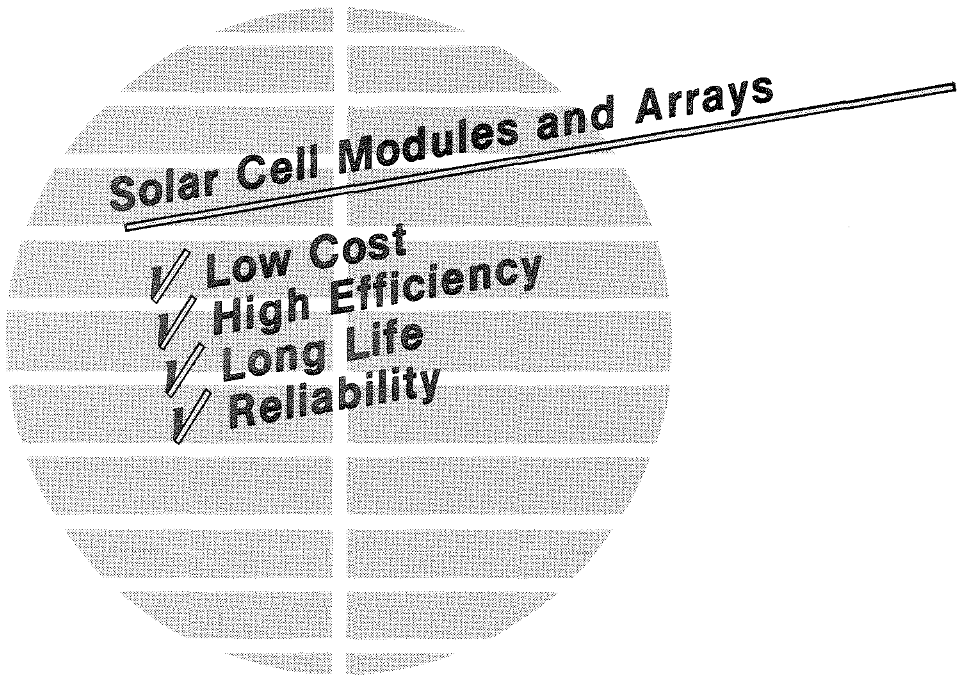
JPL Publication 86-31

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume I: Executive Summary

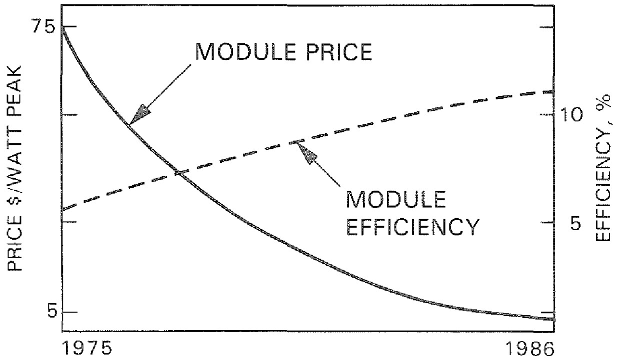
11 Years of Progress



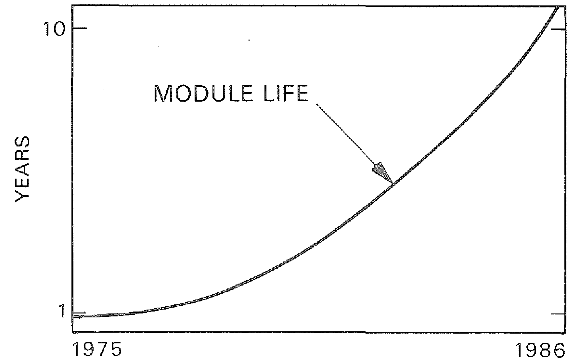
October 1986

Project Managed by the Jet Propulsion Laboratory for the U.S. Department of Energy

Photovoltaic Module Progress

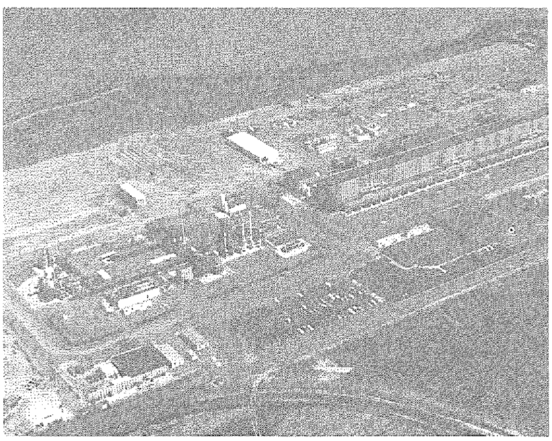


Flat or non-concentrating module prices have dropped as module efficiencies have increased. Prices are in 1985 dollars for large quantities of commercial products.

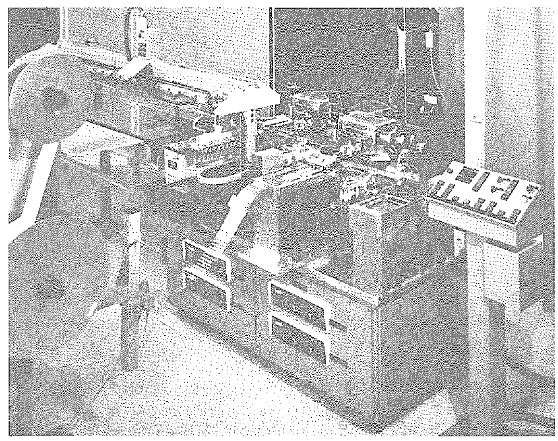


Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)

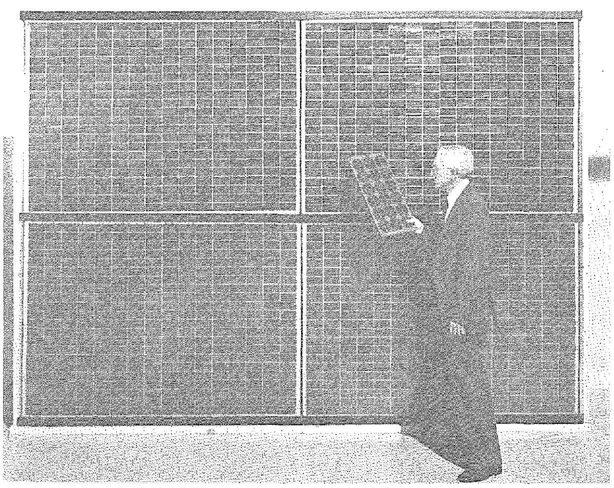
Technology advancement in crystalline silicon solar cells and modules (non-concentrating).



Union Carbide Corporation (UCC) funded the now operational silicon refinement production plant with 1200 MT/year capacity. DOE/FSA-sponsored efforts were prominent in the UCC process research and development.



The automated machine interconnects solar cells and places them for module assembly. The second-generation machine made by Kulicke and Soffa was cost shared by Westinghouse Corporation and DOE/FSA.



A Block I module (fabricated in 1975), held in front of four Block V modules, represents the progress of an 11-year effort. The modules, designed and manufactured by industry to FSA specifications and evaluated by FSA, rapidly evolved during the series of module purchases by DOE/FSA.

More technology advancements of the cooperative industry/university/DOE/FSA efforts are shown on the inside back cover. Use of modules in photovoltaic power systems are shown on the outside back cover.

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Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume I: Executive Summary

W. Callaghan
R. McDonald

11 Years of Progress

October 1986

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by
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for the
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National Photovoltaics Program

JPL Publication 86-31

Final Report Organization

This FSA Final Report (JPL Publication 86-31, 5101-289, DOE/JPL 1012-125, October 1986) is composed of eight volumes, consisting of an Executive Summary and seven technology reports:

Volume I: Executive Summary.

Volume II: Silicon Material.

Volume III: Silicon Sheet: Wafers and Ribbons

Volume IV: High-Efficiency Solar Cells.

Volume V: Process Development.

Volume VI: Engineering Sciences and Reliability.

Volume VII: Module Encapsulation.

Volume VIII: Project Analysis and Integration.

Two supplemental reports included in the final report package are:

FSA Project: 10 Years of Progress, JPL Document 400-279, 5101-279, October 1985.

Summary of FSA Project Documentation: Abstracts of Published Documents, 1975 to 1986, JPL Publication 82-79 (Revision 1), 5101-221, DOE/JPL-1012-76, September 1986.

Upon request, this FSA Final Report (JPL Publication 86-31) and the two supplemental reports (JPL Document 400-279 and JPL Publication 82-79) are individually available in print from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Abstract

In 1975, the U.S. Government contracted the Jet Propulsion Laboratory to develop, by 1985, in conjunction with industry, the photovoltaics (PV) module and array technology required for widespread use of photovoltaics as a significant terrestrial energy source. As a result, a project that eventually became known as the Flat-Plate Solar Array (FSA) Project was formed to manage an industry, university, and Government team to perform the necessary research and development. The original goals were to achieve widespread commercial use of PV modules and arrays through the development of technology that would allow them to be profitably sold for \$1.07/W_p (1985 dollars). A 10% module conversion efficiency and a 20-year lifetime were also goals of the Project.

The Project was able to develop the technology to a point where properly scaled production facilities, incorporating the latest technology, could profitably produce PV arrays for \$1.45/W_p (1985 dollars), array conversion efficiencies of more than 13%, and lifetimes approaching 20 years with 10-year manufacturer warranties as an industry standard.

It is intended that this Executive Summary provide the means by which the reader can gain a perspective on 11 years of terrestrial photovoltaic research and development conducted by the FSA Project.

Seven technology reports (Volumes II through VIII), covering the principal aspects of the technology development approach taken by the FSA Project, constitute the focus of the FSA Project Final Report. It is recommended that readers interested in the development of the Project management planning and decision-making process refer to Volume VIII, which describes the Project Analysis and Integration Area support to the FSA Project.

Foreword

Throughout U.S. history, the Nation's main source of energy has changed from wood to coal to petroleum. It is inevitable that changes will continue as fossil fuels are depleted. Within a lifetime, it is expected that most U.S. energy will come from a variety of sources, including renewable energy sources, instead of from a single type of fuel. More than 30% of the energy consumed in the United States is used for the generation of electricity. The consumption of electricity is increasing at a faster rate than the use of other energy forms and this trend is expected to continue.

Photovoltaics, a promising way to generate electricity, is expected to provide significant amounts of power in years to come. It uses solar cells to generate electricity directly from sunlight, cleanly and reliably, without moving parts. Photovoltaic (PV) power systems are simple, flexible, modular, and adaptable to many different applications in an almost infinite number of sizes and in diverse environments. Although photovoltaics is a proven technology that is cost-effective for hundreds of small applications, it is not yet cost-effective for large-scale utility use in the United States. For widespread economical use, the cost of generating power with photovoltaics must continue to be decreased by reducing the initial PV system cost, by increasing efficiency (reduction of land requirements), and by increasing the operational lifetime of the PV systems.

In the early 1970s, the pressures of the increasing demand for electrical power, combined with the uncertainty of fuel sources and ever-increasing prices for petroleum, led the U.S. Government to initiate a terrestrial PV research and development (R&D) project. The objective was to reduce the cost of manufacturing solar cells and modules. This effort, assigned to the Jet Propulsion Laboratory, evolved from more than a decade-and-a-half of spacecraft PV power-system experience and from recommendations of a conference on Solar Photovoltaic Energy held in 1973 at Cherry Hill, New Jersey.

This Project, originally called the Low-Cost Solar Array Project, but later known as the Flat-Plate Solar Array (FSA) Project, was based upon crystalline-silicon technology as developed for the space program. During the 1960s and 1970s, it had been demonstrated that photovoltaics was a dependable electrical power source for spacecraft. In this time interval, solar-cell quality and performance improved while the costs decreased. However, in 1975 the costs were still much too high for widespread use on Earth. It was necessary to reduce the manufacturing costs of solar cells by a factor of approximately 100 if they were to be a practical, widely used terrestrial power source.

The FSA Project was initiated to meet specific cost, efficiency, production capacity, and lifetime goals by R&D in all phases of flat-plate module (non-concentrating) technology, from solar-cell silicon material purification through verification of module reliability and performance.

The FSA Project was phased out at the end of September 1986.

Acknowledgments

The Flat-Plate Solar Array (FSA) Project took special pride in the fact that, at one time or another in its 11-year tenure, almost everyone in the photovoltaics (PV) community was a working partner in the attempt to achieve our goals. Without their efforts there would be very little to report. The corporate, academic, and individual interest and dedicated effort shown through the years has been effective and dramatic. Many knowledgeable observers have stated that few Government-sponsored technology development efforts can claim the degree of involvement and effective use of the tax payers' dollars as the FSA Project.

The National Science Foundation (NSF), the Energy Research and Development Agency (ERDA), and the U.S. Department of Energy (DOE) were the sponsoring agencies for the FSA Project. Their diligent support for the Project is gratefully acknowledged. DOE was an especially innovative agency in fostering the use of Industry-Government cost sharing.

Outstanding individual recognition is acknowledged to Dr. Morton B. Prince, DOE, for his personal technical competence as a founding father of PV technology, and his energy, guidance, and support for the FSA Project.

Mr. Paul Maycock and Mr. Robert Annan, in their capacity as Directors for the National Photovoltaics Program, acted through the years as the strategic planners that permitted the success of the FSA Project within the context of a Federal Program described by many Congressional leaders as one of the best managed programs ever undertaken by the Government. For their efforts, we are especially grateful.

Special thanks are given to the individuals who were responsible for the initiation of the PV Program through their vision and planning. Dr. Marshall E. Alper, Jet Propulsion Laboratory (JPL), Dr. Ralph Lutwack (JPL), Mr. John Goldsmith (now of Solarex Corp., formerly JPL), Dr. Leonard Magid (formerly with NSF, ERDA, and DOE, now Personnel Associates, Inc.), Dr. Lloyd Herwig (formerly NSF, now DOE), Dr. Paul Rappaport (formerly RCA and Solar Energy Research Institute, now deceased), and Mr. Richard Bleiden (formerly NSF, now Energy Control Devices).

Sincere appreciation is given to Ms. Joyce Murry, Dr. Irving Bengelsdorf, and Mr. Elmer Christensen whose assistance in the preparation of these FSA final reports was invaluable.

Appreciation is also given to the American people whose interest in renewable energy options, including photovoltaics, was strongly evident through their congressional representation and the legislation that enabled us to accomplish our goals.

This document reports on work done under NASA Task RE-152, Amendment 419, DOE/NASA IAA DE-A101-85CE89008.

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Part I: Executive Summary

The Flat-Plate Solar Array (FSA) Project, funded by the U.S. Government and managed by the Jet Propulsion Laboratory (JPL), was formed in 1975 to develop the module/array technology needed to attain widespread terrestrial use of photovoltaics by 1985. To accomplish this, the FSA Project established and managed an Industry, University, and Federal Government Team to perform the needed research and development (R&D). The Project's goal was to develop, by 1985, the technology needed to produce photovoltaic (PV) modules with 10% energy conversion efficiency, a 20-year lifetime, and a selling price of $0.50/W$_p$ (in 1975 dollars). The key achievement needed was cost reduction in the manufacture of solar cells and modules.

This Executive Summary is intended to provide the means by which the reader can gain a perspective on 11 years of R&D of PV technology: how it was done technically, how it was managed, the accomplishments, and the significance of these efforts.

PROJECT APPROACH

As manager, JPL organized the Project to meet the stated goals through R&D in all phases of flat-plate module technology, ranging from silicon-material refinement through verification of module reliability and performance. The Project sponsored parallel technology efforts with periodic progress reviews. Module manfacturing cost analyses were developed that permitted cost-goal allocations to be made for each technology. Economic analyses, performed periodically, permitted assessment of each technical option's potential for meeting the Project goal and of the Project's progress toward the national goal. Only the most promising options were continued. Most funds were used to sponsor R&D in private organizations and universities, and led to an effective Federal Government-University-Industry Team that cooperated to achieve rapid advancement in PV technology.

Excellent technical progress led to a growing participation by the private sector. By 1981, effective energy conservation, a leveling of energy prices, and decreased U.S. Government emphasis had altered the economic perspective for photovoltaics. The U.S. Department of Energy's (DOE's) National Photovoltaics Program was redirected to longer-range research efforts that the private sector avoided because of higher risk and longer payoff time.

To be competitive for use in utility central-station generation plants in the 1990s, it is estimated that the price of PV-generated power will need to be $0.17/kWh (1985 dollars). This price is the basis for a DOE Five-Year Photovoltaics Research Plan involving both increased cell efficiency and module lifetime. Area-related costs for PV utility plants are significant enough that flat-plate module efficiencies must be raised to between 13 and 17%, and module life extended to 30 years. Therefore, during the last few years, the FSA Project concentrated its efforts on overcoming specific critical technological barriers to high efficiency, long life, reliability, and low-cost manufacturing.

MAJOR FSA PROJECT ACCOMPLISHMENTS

- Established basic technologies for all aspects of the manufacture of non-concentrating, crystalline-silicon PV modules and arrays for terrestrial use. Module durability also has been evaluated. These resulted in:
  - Reducing PV module prices by a factor of 15 from $75/W$_p$ (1985 dollars) to $5/W$_p$ (1985 dollars).
  - Increasing module efficiencies from about 5% in 1975 to more than 15% in 1985.
  - Stimulating industry to establish 10-year warranties on production modules. There were no warranties in 1975.
  - Establishing a new, low-cost high-purity silicon feedstock-material refinement process.
  - Establishing knowledge and capabilities for PV module/array engineering/design and evaluation.
  - Establishing long-life PV module encapsulation systems.
  - Devising manufacturing and life-cycle cost economic analyses.
- Crystalline silicon, research solar cells (non-concentrating) have been fabricated with more than 20% efficiency.
- The cost per peak watt of PV power generation originally set for $0.50/W$_p$ (1975 dollars) was very nearly met based upon the assumptions that the best 1985 PV technologies were collocated and scaled to capture the economies of scale for a manufacturing production volume of 25 MW/year.
- Calculated that a multimegawatt PV power plant using large-volume production modules that incorporate the latest crystalline silicon technology could produce power for $0.27/kWh (1985 dollars).
- Transferred technologies to the private sector by interactive activities in research, development, and field demonstrations. These included 256 R&D contracts, comprehensive module development and evaluation efforts, 26 Project Integration Meetings (PIMs), 10 research forums, presentations at hundreds of technical meetings, and advisory efforts to industry on specific technical problems.
- Stimulated the establishment of a viable commercial PV industry in the United States.

Government-sponsored efforts, plus private investments, have resulted in a small, but growing terrestrial PV industry with economically competitive products for stand-alone PV power systems. A few megawatt-sized, utility-connected, PV installations, made possible by U.S. Government sponsorship and tax incentives, have demonstrated the technical feasibility and excellent reliability of large, multimegawatt PV power-generation plants using crystalline silicon solar cells. It is believed that a PV power plant will be able to generate electricity for $0.17kWh (1985 dollars) in the 1990s if there is a renewed and dedicated PV effort.

SIGNIFICANCE OF PROJECT ACCOMPLISHMENTS

The terrestrial PV effort was born of a perceived necessity at the time of the 1973 oil embargo by the oil-producing nations of the Middle East. Energy independence became a high-priority concept strongly endorsed by the U.S. Government and the American people.

Renewable energy resources were considered of prime importance to achieve the sought-after independence from foreign oil and from exhaustible fossil fuel sources of electricity generation. From these events, a large U.S. Government program evolved to develop a wide range of solar energy technologies. The California Institute of Technology (Caltech) and JPL became involved at the inception in what was to become the largest part of that program: The U.S. National Photovoltaics Program.

The PV technology advancements of the past 11 years have permitted the private sector to firmly establish itself for economical production and use of PV components for small remote applications. The feasibility and practicality of photovoltaics for rooftop and electrical utility applications has also been demonstrated. Economic competitiveness of large-scale PV power generation is possible in the future, but requires a concerted and coordinated R&D effort.

PROJECT MANAGEMENT

The portion of the National Program managed by JPL was first known as the Low-Cost Silicon Solar Array (LSSA) Project because the primary emphasis of the work was focused upon the achievement of low cost. Later, with a shift in emphasis from the DOE, it became known as the Flat-Plate Solar Array (FSA) Project.

Many changes in national priority occurred during the life of the FSA Project that affected the plans and conduct of the activities. In the early 1980s, a general feeling of lessened importance for the development of energy independence for the United States prompted the reduction in scope of the National Program.

However, significant progress was made by the FSA Project in attaining both the original U.S. National Photovoltaics Program's goals (as envisioned by the Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications sponsored by the National Science Foundation (NSF) at Cherry Hill, New Jersey, in October 1973, and in attaining the goals more recently stated in the DOE Five-Year Research Plan published in 1983.

The progress made derives from the fact that the FSA Project was able to channel the capabilities of JPL, universities, and industry to meet a national need through the use of applied research that emphasized technology development and technology transfer. The process by which the efforts of the Project, acting as an arm of a Federal research laboratory, was able to successfully stimulate the development of an infant industry infrastructure that could manufacture high-quality, low-priced, long-life PV modules is viewed by some as the most important accomplishment.

Specific technologies were identified as driving the ability to succeed in achieving the goals of low price, high quality, and long life. Parallel paths of R&D were then undertaken by the Project by bringing university and industry participants under contract in a highly competitive environment designed to foster the best technical achievements and to eliminate lesser accomplishments from further consideration.

The contract actions numbered 256 involving 103 separate U.S. institutions during the 11-year life of the Project. The Project was funded to a level of almost $235 million during that period of time.

These contract activities were integrated with each other regarding goal achievement and, equally important, were an integral part of a comprehensive technology transfer process:

(1) This process consisted of conducting PIMs to provide an exchange of data and information with all contractors; to identify, implement, and evaluate integration activities; to gain perspective on trends and new developments; and to guide the Project's near- and long-term planning and adjustments in priorities. During the 11 years of the Project, 26 PIMs were conducted.

(2) Ten research forums were held that focused upon specific technical problems of concern wherein invitees from non-PV technical communities and members of the PV community were able to engage in problem solving from several perspectives.

(3) Numerous professional society meetings and authored papers (in collaboration with contractors and DOE meetings with other laboratories of the National Program) contributed to the exchange of information.

(4) Contractors were able to use Project laboratory facilities in an effort to solve specific problems in collaboration with Project personnel.

(5) Extensive briefings on specific technical problems were held for the benefit of the PV manufacturers.

(6) Five procurement cycles were initiated with the PV industry to infuse increasingly better technology from the Project to industry by requiring that increasingly rigorous specifications be met in terms of cost, performance, and lifetime. JPL tested these modules, performed failure analyses, and then established an iterative loop between module designer/fabricator and evaluator.

The comprehensive technology transfer process enhanced the ability of the Project to define price and performance allocations for each technology thrust in a way that permitted formal assessments of progress. A system of computer models that simulates the PV module manufacturing process with great detail, develops cost-effective operations and maintenance strategies, assesses probabilities of success in research activities whose required results are specifically defined, and details array performance with different engineering designs contributed to the formal Project assessment of contractor progress.

PROJECT TECHNOLOGY SUMMARIES

Volume II: Silicon Material

The objective of the Silicon Material Task was to develop processes capable of large-scale production of polysilicon, suitable for the fabrication of solar cells, at a market price of less than $10/kg (1975 dollars). Eleven alternative processes were investigated. The most promising of these was the Union Carbide Corp. silane process for which the steady-state operation of a 100-MT/year pilot plant was successfully demonstrated, followed by the full-scale operation of a 1200-MT/year production plant. The silane products of these plants have been shown to be purer than semiconductor grade. The silane-to-silicon conversion units in these plants are conventional Siemans-type reactors. The Project goal of $10/kg can probably be achieved if development efforts were to be completed on fluidized-bed reactor silane-to-silicon conversion units.

Volume III: Silicon Sheet: Wafers and Ribbons

The objective of the Silicon Sheet Task was to develop methods for producing silicon sheet of a quality and a cost commensurate with the requirements of the Project goal: to demonstrate the production of solar cell modules at a price less than $\$0.50/W_p$ (1975 dollars), and with an energy conversion efficiency greater than 10%. For sheet growth, this required a value added of $\$0.14/W_p$ or $\$14/m^2$ (1975 dollars). Ribbon growth, ingot growth and wafering, and several other sheet growth processes were investigated during the first 6 years of the Project. After that, the emphasis was placed upon ribbon growth and understanding the influence of growth dynamics on silicon sheet quality and upon solar cell performance.

Silicon wafers made from Czochralski (Cz) ingots sold for $\$1000$ to $\$1200/m^2$ in 1975. Today's price is substantially lower and it has been estimated that if all the demonstrated improvements were collocated in production, they could be sold for about $\$100/m^2$ (1975 dollars).

The ribbon technology developed by Mobil Solar Corp. has become a commercial process. Development of dendritic-web ribbon growth continues at Westinghouse Electric Corp.; commercial production has been planned.

Volume IV: High-Efficiency Solar Cells

The High-Efficiency Solar Cells Task was formed in 1982 for the purpose of gaining an understanding of the reasons for losses within solar cells, within the bulk material and at the surface, and to devise means for reducing these losses, and, hence, to gain the capability for producing cells with increased efficiency. An improved understanding of the nature of the losses was achieved and lead to the means for increasing the efficiency of cells; the Project fabricated 16 cells with an area of 4 cm^2 each with conversion efficiencies of 20.1 to 19.5% (AM 1.5-global). During the period 1982 to 1986, research solar cell efficiencies reported by the PV community increased from 17% to more than 21% because of the direct and indirect contributions of the FSA Project.

Volume V: Process Development

The Process Development Area initially had the objective of developing low-cost solar cell and module fabrication processes and equipment. Later, the objective was changed to emphasize processes leading to high efficiency. A total of more than 75 contracts were directed to achieve the stated objectives in four major aspects of process development: surface preparation, cell junction formation, cell metallization, and module assembly. The cost reduction objectives were achieved, and the transfer of this technology to industry was accomplished with the documentation of more than 140 processes.

Volume VI: Engineering Sciences and Reliability

The activities of the Engineering Science and Reliability Area were directed toward developing the engineering technology base needed to meet the functional, safety, and reliability requirements of PV modules. The key objectives of this area included: (1) identification of functional, safety, and reliability requirements; (2) development of the means to meet the requirements; (3) procurement of candidate module designs for test and evaluation; and (4) module testing, evaluation, and failure analysis to determine design deficiencies requiring additional development.

Each of these four objectives has been satisfactorily accomplished and the results are apparent in numerous residential and multi-megawatt central station applications. The engineering technologies developed within this area have contributed significantly to improvement in module lifetime.

Volume VII: Module Encapsulation

The objectives of the Encapsulation Task were to develop encapsulation systems that would meet the overall Project goals of cost, efficiency, and lifetime and the development of techniques for controlling degradation in order to achieve a 30-year module lifetime. It was determined that existing materials were too expensive to meet the Project goals. Working closely with material supply industries led to the development of new materials that did meet the Project goals. This new encapsulation technology has been transferred to and adopted by the PV module manufacturers. Accelerated testing has indicated the likelihood of a 30-year lifetime.

Volume VIII: Project Analysis and Integration

The Project Analysis and Integration (PA&I) Area was formed to provide the Project with information needed for decision-making and planning. The Area helped reformulate the original Project goals to reflect what had been learned about PV technology and to expand it to cover commercialization and industrialization. Several analytical models to assess technical progress were developed including a detailed manufacturing-cost model. Price allocations were formulated for each of the major technical elements of the Project in order to provide a set of internally consistent targets. The PA&I Area participated in many studies relating to the economic prospects of photovoltaics including a joint study with the Solar Energy Research Institute (SERI) to assess and compare the prospects of the many silicon sheet material options that had been investigated by the PV industry.

The remainder of this Executive Summary volume is a presentation of the management approach, Project performance, Project accomplishments in terms of module cost, lifetimes, efficiency, production, and an outlook for photovoltaics.

This Executive Summary has been prepared to give the needed traceability as to how the FSA Project evolved, developed, performed, and its final status. This will be important to those who will be charged with the decision on how to develop a renewable resource electricity generation option for the United States the next time world events underscore the dependence upon foreign oil and depletable fossil fuels. This final report, therefore, attempts to be as clear as possible regarding an audit trail.

Part II: Management Overview

ORIGINS OF THE PROJECT

Need for Alternative Energy Development

In the early 1970s, an "energy crisis" left the Nation faced with the prospect of meeting the future demand for energy under the constraints of a rapidly diminishing supply of nonrenewable resources and necessarily stringent environmental protection regulations. Concerns over the national security implications of an energy shortage and the overall economic well-being of the Nation prompted a public involvement in planning for and developing national energy resources.

The energy crisis spurred the Nation into activities designed to help achieve energy independence. Among the responses to the crisis were innovative attempts to deliver alternative sources of electrical energy, including the development of PV conversion technology. At the time, the common conclusion to be drawn from predictions of future energy needs was that the projected patterns of electricity consumption could not be satisfied merely by expanding conventional power generation as fossil fuel, and nuclear additions to generating capacity would pose undue environmental risk. With the possible exception of hydroelectric power, for which few major sites remained to be developed without causing major ecological consequences, solar PV systems afforded the most attractive means of meeting the predicted energy needs. PV conversion technology uses a renewable energy source and concurrently minimizes pollution and ecological disadvantages.

The Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, sponsored by the National Science Foundation, Research Applied to National Needs (NSF-RANN), held at Cherry Hill, New Jersey, in October 1973, initiated an evaluation of the use of PV conversion devices for terrestrial application, and defined an active role the Government could play in supporting its development (Reference 1).

Solar PV conversion systems were first used extensively in the U.S. space program. These systems had a capacity of as much as 10 kW_p. The basic PV conversion technology had been proven, and very small terrestrial applications of solar PV systems already existed. It was thought that expansion of the terrestrial applications could furnish a significant contribution to the Nation's energy needs if certain questions regarding the reduction to commercial practice of the PV technology could be resolved and systems costs reduced.

U.S. Government involvement rapidly followed the Cherry Hill Conference. The Energy Research and Development Administration (ERDA) was formed in early 1975 and immediately became involved in structuring a Photovoltaic Conversion Program.[1] Plans were quickly forthcoming (References 2, 3, and 4). In the years that followed, momentum was developed and sustained by action of DOE (formed by Congress in 1977), the research community, and an eager private sector. One of the fundamental precepts of the structuring of the national programs was to accelerate the technology transfer process.

Formation of the JPL Solar Photovoltaic Project

The Cherry Hill Conference was composed of three major sections: invited papers, panel discussions, and workshops. Conclusions and recommendations for a program, which eventually became the National Photovoltaics Program, were derived from the summaries of the workshop discussions.

A 10-year technology development program with a budget of \$250 million was recommended by the Single-Crystal Silicon Solar Cell Workshop, with milestones through fiscal year (FY) 1985. The Polycrystalline Silicon Solar Cell Workshop also recommended a \$45 million budget for the 10-year technology development program. Thus, the recommendation from Cherry Hill for funding all crystalline-silicon technology development amounted to \$295 million (1974 dollars) (Reference 5).

Cherry Hill conferees attached a great deal of importance to price reduction and the establishment of significant production capacity. The Single-Crystal Silicon Solar Cell Workshop recommended a \$0.50/W_p cell, very high cell efficiencies, and a production capacity of 500 MW/year to be achieved by 1985. Similarly, the Polycrystalline Silicon Solar Cell Workshop established objectives for the production of cells with 10% conversion efficiency at a price of \$0.50/W_p, and a commercial production capacity of 10 MW/year by 1985. The workshops also concluded that the development of low-cost encapsulation techniques should be pursued to ensure satisfactory electrical performance over a 20-year lifetime.

A report was prepared by JPL which analyzed the Cherry Hill Conference findings and made recommendations to aid the NSF in planning resources, and developing goals and milestones for the National Photovoltaic Program (Reference 6). Although early goal statements referred to cell conversion efficiencies, subsequent interpretation of the Cherry Hill recommendations changed these to module efficiencies.

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[1] Later, to be known as the National Photovoltaics Program.

The LSSA[2] Project was organized at JPL in 1975 to implement the flat-plate crystalline silicon goals established by the National Photovoltaics Program. Specifically, goals in 1975 were listed as follows;

(1) Develop a process for obtaining solar-cell quality, silicon material suitable for making single-crystal silicon at a price of less than \$35/kg (changed in 1976 to \$10/kg).

(2) Develop and demonstrate automated processes for producing single-crystal silicon sheets.

(3) Develop and demonstrate automated processes for the complete fabrication of solar cells into array systems at a production rate of more than 500 MW/year at a price of less than \$0.50/W_p (1975 dollars).

(4) Develop encapsulation materials and techniques for arrays with a design operating lifetime greater than 20 years.

(5) Develop a capability and produce single-crystal silicon cells for tests of 200-, 400-, and 600-kW systems. Price goals for successive 200-kW increments of production were \$5.00, \$2.00, and \$1.00/W (1975 dollars) (Reference 7).

The first Federal-level planning document to formally adopt efficiency goals for crystalline-silicon, flat-plate modules was published in 1977 (Reference 8). The LSSA Project was formally acknowledged in that document to have the goal of working with industry to develop reliable, low-cost (\$0.50/W_p, 1975 dollars)[3] silicon solar modules having at least 10% conversion efficiency and a 20-year module service life.

Original JPL Project Mission and General Management Approach

JPL had been asked by DOE's predecessor, ERDA, to implement the LSSA Project. The Project was to help develop an infrastructure that would allow an infant industry to survive so that a Government-industry partnership could reduce the cost of PV power generation to the point where it would be competitive with conventional fossil-fuel-based power generation. The decision was made to involve as many members of the fledgling PV industry as possible to give it both momentum and credibility.

A process evolved in the work that was called "technology development." It was more than just a label for one of many activities. The term took on real meaning, denoting a day-to-day process of moving a concept from applied science toward verification of commercial viability. A potential for scaling systems to commercial dimensions had to be shown; prototypes had to be made; field tests had to be designed and conducted; engineering, environmental, and safety tests had to be made; and, eventually, end-user acceptance had to be demonstrated in the willingness of non-Government consumers to buy the product.

Years of hard work, involving countless concepts covering the full range of PV technologies (silicon feedstock refinement, silicon sheet substrate formation, cell processing, encapsulation, engineering, testing, economic analysis, module design, and the development of manufacturing processes) followed as participation widened and came to include, at one time or another, just about everyone in the United States who claimed to be a part of the PV community.

As the National Photovoltaics Program and the FSA Project progressed through shrinking budgets and a reordering of energy priorities, the most difficult tasks were the almost continuous reassessment of objectives, measuring progress, and communicating this information to others. This project approach, or process of working, is discussed in the following two sections.

PROJECT APPROACH

The LSSA Project was organized at JPL in January 1975 in a manner similar to the organization of JPL flight projects. The LSSA Project Management, reporting to and part of the JPL Civil Systems Program Office, was responsible for the achievement of the stated objectives and the delivery of the required products within the negotiated schedule and budget. Consistent with the matrix organization of JPL, the technical staffing was provided by technical divisions of the Laboratory.

A major difference from JPL flight projects was the nature of the goal of the LSSA Project. The overall goal of the Government program was to establish the commercial practicality of PV systems. Consequently, the LSSA Project needed to involve a significant portion of the industrial community interested in PV products in addition to the research communities in Government laboratories and universities. It was necessary for the LSSA Project to work directly with and to stimulate industry to develop a production capability for PV arrays at a price one hundred times less than the prevailing price in 1975.

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[2]The LSSA Project was later called the Low-Cost Solar Array (LSA) Project and then called the Flat-Plate Solar Array (FSA) Project.

[3]The plan cited in Reference 8 did not acknowledge the inflation on prices that occurred between the Cherry Hill goal statement of \$0.50/W_p in October 1973 and the 1977 date of plan.

Staffing of the Project required technical disciplines typical of some portions of flight projects. However, because of the industrial cost nature of the Project goal, professional economists were used in the planning, analysis, and integration. These economists were a permanent, integral part of the LSSA Project. They brought a different perspective to the PA&I activity which was formed to provide the ability to plan, develop, and apply the systems simulation tools needed for technology assessment and resource allocation. The special training of the economists permitted them to focus on the problems of allocation of scarce resources in an uncertain environment. They also provided valuable insight into the business, financial, and economic environment in which the contractors would have to function.

Organization

The overall National Photovoltaics Conversion Program was organized under three sub-programs in 1975: (1) Systems and Applications, (2) Test and Evaluation, and (3) Research and Technology.

The Research and Technology program was further divided into two elements: advanced technology and low-cost single-crystal silicon. Advanced technology included development of thin-film silicon devices, cadmium sulfide/copper sulfide devices, improved silicon solar cells, and the development of other materials and devices. The JPL LSSA Project, which had been under way since January 1975, was responsible for the low-cost single-crystal silicon element.

The original organization of the LSSA Project followed the technical partitioning of the work effort. Those areas were:

(1) Silicon material refinement.

(2) Single-crystal silicon sheet formation.

(3) Automated PV array assembly.

(4) Module encapsulation.

(5) Large-scale production.

A manager was assigned in each of these five areas. This manager was responsible for the management of the area, the technical monitoring of subcontract activities, the conduct of in-house activities, and assisting the LSSA Project Office in technical analysis and support.

The first four areas addressed the technical problems which were considered to be the most significant technical obstacles in achieving the Project goals. Appropriate objectives were established for each. The manager of the fifth area, Large-Scale Production, had the responsibility for procuring large production runs of low-cost PV modules for a series of system tests to be conducted by companion efforts of the National Photovoltaics Conversion Program at other research laboratories.

In addition to these five areas of the Project, a PA&I Area was established, as mentioned previously. The PA&I Area performed system analysis and trade-off studies and conducted system integration of the five areas of the LSSA Project as well as provided system integration support for the overall National Photovoltaics Conversion Program.

A staff engineer was assigned from the JPL Quality Assurance and Reliability Office to provide support in quality assurance and quality control.

Implementation

In conjunction with the technical partitioning described, the work was partitioned contractually. Each of the five technical areas had multiple contractors to obtain a broad spectrum of innovative ideas. In addition to multiple contractors and parallel technical approaches, the contracts were time phased. Each subsequent phase required increasingly more specific identification of the desired achievements. A final phase was planned to demonstrate the required technical capability, and to provide information enabling cost projections to be made to ensure that the technology would satisfy the overall cost objectives of the LSSA Project. It was originally planned that the number of contractors and technical approaches would be decreased with each subsequent phase, limiting the approaches to the most promising.

In order to assess the various approaches in an objective and quantitative manner, some new system simulation tools were developed. The price goal for the entire module, stated in terms of module price per peak watt, was sub-allocated to the major technical elements by the Project Manager with the help of the PA&I Area. Table 1 shows the price allocation used in 1976. The objective of this price allocation process was to provide a set of internally consistent targets for each technical area within the LSSA Project to achieve the overall price reduction goal. These allocations were revised from time to time to reflect progress in each area.

Table 1. Price Allocation (Reference 9)

Technical Element	Price Per Peak Watt
Silicon material	$0.03
Sheet growth	0.14
Cell manufacture	0.13
Module fabrication	0.20
Module price goal	$0.50 (1975 dollars)

A computer model of solar array manufacturing was developed to provide a standardized approach for making economic cost comparisons of competing technologies. Standards were formulated in conjunction with the industry. The model uses standardized costs for labor, material, utilities, services, and capital costs, and determines a required price for the product to provide a certain return on equity. The way in which the required price varies with production volume is a valuable output of the program. The model was subjected to rigorous critique by many industrial firms to ensure its acceptability in the PV community.

In addition to the solar array manufacturing model, another model, Simulation of Research and Development Projects (SIMRAND), was used. This model permitted technical people, knowledgeable in specific areas of the Project, to include uncertainty in their technical assessments and to develop probabilistic curves of potential performance at the subsystem technology level. The methodology then combined these probabilistic curves to permit the Project staff, freed from the limitation of working with point estimates, to determine which combinations of technologies had the higher probability of meeting the specific technical and cost goals. The result is an improved degree of consistency and objectivity in Project decision-making.

Technology Transfer

A critical part of the approach to achieve the Project's objectives included the direct involvement of industry. This was accomplished by direct participation in technology development by early large annual procurements of solar arrays and by the transfer of technology to commercial practice. The LSSA Project, as part of the National Photovoltaics Conversion Program, was ultimately concerned with the creation of a new product, a demand for the product, and an industrial capacity for supplying the product. There was a perceived national need at the time to establish new energy sources as soon as possible, certainly faster than the typical 20 to 50 years from laboratory to marketplace. Accordingly, there was an active effort to accelerate the technology transfer process.

It was anticipated that the dozen or more subcontracts with industry during FY 75 would include several firms with national production and marketing structures. Therefore, it was expected that the impact of these participating industries would be significant.

The Project's technology transfer plan included the following activities:

(1) Publication of results in scientific, technical, and trade journals representative of the supplier, user, and regulatory communities.

(2) Presentation at scientific, technical, and trade conferences representative of the three communities.

(3) Organization of periodic informal workshops for participants and non-participants in the Project.

(4) Project Integration Meetings (PIMs) were held quarterly in the early years of the Project and semiannually in the latter years. These meetings usually lasted 2 days and included meetings for information exchange within each of the Project areas as well as a general meeting for presentations and discussions of broad interest within the Project. PIMs were attended by 300 to 500 individuals from the PV community and from the Project.

In addition to these planned activities, the Project also planned to accomplish technology transfer through interface with companion activities at other research centers within the National Photovoltaics Program.

Project Milestones

The approach to the accomplishment of Project milestones was to conduct the major part of the technology development tasks through contracts with industry and universities, to carry out critical supporting technical research and development in-house, to procure state-of-the-technology arrays from manufacturers in the marketplace, and to conduct the major part of the PA&I activity as an in-house JPL effort.

The initial phase of the LSSA Project, during FY 76, was essentially devoted to assessment, the definition of technology requirements, and the evaluation of processes and techniques necessary to reach the Project's goals. The next phase, scheduled for FY 77, was planned for evaluation of the scalability of the various processes and materials being considered. It was planned that this would lead to an interim demonstration in FY 80. The final milestone of the Project was scheduled for FY 85. These two major milestones later became formally designated Technical Readiness and Commercial Readiness, respectively.

Technical Readiness in FY 80, relative to the FY 85 goals, was defined as: production processes identified and all individual process steps and production prototype equipment successfully demonstrated with production rates and product quality consistent with required market price. In this context, Technical Readiness refers to the proven ability of technologies that, if scaled up to commercial levels, would allow production of PV modules at a price of no more than $0.70/W$_p$ (1980 dollars).

Commercial Readiness is defined as products or systems for a given application class which can be offered for sale and purchased at a given price (Reference 10).

An example of this time-phasing for the Automated Array Assembly Area is shown in Figure 1.

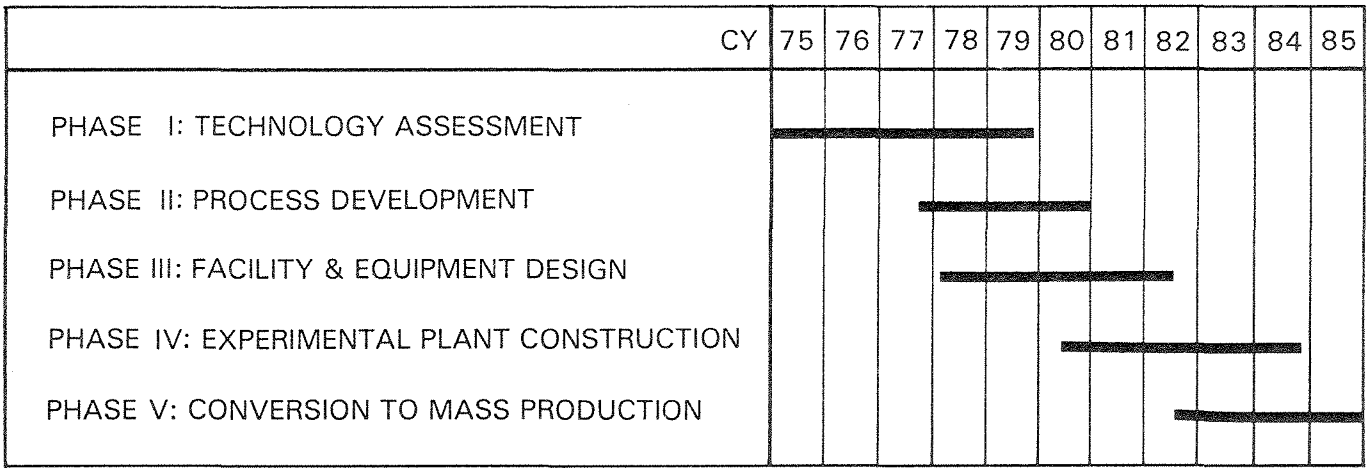

Figure 1. Contract Time-Phasing for the Automated Array Assembly Area (see Reference 8)

PROJECT PERFORMANCE

This section describes the major changes in approach from the original approach described in the previous section. Most of these changes were caused by changes in objectives established by the DOE. The detail presented here will allow the reader to gain insight into the process by which actual performance consistently evolved from what was originally planned.

Changes in Project Organization

During the first year of the Project, a design and test activity was added to the Project organization. The scope of this activity included: (1) design and test effects upon configuration, (2) electrical performance reliability analysis and test, (3) cabling design and test, (4) structural analysis and test, and (5) thermal analysis and test. By the second year, the design and test activity was divided into an Engineering Area and an Operations Area. Also during the first year, three support activities were added to the Project: (1) procurement, (2) financial resources, and (3) reporting and documentation.

In 1977, the Silicon Material Task, the Large-Area Silicon Sheet Task, and the Encapsulation Task were grouped together within the Technology Development Area, and the Automated Array Assembly Task became the Production Process and Equipment Area. The Large-Scale Production Task (renamed Large-Scale Procurement) was made a part of the Operations Area, and a new activity, the Cell Development Task, was formed within the Technology Development Area. The objective of the Cell Development Task was to demonstrate the feasibility of obtaining the required efficiency in solar cells fabricated with materials and processing that satisfied the cost goals of the Project.

Although there were numerous minor changes in the Project organization as a result of a more complete understanding of the scope of the work, the basic structure in place at the end of 1977, as shown in Figure 2, was maintained during the remainder of the Project.

Changes in Project Objectives

The original objectives of the LSSA Project were to develop, by 1985, the national capability to produce solar arrays at a price of less than $0.50/W_p$ (1975 dollars) in annual quantities of 500 MW, having an efficiency greater than 10%, and a 20-year minimum lifetime.

By October 1976, the end date for the Project objective had been changed to 1986 because of a programmatic change in the Silicon Materials Task. ERDA requested that a 25-MT/year silicon pilot plant be operational by January 1981. The revised schedule required a division of technical effort and resources, necessitating a delay until June 1986 for the large-scale silicon materials pilot plant to become operational.

In September 1977, an interim objective was established to demonstrate the Commercial Readiness of producing solar arrays by 1982 at a price of $2.00/W_p$ (1975 dollars).

The name of the Project had been changed, in September 1978, to the Low-Cost Solar Array (LSA) Project to indicate that PV materials other than silicon were to be included within the scope of the Project's responsibilities.

In March 1979, a major technical milestone was formalized for the LSA Project: a projection for the achievement of Technical Readiness by the end of FY 82 for a $0.50/W_p$ (1975 dollars) technology in 1986. The purpose of this milestone was to demonstrate industrial readiness for commercial operation by 1986, i.e., Commercial Readiness for $0.50/W_p$ (1975 dollars).

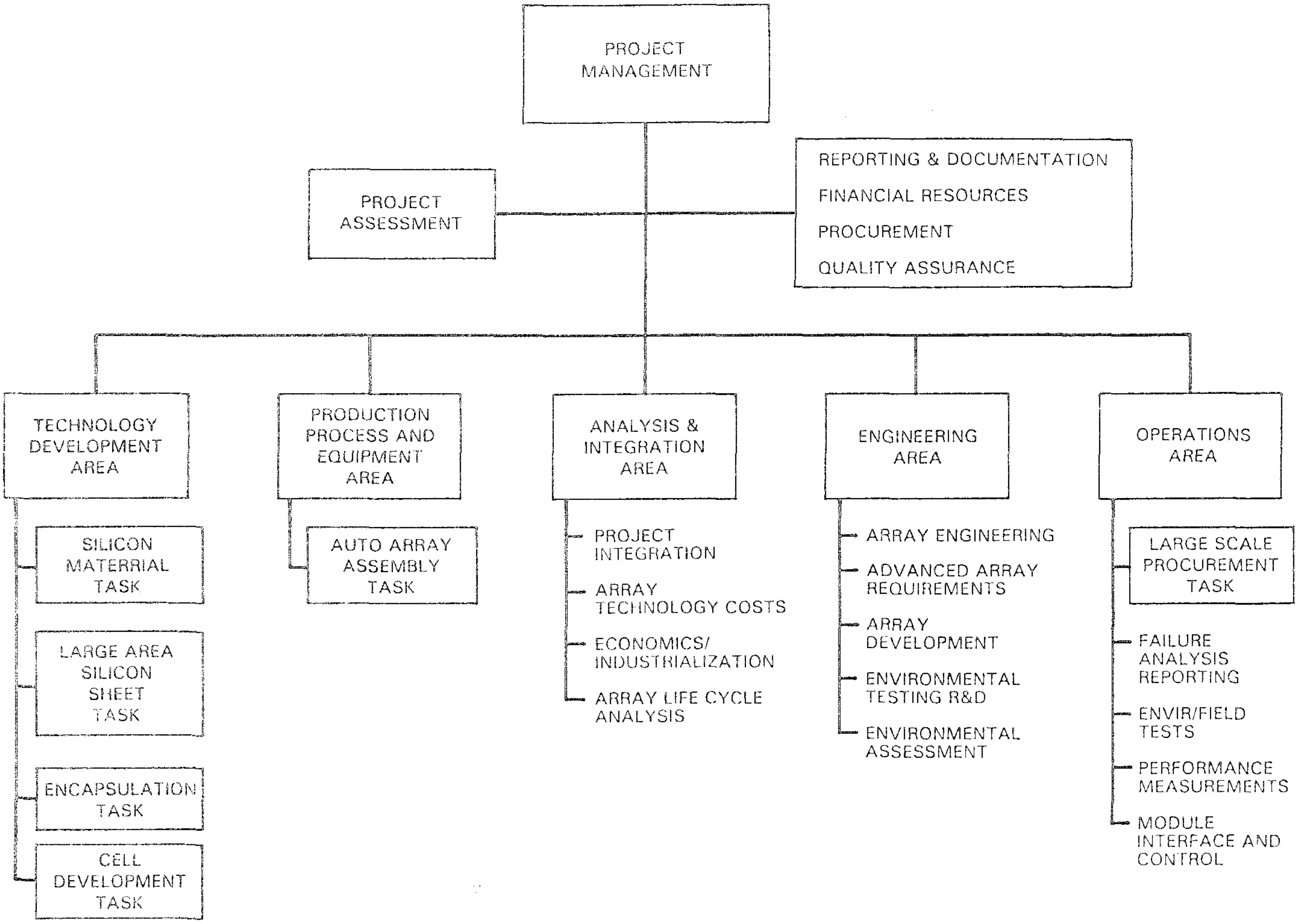

Figure 2. LSSA Project Organization

In August 1979, the Project objective for Commercial Readiness by 1986 was modified as follows: (1) The price was stated as $\$0.50/W_p$ (1975 dollars) and $\$0.70/W_p$ (1980 dollars), (2) the production capacity was changed from 500 MW/year to production rates commensurate with realizing economies of scale. Efficiencies of greater than 10% and operating lifetimes greater than 20 years remained unchanged.

As a result of major changes of national policy within DOE, the Project name was changed to the Flat-Plate Solar Array (FSA) Project and the Project objective was changed significantly in December 1981 as follows: to conduct research on new state-of-the-art, long-life flat-plate PV arrays establishing their technical feasibility so that industry could meet a target module price of less than $\$0.70/W_p$ (1980 dollars). The array performance objectives included an efficiency greater than 10%, and operating lifetime in excess of 20 years. The culminating activity of the research effort for the FSA Project, to establish technical feasibility, was scheduled to occur in the FY 84/FY 85 time frame. Commercial Readiness was no longer a Project objective because of the new DOE policy that commercialization should be undertaken by industry.

By October 1982, all specific Project objectives for Technical Readiness, Commercial Readiness, and Technical Feasibility had been eliminated, and the activities of the Project were directed toward "necessary research leading toward cost-competitive, long-life photovoltaic arrays." The primary activities of industrialization were to be performed by industry with the FSA Project playing a secondary role by encouraging technology transfer and by reducing the technical uncertainties in the large-scale production of photovoltaics.

In May 1983, DOE established a National Photovoltaics Program goal of \$0.15/kWh (1982 dollars) with a system life expectancy of 30 years (Reference 11). This program goal was translated to a 1985 goal for flat-plate collectors with an efficiency of 12% at a price of $\$100/m^2$ (1982 dollars), and a 1988 milestone of 15% efficiency at $\$90/m^2$ (1982 dollars).

In February 1985, DOE directed JPL to develop and implement a plan to phase out the FSA Project by the end of FY 86.

Changes in Sponsorship and External Interfaces

The National Photovoltaics Program received its start as a result of the Workshop Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Appli cations held at Cherry Hill, New Jersey, in October 1973. This conference was sponsored by the Research Applied to National Needs (RANN) Program of the NSF.

JPL was funded by the NSF to publish the proceedings of the conference (see Reference 5) and to prepare a comprehensive program plan for the technology development required to meet the goal stated at the conference (see Reference 6). On November 15, 1974, JPL submitted a program plan to NSF to manage one program element of the total national program: the Low-Cost Silicon Solar Array (LSSA) Project (see Reference 8). This plan was approved by the Director of the National Science Board on December 5, 1974.

ERDA was formed in January 1975 and took over sponsorship of the JPL LSSA Project from the date of original Project authorization on January 17, 1975. ERDA was replaced by DOE in 1977. The JPL Project has been sponsored by the DOE Photovoltaic Conversion Program (known since 1981 as the Photovoltaic Energy Technology Program).

During the life of the Project, JPL has worked with numerous other organizations who have contributed to the National Photovoltaics Conversion Program:

Aerospace Corp.

Brookhaven National Laboratory.

Massachusetts Institute of Technology Energy Laboratory.

Massachusetts Institute of Technology Lincoln Laboratory.

NASA Lewis Research Center.

Sandia National Laboratories.

Solar Energy Research Institute (SERI).

U.S. Army Mobility Equipment Research and Development Command (MERADCOM).

In November 1978, the Photovoltaic Technology Development and Applications Lead Center was established at JPL to assist the DOE Photovoltaic Conversion Program Office in the management of the many organizations participating in the National Photovoltaics Program. The JPL LSA Project assisted in establishing the JPL Lead Center, but remained a separate organizational entity after its formation.

Budgetary History

A 10-year technology development program with a budget of $250 million was recommended by the Single-Crystal Silicon Solar Cell Workshop of the Cherry Hill Conference with milestones through FY 85. The Polycrystalline Silicon Solar Cell Workshop also recommended a $45 million budget for the 10-year technology development program. Thus, the recommendation from Cherry Hill for funding all crystalline silicon technology development amounted to $295 million (1974 dollars) (see Reference 5).

Efforts to measure progress in crystalline silicon technology since the Cherry Hill Conference have been made difficult by changes in the level of prices for goods and services in the U.S. economy. Through the years, inflation has tended to distort and obscure the actual progress made.

Table 2 shows the upward trend in the general level of prices of goods and services since 1974. The total impact is summarized in the cumulative Gross National Product (GNP) Implicit Price Deflator, which more than doubled since the beginning of the program. (This statistic is published quarterly by the Bureau of Economic Analysis, U.S. Department of Commerce.) The changing level of prices makes it difficult to see the more subtle changes that have taken place in program goals.

Table 2. GNP Implicit Price Deflator

Year	Average Annual Inflation Rate, %	Cumulative
1974	9.7	1.000
1975	9.5	1.097
1976	5.2	1.201
1977	5.8	1.264
1978	7.4	1.337
1979	8.7	1.436
1980	9.3	1.561
1981	9.4	1.706
1982	6.0	1.866
1983	4.2	1.978
1984	3.6	2.049
1985	3.7	2.125

Source: Department of Commerce, Survey of Current Business, May 1986.

The original Cherry Hill goal envisioned for the technology was $0.50/W_p$ in 1974 dollars. Using the Implicit Price Deflator, the equivalent value for the goal in 1985 dollars is $1.07/W_p$. If this module cost is used in the energy price algorithm in the present DOE Five-

Year Research Plan (see Reference 11), a PV system would produce electricity at a price of \$0.264/kWh, in 1985 dollars. A module efficiency of 10% and a 20-year module service life, as originally specified at Cherry Hill, were used to derive this result.

Since Cherry Hill, PV program goals have changed to reflect revisions in the outlook for conventional energy resources, and progress in understanding the potential of PV technology. Present program goals call for 15% module efficiency and a 30-year module service life. Expressed in 1985 dollars, the present goals call for an energy price of \$0.17/kWh, making them much more demanding than the previous goals. The Cherry Hill conferees made no mention of the budgetary recommendation being expressed in anything other than 1974 dollars. Indeed, they had no way of knowing the impact inflation would have on the dollar in the succeeding decade. In order to compare the budget recommended by the Cherry Hill Workshop with what was received, it is necessary to adjust the funds received from the U.S. Government (ERDA and DOE) back to 1974 dollars by using the GNP Implicit Price Deflator (see Table 2).

The funds disbursed by the U.S. Government from FY 75 through FY 85 for crystalline-silicon, flat-plate technology development were received almost entirely by the JPL FSA Project. Accordingly, the total funds received from the Government for crystalline-silicon, flat-plate PV array technology development from FY 75 through FY 85 were \$228 million in current year dollars, as shown in Table 3. When these funds are adjusted to 1974 dollars, the funding received in real terms (to reflect purchasing power in 1974) amounted to \$148 million. Thus, approximately 50.2% of the \$295 million recommended by the Cherry Hill conferees was actually received by the FSA Project, as shown in Figure 3. Figure 3 also shows the decline in funding relative to what was originally envisioned at Cherry Hill, especially in the later years of the FSA Project.

PROJECT ACCOMPLISHMENTS

Although a major change in national priorities led to a shift in the FSA Project goal from industrialization of PV modules (which would be competitive in the area of national electrical production) to research into long-term, high-risk technical options, the original objectives of the LSSA Project were either met or substantial progress was made.

Cost

In 1974, terrestrial PV modules sold for \$70/W_p to \$120/W_p (1985 dollars). The goal, as envisioned in 1974, was a price of \$1.07/W_p (1985 dollars). In 1976, the Project made an "off-the-shelf" purchase to assess the state of technology and identify areas of required-improvements. The average price from five manufacturers was \$43/W_p (1985 dollars). Subsequent purchases by the Project were made to introduce industry to the most recent technology developments, thereby

Table 3. Crystalline-Silicon, Flat-Plate PV Array Technology Development Funding, 1975-1985

Fiscal Year	Funds Received in Current Dollars, \$M	Value in 1974 Dollars, \$M
1975	\$ 0.6	\$ 0.6
1976	11.7	9.9
1977	30.9	24.4
1978	31.8	23.8
1979	32.9	22.9
1980	30.5	19.5
1981	28.6	16.8
1982	16.7	9.0
1983	13.6	6.9
1984	15.0	7.3
1985	15.5	7.3
Total	\$227.8	\$148.4

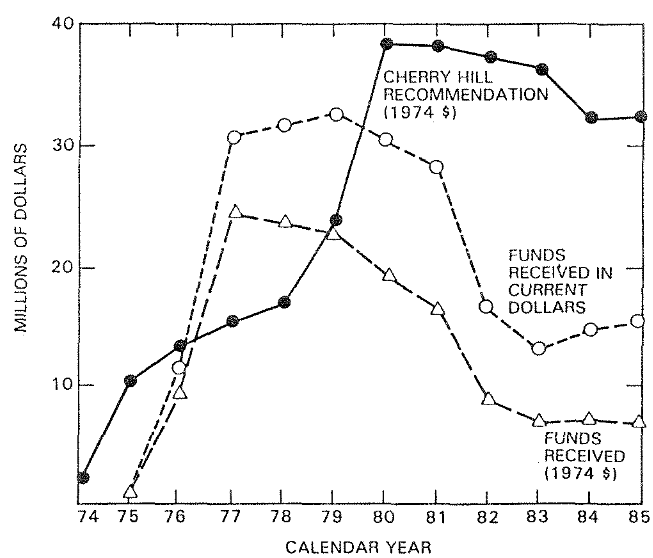

Figure 3. Recommended Versus Actual Project Funding

expediting the transfer of technology from the DOE/JPL program to the private sector. By the time of the third major purchase at the end of 1977, the average price had dropped to \$20/W_p (1985 dollars).

In October 1980, achievement of Technical Readiness was established for the potential production of modules by 1982 at a price of \$2.00/W_p (1975 dollars). It was shown that the 1980 state-of-the-art technology developed by the FSA Project, if scaled to production rates commensurate with realizing economies of scale, was capable of achieving Commercial Readiness for $\$2.00/W_p$ (1975 dollars) in 1982.

The most recent large purchase for which the market price is available is the Sacramento Municipal Utility District (SMUD) purchase in 1983 of 1 MW for $\$5.65/W_p$ (1985 dollars).

In 1985, a state-of-the-art assessment was made for a large Czochralski-based 25-MW/year factory operating in 1988. The result, based upon a module of efficiency of 13.5%, was $\$1.45/W_p$ (1985 dollars), compared to the original Cherry Hill goal of $\$1.07/W_p$ (1985 dollars). If the module cost of $\$1.45/W_p$ (1985 dollars) and the efficiency are combined with the balance-of-system costs and financial parameters used in the DOE Five-Year Research Plan, dated May 1983, an energy price of \$0.275/kWh (1985 dollars) is obtained which compares to the \$0.264/kWh (1985 dollars) for the $\$1.07/W_p$ (1985 dollars) Cherry Hill goal. Thus, it is apparent that Czochralski technology has essentially fulfilled the technology development part of the Cherry Hill promise.

Lifetime

In 1975, typical modules were fabricated using a silicone rubber encapsulant on a fiberglass substrate. The cell interconnection and the module fabrication was a very labor-intensive process that resulted in considerable product variation and high failure rates. Module lifetime was estimated to range from as little as 6 months to as much as 2 or 3 years.

As a result of technology development sponsored by the FSA Project in cell processing, encapsulation materials, reliability physics, performance testing, failure analysis, and module design, the expected lifetime of PV modules has improved considerably. Encapsulation materials have been tested in accelerated environments to 20 years; advanced materials are expected to have a 30-year lifetime after additional development effort. The estimated life of current production modules is more than 10 years. Modules from the major manufacturers are now offered with 10-year warranties. No module warranties were offered in 1975.

Efficiency

In 1975, module efficiencies were approximately 5%. Steady improvement has occurred as a result of technology development funded by the FSA Project in silicon material, sheet formation, cell processing, encapsulation materials, and module design and testing, and the transfer of this technology into industrial practice.

In 1984, the last year in which the Project purchased and tested modules, efficiencies ranged from about 8 to 11%. This year, 1986, a module manufacturer has reported an improved design with a module efficiency higher than 15%.

In July 1986, silicon solar cells with an area of 4.0 cm^2 and a conversion efficiency of 20.1% (AM 1.5 global) were processed at JPL by the FSA Project. Out of 16 cells processed, two measured 20.1% and two measured 19.8%. The remaining cells measured 19.5% or better. These cells incorporate refined versions of conventional processing methods with the exception of certain advanced techniques that bring about a significant reduction in the major mechanism (surface recombination) that limits cell efficiency. Wacker Siltronic p-type float-zone 0.18 Ω-cm wafers were used. Conversion efficiencies in this range have previously been reported by other researchers, but generally on much smaller (<0.5 versus 4.0 cm^2) devices which have undergone extremely sophisticated and costly processing steps. The FSA Project cells demonstrate that the potential exists for economical production of terrestrial PV power systems with high conversion efficiencies, one of the FSA Project goals.

Production

In 1975, the total terrestrial PV module production in the United States, from three or four companies, was less than 100 kW. Foreign PV production totaled less than 50 kW and came primarily from Germany.

As a result of market demand stimulated by the National Photovoltaics Program, and from improvements in production technology sponsored by the FSA Project and from perceived market expansion, total production in the United States in 1985 increased to about 8 MW and came primarily from five companies. Worldwide, flat-plate module production was about 16 MW.

Other Accomplishments

Although not specifically stated as objectives of the Project, there are many other accomplishments that have been stimulated by the close cooperation between the FSA Project and the PV industry.

The simulation and assessment tools developed by the FSA Project are significant contributions to the field of Project Management, especially when the price of a product is a stated objective. These technologies and the general approach in working with industry, adopted by the Project and described more fully elsewhere in the report, should be useful for future projects involving economic performance.

ARCO Solar has installed central-station PV power plants in California using two-axis sun trackers for silicon flat-plate modules. A 1-MW plant has been built at the Lugo Substation near Hesperia, and a 7-MW plant has been built in Carissa Plains. Each plant has operated successfully and reliably, and has provided electricity to the Southern California Edison Company and the Pacific Gas and Electric Company, respectively.

In the residential sector, a 190-kW PV power plant has been built by ARCO Solar for the John F. Long Homes of Phoenix, Arizona. In addition to the PV-supplied electricity, the homes contain many energy saving features.

Union Carbide built a 100-MT/year pilot plant that successfully demonstrated the steady-state silane production section of a silicon purification process. Then, using the same technology, they fabricated and operated a 1200-MT/year production plant. The products of these plants have a purity better than semi-conductor grade silicon. The capacity of the 1200-MT/year plant will be doubled, and another plant of 3000-MT/year capacity is being designed. Plants of this size represent a major step toward production of low-cost silicon for use in the PV industry.

OUTLOOK FOR THE FUTURE

Photovoltaics is Here to Stay

The idea of sunlight-powered electricity generation is instrinsically appealing. Environmentally benign with no moving parts required and modular for a wide range of uses, PV systems make sense. That is probably necessary for its widespread adoption into use, but it is not sufficient for it to happen. The practical matters are that PV systems must meet the economic concerns that the consumer has regarding something like electricity generation. Namely, will the PV system be able to compete with the conventional method of generation in price, performance, and life expectancy?

Based on those criteria, the answer is yes, it will. It will, almost certainly, but it cannot do so today. It will, because the basic research for competitive PV electricity generating systems has been completed. The engineering prototypes have been built, the field testing has been done, and the first tier of the PV technologies, crystalline silicon, has been proven capable of commercial success.

The success is not yet resounding because of non-technological reasons. The technology *is* a success. Manufacturers are offering 10-year performance warranties on their products based upon the technology. Conversion efficiencies are higher than most people dreamed they would be 11 years ago when the FSA Project began. They are 50% higher than the original planners set as a goal, and they are equal to today's more rigid efficiency demands.

The last barrier, price, will fall in time. Photovoltaics is close to what is required. The technology has permitted modules to be produced that are 15 times less expensive than they were when the FSA Project started. It still needs to be about 2½ times less expensive to move from the $250 million annual sales of today to the resoundingly, convincing multibillion dollar per year sales that are almost certain by all forecasts.

No technical barrier of real consequence stands in the way of that larger market. What is needed is the time for investors to be convinced that building the 20- to 25-MW/year-sized plants will capture the economies of scale of today's technology. That alone will allow the price to fall, profitably, the 2½ times from today's prices, and open the gates to the solar PV future that FSA has tried to facilitate for more than 11 years.

How long this confidence-building will take is difficult to predict. The continuing improvements in conversion efficiency, performance, and lifetime will make the required, competitive price an easier accomplishment because the consumer will be able to afford a higher price for a PV product that is better. Entrepreneurs will carefully watch the progress because the stakes are very high. Expansion will occur as the confidence builds. Certainly, there are factors that could accelerate the timing such as another oil shortage or other concerns regarding the security of the means to generate electricity.

There is widespread public interest in the future of photovoltaics. Many concepts have been proposed for the adoption of photovoltaics as an alternative energy source. One concept that has received considerable attention is the development of a very large, 4000 MW_p, solar power plant (Reference 12).

With this general state of affairs existing today with PV technology, it is relatively easy, even safe, to state that photovoltaics is here to stay.

Effects of Photovoltaics Upon Oil Displacement

A flat-plate PV solar array in a utility application is not a source for large crude oil displacement. About 3.2 to 4.3 barrels per peak kilowatt per year of installed capacity of photovoltaics is all one can expect to be displaced. This means that it willl take a gigawatt (10^9) of installed capacity to displace about 4 million barrels of oil per year. By using single-axis tracking, the oil displacement could be increased by about 20%. This information is based upon three separate studies by the Electric Power Research Institute (EPRI) using six synthetic utilities representative of different regions in the country (References 13, 14, and 15). What can be displaced by a gigawatt of photovoltaics in a year's time is about the same as the oil imported daily by the United States today.

Advocates for photovoltaics are convinced that multiple gigawatts of PV-generating capacity will ultimately be installed. In that event, photovoltaics can become a source of significant oil displacement. Most observers forecast this to occur after the year 2000.

The advent of an oil shortage in the shorter time frame of the late 1980s or early 1990s, and the effects upon photovoltaics are, however, of interest for other reasons.

The general experience of the FSA Project in analyzing energy scenarios implies that the first impact of an oil shortage in the late 1980s or early 1990s would be to stimulate an interest in renewable energy options similar to the interest shown in the 1973/1974 time frame when the OPEC nations embargoed oil shipments. The principal difference for photovoltaics would be that the state of technical knowledge regarding photovoltaics will be much more advanced. Presuming a modest, but continued growth of today's PV industry, there will be a significant infrastructure to build upon in the late 1980s or early 1990s that was virtually non-existent in 1973/1974.

With all this in mind, one can imagine a U.S. Federal Government interest in quickly increasing the installed PV generating capacity to reduce the impacts of an oil shortage. The Federal response would logically be concerned with the national security aspects of even a short-term economic disruption caused by an oil shortage.

Accordingly, one might expect subsidy measures to stimulate the production of photovoltaics for large-scale use, and one could probably expect to see infusions of Federal funds into PV research and development to reduce costs and improve performance.

Although it would still take many years to reach a position where photovoltaics would act as a large oil displacement source, the action taken by the Federal Government might be driven by the imperative of national security and the feeling that the Nation must seriously plan to displace expendable fossil fuels.

SOURCES OF ADDITIONAL INFORMATION

Government Documentation

Photovoltaic Energy Systems Program Summary

A summary is prepared each year to provide an overview of the Government-funded activities within the National Photovoltaic Program. Tasks conducted under contract by industrial, academic, and other research organizations are described in this annual summary as well as tasks conducted in-house by participating national laboratories.

The most recent document, DOE/CH-10093- H1, was published December 1985 and covers those activities initiated, renewed, or completed during FY 85.

U.S. Department of Commerce

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, Virginia 22161

NTIS is the central source for public sale of U.S. Government-sponsored research, development, and engineering reports.

U.S. Department of Energy

Technical Information Center (TIC)
Publication Request Section
P.O. Box 62
Oak Ridge, Tennessee 37831

This information center, founded in 1947, contains about 8000 books, 100 bound periodical volumes, 600,000 technical reports, and 5000 conference proceedings on the subject of energy. More than 100 FSA reports authored by JPL personnel, and more than 700 reports written by FSA contractors are at the DOE TIC. Reports on file in TIC are available from NTIS.

Technical Journals and Professional Meetings

Numerous articles written by FSA personnel may be found in the following journals:

American Ceramic Society Journal
American Chemical Society
American Institute of Aeronautics & Astronautics Energy Conversion Engineering Conference
Applied Physics Letters
European Congress on Operations Research
Institute of Electrical & Electronic Engineers Photovoltaic Specialists Conference
Institute of Environmental Sciences
International Solar Energy Society
Journal of Applied Physics
Journal of Crystal Growth
Journal of Electrochemical Society
Journal of Solar Energy Engineering ASME
Metallurgical Society of AIME
Photovoltaic Solar Energy Conference
Physical Metallurgy & Materials Sciences
Society for the Advancement of Material & Process Engineering
Society of Photo-Optical Instrumentation Engineers

See Appendix C of Reference 16 for specific references.

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15. Neal, R., Deduck, P., and Marshall, R., *Assessment of Distributed Photovoltaic Electric Power Systems*, EPRI Report AP-2687, Electric Power Research Institute, Palo Alto, California, October 1982.
16. Phillips, M.J., *Summary of Flat-Plate Solar Array Project Documentation*, JPL Publication 82-79, Revision 1, 5101-221, DOE/JPL-1012-76, Jet Propulsion Laboratory, Pasadena, California, September 1986.

APPENDIX

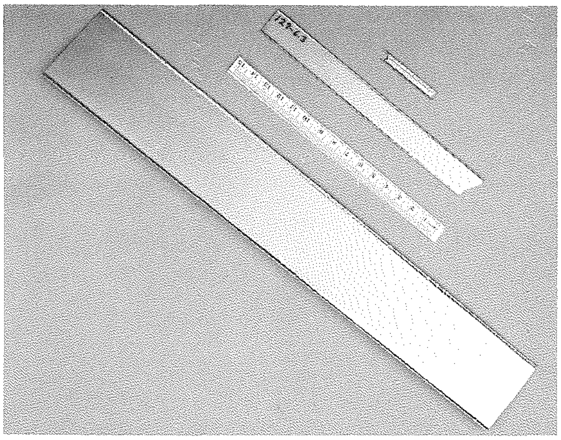
Glossary

Caltech	California Institute of Technology
Cz	Czochralski
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration
FSA	Flat-Plate Solar Array (Project)
FY	fiscal year
FZ	float-zone
GNP	Gross National Product
JPL	Jet Propulsion Laboratory
LSA	Low-Cost Solar Array (Project)
LSSA	Low-Cost Silicon Solar Array (Project)
MERADCOM	U.S. Army Mobility Equipment Research and Development Command
NSF	National Science Foundation
NTIS	National Technical Information Service
PA&I	Project Analysis and Integration
PIM	Project Integration Meeting
PV	photovoltaic(s)
RANN	Research Applied to National Needs
SERI	Solar Energy Research Institute
SIMRAND	Simulation of Research and Development Projects
SMUD	Sacramento Municipal Utility District
TIC	Technical Information Center
W_p	peak watt

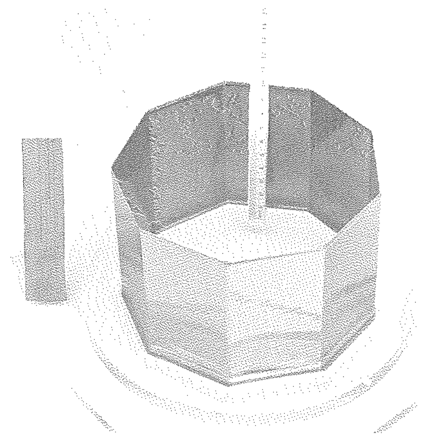
Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the National Photovoltaics Program to initiate a major effort toward the development of cost-competitive solar arrays.

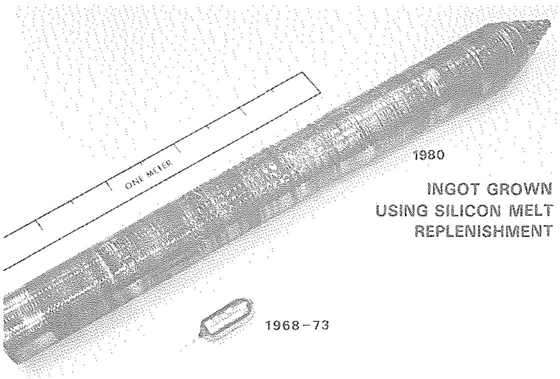
More Technology Advancements



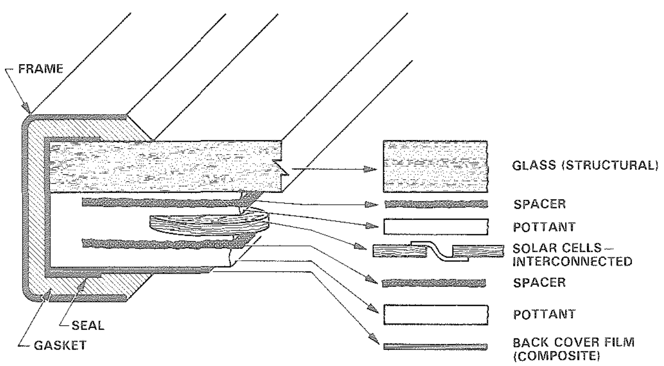
Dendritic web silicon ribbons are grown to solar-cell thickness. Progress is shown by experimental ribbons grown in 1976 and 1978 and a ribbon grown in a Westinghouse Electric Corporation pilot plant.



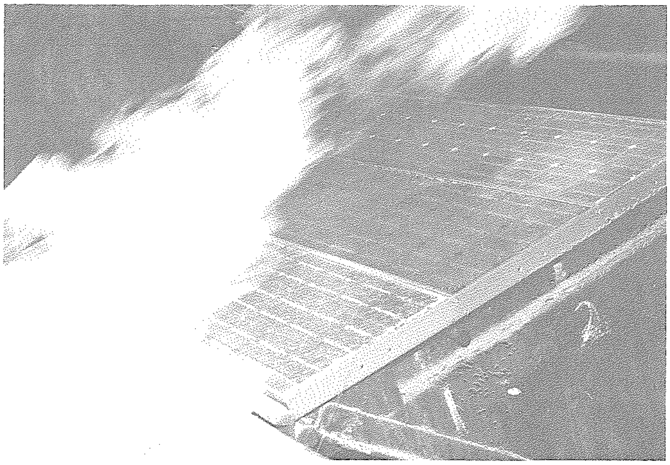
The edge-defined film-fed growth silicon ribbons are grown to solar-cell thickness. A DOE/FSA-sponsored research ribbon grown in 1976 is shown next to a nine-sided ribbon grown in a Mobil Solar Energy Corporation funded configuration.



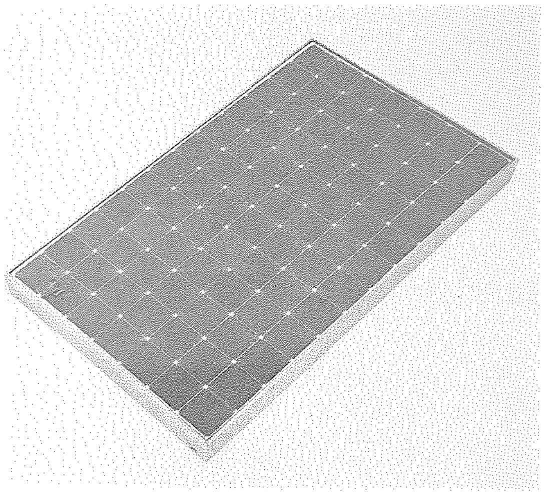
Czochralski silicon crystals as grown are sawed into thin circular wafers. (Support for this effort was completed in 1981.)



Typical superstrate module design is shown with the electrically interconnected solar cells embedded in a laminate that is structurally supported by glass. Materials and processes suitable for mass production have been developed using this laminated design.



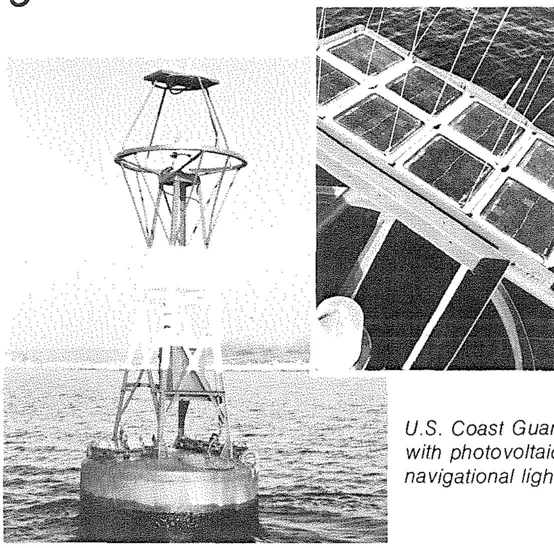
Prototype modules have passed UL 790 Class A burning brand tests which are more severe than this spread of flame test.



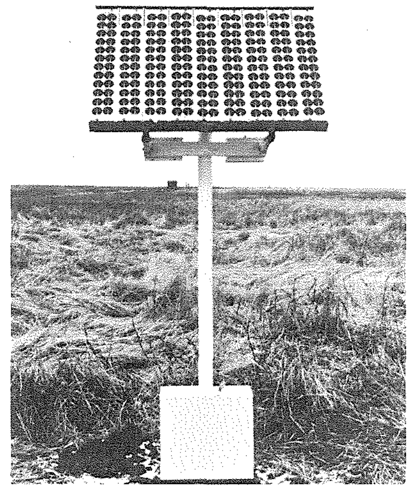
A 15.2% efficiency prototype module (21 x 36 in.) was made by Spire Corp. using float-zone silicon wafers. Recently, similarly efficient modules were fabricated from Czochralski silicon wafers.

Photovoltaic Applications

1975

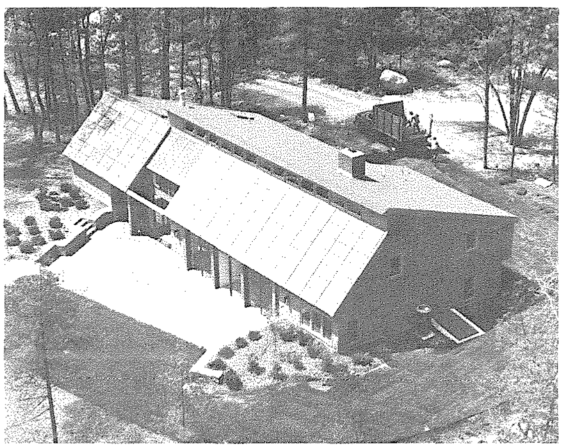


U.S. Coast Guard buoy with photovoltaic-powered navigational light.

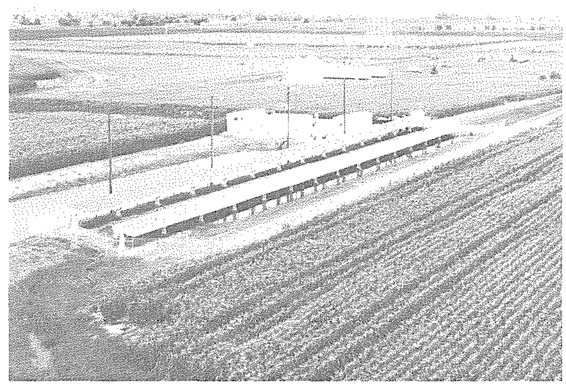


Photovoltaic-powered corrosion protection of underground pipes and wells.

Later...

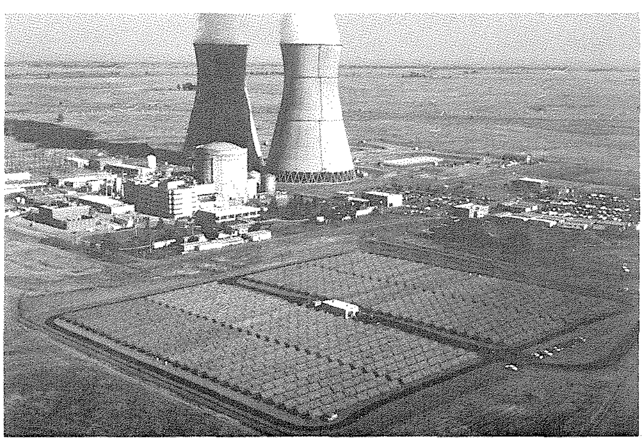


House in Carlisle, Massachusetts, with a 7.3-kW photovoltaic rooftop array. Excess photovoltaic-generated power is sold to the utility. Power is automatically supplied by the utility as needed.



A 28-kW array of solar cells for crop irrigation during summer, and crop drying during winter (a DOE/University of Nebraska cooperative project).

1985



1.2 MW of photovoltaic peaking-power generation capacity for the Sacramento Municipal Utility District. (The 8 x 16 ft panels are mounted on a north-south axis for tracking the sun.)