrical energy costs competitive with conventional sources. The success of the research is gauged by aggressive milestones over a long term. As with any high risk approach, short term success may be sacrificed in favor of a future high return. Such investment in the future of PV is necessary to ensure that a sound technology base is available on which to build and grow. We feel that the program outlined in this paper provides approaches with acceptable risk and reasonable probability of achieving this technology base.

Looking ahead

Population projections for world's most populous nations (in millions)

	1980	2000	2025	2050	2100	Total fertility rate* (1984)
China	980.3	1,196	1,409	1,450	1,462	2.173
India	687.3	995	1,311	1,518	1,639	4.637
Soviet Union	265.5	306	339	358	376	2.335
United States	226.5	259	286	288	289	1.846
Indonesia	146.3	212	284	332	358	4.214
Brazil	121.3	181	243	279	299	3.816
Japan	116.8	128	132	129	128	1.710
Bangladesh	88.5	157	266	357	434	6.300
Nigeria	84.7	169	329	471	593	6.902
Pakistan	82.1	140	229	302	361	5.840
Total world	4,435	6,145	8,297	9,778	10,869	3.528

*number of children an average woman would have during her lifetime. Source: World Bank

Figure 2.

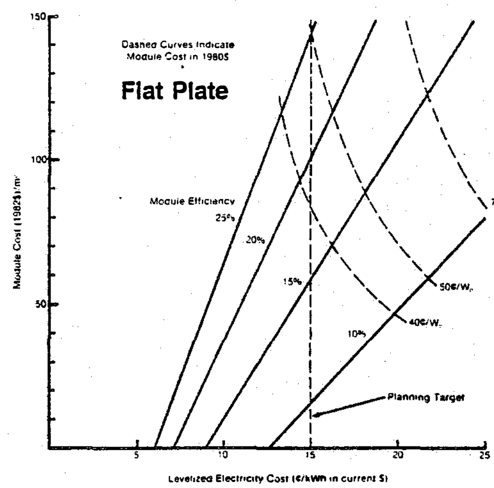

Figure 3(a).

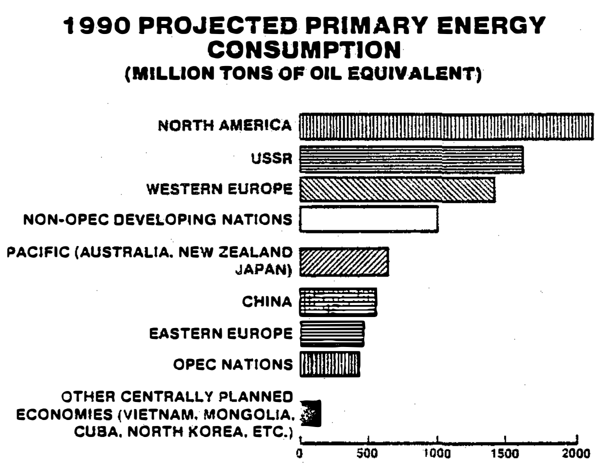

Figure 1.

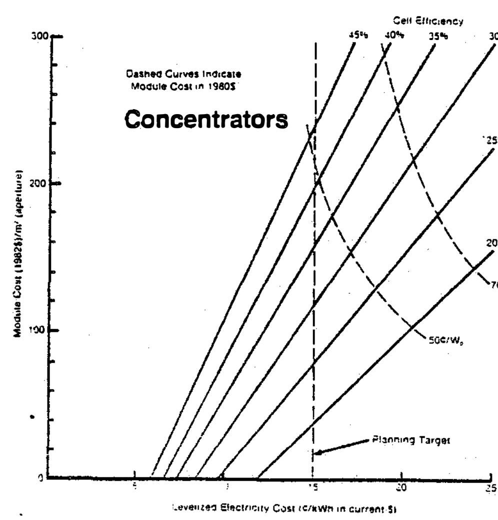

Figure 3(b).