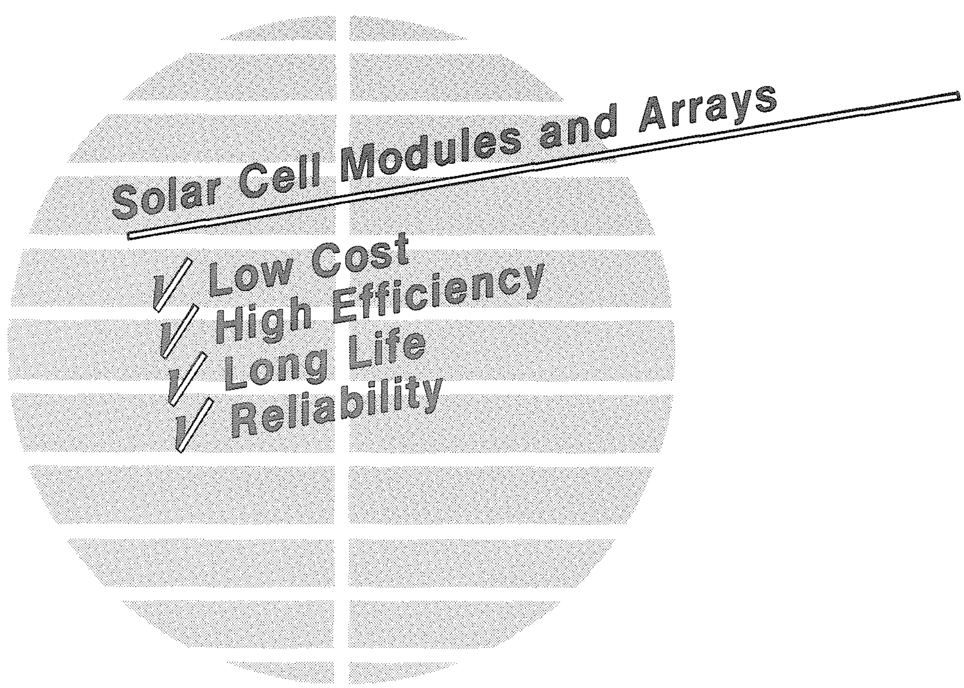
JPL Publication 86-31

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume VIII: Project Analysis and Integration

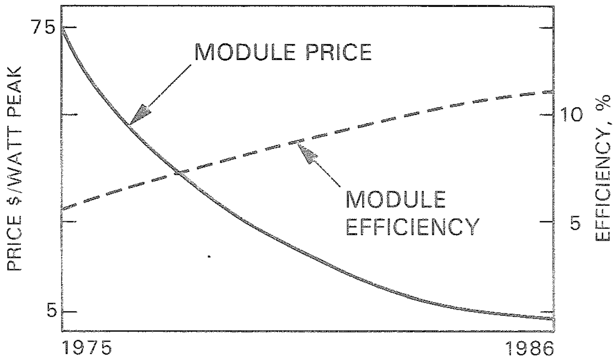
11 Years of Progress



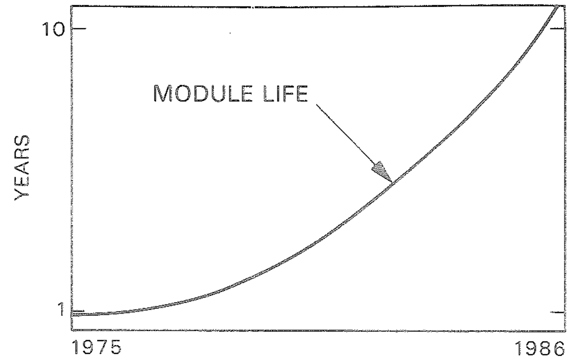
October 1986

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

Photovoltaic Module Progress

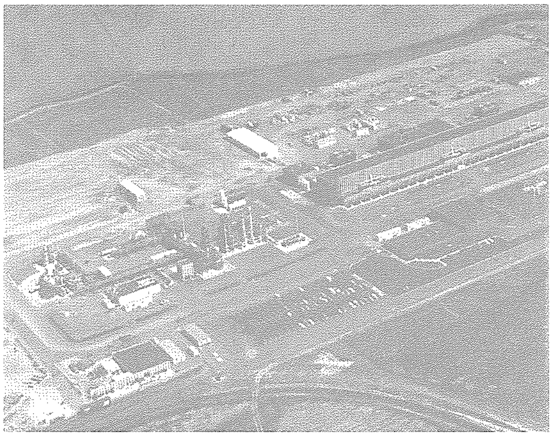


Flat or non-concentrating module prices have dropped as module efficiencies have increased. Prices are in 1985 dollars for large quantities of commercial products.

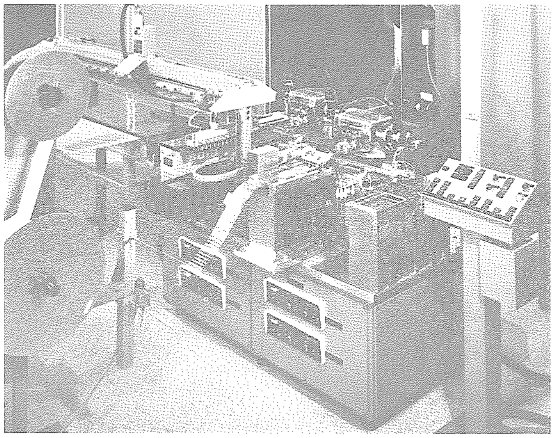


Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)

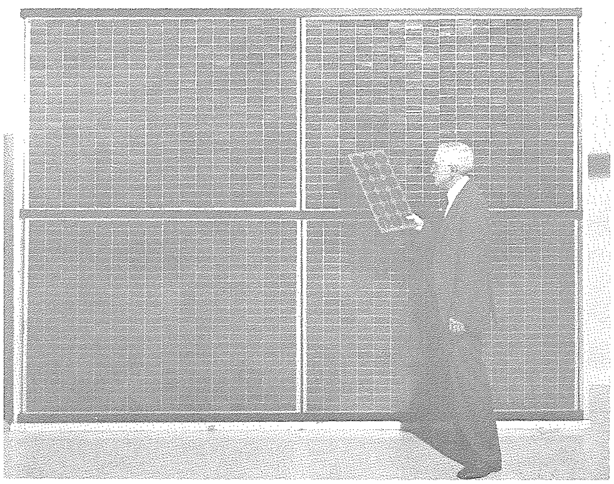
Technology advancement in crystalline silicon solar cells and modules (non-concentrating).



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.

5101-289
Flat-Plate
Solar Array Project

DOE/JPL-1012-125
Distribution Category UC-63b

Electricity from Photovoltaic Solar Cells

Flat-Plate Solar Array Project Final Report

Volume VIII: Project Analysis and Integration

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11 Years of Progress

October 1986

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 86-31

Project Managed
by the
Jet Propulsion Laboratory
for the
U.S. Department of Energy's
National Photovoltaics Program

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

The Flat-Plate Solar Array (FSA) Project, funded by the U.S. Government and managed by the Jet Propulsion Laboratory, 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).

PA&I performed planning and integration activities to support management of the various FSA Project R&D activities. Technical and economic goals were established by PA&I for each R&D task within the Project to coordinate the thrust toward the National Photovoltaics Program goals.

A sophisticated computer modeling capability was developed to assess technical progress toward meeting the economic goals. These models included a manufacturing facility simulation [Solar Array Manufacturing Industry Costing Standards (SAMICS)], a photovoltaic power station simulation [Lifetime Cost and Performance (LCP)] and a decision aid model incorporating uncertainty [SIMulation of Research ANd Development Projects (SIMRAND)]. This family of analysis tools was used to track the progress of the technology and to explore the effects of alternative technical paths. Numerous studies conducted by PA&I signaled the achievement of milestones or were the foundation of major FSA Project and National Program decisions.

This document summarizes the most important PA&I activities during the Project's history. It discusses the PA&I planning function and how it related to Project direction and reviews important analytical models developed by PA&I for its analytical and assessment activities. The document summarizes major studies completed during the term of the Project and provides considerable insight into the role played by PA&I in supporting Project management.

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 following Jet Propulsion Laboratory (JPL) staff members have contributed significantly to the Project Analysis and Integration (PA&I) activity: P. McGuire (Area Manager), W. Callaghan, P. Henry, and H. Macomber (former Area Managers), B. Jackson, R. Chamberlain, R. Aster, R. Daniel, C. Borden, and R. Miles. Former JPL staff members who contributed to the early PA&I efforts include: P. Firnett, and J. Doane. The contribution of M. Alper, who conceived the idea of an independent PA&I activity, also is gratefully acknowledged.

This document reports on work done under NASA Task RE-152, Amendment 419, DOE/NASA IAA No. DE-A101-85CE89008.

FSA Project Summary

The Flat-Plate Solar Array (FSA) Project, a Government-sponsored photovoltaic (PV) project, was initiated in January 1975 with the intent to stimulate the development of PV systems for economically competitive, large-scale terrestrial use. The Project's goal was to develop, by 1985, the technology needed to produce 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.

As manager, the Jet Propulsion Laboratory organized the Project to meet the stated goals through research and development (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 manufacturing 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 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. Thus, FSA concentrated its efforts on overcoming specific critical technological barriers to high efficiency, long life, reliability, and low-cost manufacturing.

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. Crystalline silicon, research solar cells (non-concentrating) have been fabricated with more than 20% efficiency. A full-size experimental 15% efficient module also has been fabricated. It is calculated that a multimegawatt PV power plant using large-volume production modules that incorporate the latest crystalline silicon technology could produce power for about $0.27/kWh (1985 dollars). It is believed that $0.17/kWh (1985 dollars) is achievable, but only with a renewed and dedicated effort.

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 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.

Major FSA Project Accomplishments

- Established basic technologies for all aspects of the manufacture of nonconcentrating, 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 5 to 6% 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.
- 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, 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.

Project Analysis and Integration Summary

The Project Analysis and Integration (PA&I) Area was formed as part of the original Flat-Plate Solar Array (FSA) Project. Its function was to provide analyses needed to guide the Project's technical development toward achievement of the National Photovoltaics Program's goals, and to serve as a communication link between the various areas of the FSA Project and other elements of the National Photovoltaics Program. PA&I fulfilled these objectives by supporting Project management with information needed for planning and decision-making, by developing analytical models used to assess technical progress, by preparing key studies used to set the direction for Project activities, and by operating an information exchange program that interacted in varying degrees with every other element of the FSA Project and the National Program.

PA&I played a significant role in planning throughout the Project's history, reflecting the emphasis placed on economic performance in measuring progress. During the last half of the 1970s, PA&I helped reformulate original Program goals to reflect what had been learned about photovoltaic (PV) technology and to expand it to include concentrator PV technology, tests and demonstration plans, and a broadening of scope to cover commercialization and industrialization goals. In 1979, PA&I developed a detailed Project plan describing the path to technical readiness in 1982. This plan guided Project activity during its most active years. More recently, PA&I was involved in planning for the remaining years of the Project when the National Program emphasized potentially large payoff, high-risk technology developed for long-term industry use.

PA&I developed several important models used to support the planning and decision-making activities of Project management. The most important model, Solar Array Manufacturing Industry Costing Standards (SAMICS), is a detailed manufacturing-cost model, supported by a complete overhead cost structure and an extensive cost-account catalog. SAMICS has been used to prepare consistent and reliable module-production cost estimates for technical options during most of the Project's history. Another important model developed by PA&I, SIMulation of Research ANd Development (SIMRAND), is a Monte Carlo simulation model with the capacity to analyze complex research and development (R&D) decisions involving uncertain information. The SIMRAND model was used successfully to compare the various technical options supported by the National Program. The final major model developed was Lifetime Cost and Performance (LCP), which is a simulation model for estimating the output, costs, and revenues of a PV system over its lifetime. LCP can model the performance of a PV system in a specific application involving the exact conditions of diverse geographical locations. LCP has been used to explore many application issues including operation and maintenance schedules and tracking configurations.

PA&I prepared several significant studies during the Project's tenure to assess the status of the technology, to determine the potential economic status of various options, and to illustrate reasonable courses of action for reaching the Project goals. The first thorough application of the SAMICS methodology was in preparation of the "Economic Analysis of a Candidate $0.50/$W_p$ Flat-Plate Photovoltaic Manufacturing Technology." The study showed, for the first time, that a silicon-ribbon technology had the economic capability to meet the Project goals. The first attempt to set guidelines for the development of individual aspects of the technology was the "Price Allocation Guidelines." By considering such things as maturity of technology and resources available to deal with the problem, goals were set for specific aspects of the technology. In 1981, in another significant study, the Jet Propulsion Laboratory joined forces with the Solar Energy Research Institute to assess the prospects for the various silicon sheet options. Using the SIMRAND model, the uncertainty surrounding the prospects for various technology elements were incorporated in comparisons between technologies.

As the Project drew toward its close, PA&I made some final assessments of the leading PV technologies under development. These studies showed that the FSA Project had achieved many of the goals originally set by the National Photovoltaics Program and had made significant progress toward attainment of the more demanding goals of the U.S. Department of Energy Five-year Research Plan. More R&D work is necessary, however, for photovoltaics to be competitive in today's energy markets. PA&I hands down the economic and decision-making tools necessary to support future efforts to complete the technology development task. It also provides documentation of the Project's history in economic terms.

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SECTION I

Introduction

A. PURPOSE

The Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, held at Cherry Hill, New Jersey, in October 1973, initiated an evaluation of the use of photovoltaic (PV) conversion devices for terrestrial applications. Subsequently, a Federal National Photovoltaic Program was formed in 1975 that defined an active role for the Government in support of PV research and development (R&D). The Conference found that PV development for terrestrial applications could make a significant contribution to the Nation's energy needs if certain technical questions could be resolved and system costs reduced.

The Flat-Plate Solar Array (FSA) Project[1] was organized at the Jet Propulsion Laboratory (JPL) in 1975 to implement a research program to achieve the flat-plate, crystalline-silicon module goals established by the National Program. At that time, the FSA Project assumed responsibility to support the industrial development of reliable, low-cost ($0.50/$W_p$), silicon solar modules having at least 10% conversion efficiency and a useful life of 20 years. Since then, FSA R&D has encompassed all phases of flat-plate module technology, from basic feedstock materials of the PV manufacturing processes, through verification of module reliability and performance in the field.

Organization of the Project showed it to be unique, not only for its broad spectrum of activities as well as its system integration activities, but also because of the number of industrial organizations, Government laboratories, academic institutions, and other entities with which JPL would have to interact.[2] Communication between JPL and the other participating organizations, therefore, would be an important factor in the Project's success. FSA was one of the first projects at JPL, and certainly the largest, for which economic performance was the principal measure of success. Technical performance was not the ultimate goal, but only a contributing factor to the attainment of the economic goals. Thus, new analytical methods would be needed to translate technical performance into future economic performance. The Project Analysis and Integration (PA&I) Task was formed as part of the original Project structure to address the problem of communication and to provide the analyses needed to guide the Project's technical development toward achievement of the National Photovoltaic Program's goals.

The purpose of this document is to reflect upon the activities undertaken by the PA&I task to fulfill the objectives set for it both at the time of the formation of the FSA Project and as the Project evolved. The PA&I contributions to the Project essentially have been supportive, involving the preparation of analytical studies to aid Project management in its planning and decision making, and the preparation and documentation of detailed plans to integrate Project tasks and ensure their timely completion. Activities undertaken by PA&I as the planning and analysis wing of the Project will be described, along with a perspective on PA&I's role vis-a-vis other elements of the National Photovoltaics Program.

B. ORGANIZATION OF THE REPORT

Section II briefly describes some of the activities PA&I initiated within FSA to help establish and maintain an effective, goal-oriented technical program. Early Program goals and changes in goals and philosophy are discussed in Section III, along with a description of how the PA&I planning task responded to the changes. Section IV not only discusses some of the more important models developed at JPL to evaluate technologies, but also those project results that might have been anticipated if alternative R&D paths were pursued by the Project. Section V discusses some of the more important PA&I studies and how they affected decision-making during the tenure of the Project. Section VI summarizes the status of crystalline-silicon technology today. Section VII summarizes some "lessons learned" and the legacy left by significant accomplishments of the PA&I activity.

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[1] The JPL Project, first called the Low-Cost Silicon Solar Array (LSSA) Project, later became the Low-Cost Solar Array (LSA) Project, and finally the FSA Project.

[2] Technology development at the PV-array level has been managed by JPL. Balance-of-system (BOS) and test and evaluation activities have been managed by the Sandia National Laboratory (SNL), and PV-array research activities have been managed by the Solar Energy Research Institute (SERI).

SECTION II

Project Perspective

At the outset, the National Photovoltaics Program intended to promote a private, competitive PV industry. This meant the industry being able to produce PV systems at a cost (including a return on equity) no greater than the price at which they could be sold in a competitive market. The Program developed price goals derived from this consideration. Early in the Program, JPL's FSA Project became responsible for the support of the development of flat-plate modules capable of producing electrical power at a cost of $0.50/$W_p$ in 1974 dollars. Technology goals of the Project were directly adopted from the original goals established at the Workshop on Photovoltaic Conversion of Solar Energy for Terrestrial Applications held at Cherry Hill, New Jersey, in late 1973 (Reference 1).[3]

Almost all technology development was to be done by industry with JPL providing coordination and leadership to permit an effective goal-oriented technical program. The ensuing years saw many important developments in PV technology. New crystal growth methods were developed to increase crystal ingot growth-size, and a number of innovative ribbon-crystal growth methods were nurtured. Methods of sawing the crystal into thin wafers were investigated, and energy efficient, low-labor cost processes were developed for processing silicon wafers into solar cells. Automated assembly of cells into electrical networks of cells replaced hand soldering. Entirely new low-cost materials for encapsulating the electrical networks were developed to produce modules of much longer service lifetime in the field. A systematic test and failure analysis program was begun to allow industry to avoid many costly failures in the field and to quickly rectify those that did occur. Engineering of the entire array as an integrated structure helped eliminate redundant structural materials.

From the beginning of the Project, a rapid flow of technical information was generated that required systematic assessment. A major role of the PA&I Area was to establish and maintain Project standards and methodologies for comparison of Project options. Acting as the Project translator between technical and economic performance, PA&I tracked and assessed Project progress to derive maximum technical and economic benefit while keeping cost and risk to a minimum.

A. PROGRESS ASSESSMENT

In the early years, two major tools were developed for economic assessment of candidate technologies:

(1) Price Allocation Guidelines (PAG) is a "top-down" apportioning of the Project goal to each major step in the production of modules.

(2) Solar Array Manufacturing Industry Costing Standards (SAMICS) is a "bottom-up" computation of the required market price of each candidate technology to assess its potential for meeting the allocation in the PAG and to compare it to the potential of other candidate technologies.

Because a wide range of activities was to be pursued, the module development process was divided into basic activities, each of which was responsible for meeting a certain fraction of the total cost reduction required to meet the Program goal. Technical experts were queried by PA&I as to the methods by which costs might be reduced in their fields of expertise. Allocations among the activities were derived through joint consideration of technical possibilities thought to be available. Allocations were formalized through a review process into price allocation guidelines for Project activities.

In this manner, allocations were determined for silicon material, for the creation of silicon sheet, for processing sheets into cells, and for encapsulating and assembling PV modules. As technical innovations were achieved, these allocations were revised. The price-allocation process became an integral function of the PA&I task as the FSA Project's technological history unfolded. Juxtaposed against this process was the problem of determination of the economic worth of innovations and how it contributed to attainment of the Project goal.

Given the importance of the projected manufacturing costs of various processes involved in the choice of which technical path to pursue, it was essential that technology assessments be made with consistent methodological assumptions and approaches. For comparing

[3] The goal of $0.50/$W_p$, established at the Cherry Hill Conference, was in late 1973 or 1974 prices. A subsequent goal statement for the Project of $0.50/$W_p$ in 1975 dollars did not account for inflation between late 1973 and 1975. In this report, economic results are referenced to the 1974 dollars proposed at Cherry Hill.

PV module manufacturing processes, PA&I developed and applied a methodology that employed standardized and appropriate costs for labor, materials, utilities, and services, while using validated cost-estimating relationships. Development of SAMICS methodology began early in the history of the Project, and was further expanded and refined as time progressed. SAMICS became the single most important tool of the FSA Project in guiding research priorities and measuring progress toward achievement of price goals. (SAMICS and other methodologies developed and applied by PA&I are discussed in more detail in Section IV of this report.)

As time progressed, complex choices were required among the alternative research paths for technology development. To complicate matters further, information available on elements of each research path often was relatively uncertain in nature (several outcomes were possible). In 1981, SIMulation of Research ANd Development Projects (SIMRAND) was developed specifically to support decision-making in an uncertain environment. SIMRAND can estimate the probability that a specific research path will be the best from a network of possibilities. Using the opinions of experts, SIMRAND directly incorporates the uncertain outlook surrounding elements along each research path. The use of SIMRAND resulted in an improved degree of consistency and objectivity in R&D decision-making.

As research needs were revealed, the PA&I task continued to develop expertise and support for the development of models required to perform the new assessment functions. With the beginning of application experiments in the field, it became important to model PV systems in a specific application and geographic location. In evaluating the real value of a PV system, all costs and revenues over its operating lifetime must be included. These considerations led to the development of the Lifetime Cost and Performance (LCP) model. LCP is a simulation program capable of modeling the lifetime performance of a PV array. The product of an LCP simulation is the electrical energy output, and the cost and revenue streams from the system's operation. With LCP in place, studies could be performed, for example, to determine the value of improvements to the lifetime power output of a system and how much additional expense could be incurred during cell and module fabrication to acquire added performance.

During the tenure of the FSA Project, the allocations and models described above were applied either individually to specific problems, such as narrow technical decisions, or as an integrated set when high-level, long-range management decisions were required. The top-down, price-goal allocations provided each technical area with its own economic/technical subgoals. The technical manager of each area had broad discretion how that subgoal would be met. The manager continuously could evaluate various options by applying the bottom-up manufacturing cost simulation (SAMICS), and compare the result to that of the top-down price-goal allocation.

Manufacturing cost-point estimates generated by SAMICS were combined via SIMRAND, with the uncertainties associated with those estimates, to form probability distributions of technical performance and/or cost. These distributions were used either individually to assess the probability of meeting a sub-goal, or were aggregated into probabilities of meeting higher level goals. In this way, the results of a SAMICS analysis of various technical options were assessed on the basis of the probability of meeting the top-down goals of the Project. Progress made toward development of a cost competitive technology for terrestrial applications was evaluated by integrating the results of the SAMICS calculations with the results of the solar array operating environment using LCP. Lifetime performance calculations were made which recognized changing price levels and solar cell output degradation over time. Using these models, PA&I was able effectively to recommend to Project management the technical paths likely to achieve the long-term goal of a competitive PV energy technology.

B. IMPACT OF INFLATION

Efforts to measure progress in crystalline-silicon technology during the tenure of the FSA Project 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 actual progress made. The goals, therefore, have been restated, and technology improvements have been measured in 1985 U.S. dollars using the Gross National Product (GNP) Implicit Price Deflator. This statistic is published quarterly by the Bureau of Economic Analysis, U.S. Department of Commerce.

Table 1 shows the upward trend in the general level of prices of goods and services since 1974. The total

Table 1. 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	9.0	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: U.S. Department of Commerce, *Survey of Current Business*, May 1986.

impact is summarized in the cumulative GNP Implicit Price Deflator, which more than doubled since the beginning of the FSA Project. The changing level of prices makes it difficult to detect the more subtle changes that have taken place in program goals. The original price 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$.

C. IMPACT OF SHIFTING PROGRAM GOALS

In May 1983, the U.S. Department of Energy (DOE) Photovoltaic Energy Technology Division issued a *National Photovoltaics Program Five-Year Research Plan, 1984-1988* (Reference 2) that significantly altered the original goals of the FSA Project. The goal since the Cherry Hill Conference in late 1973 had been $0.50/W$_p$ ($1.07/W$_p$ in 1985 dollars). Thus, a PV system would have to produce electricity at a cost of $0.263/kWh in 1985 dollars, using the energy cost methodology in the DOE Five-Year Research Plan.[4]

With the Five-Year Plan, National Program goals changed to reflect revisions in the outlook for conventional energy resources and progress made in understanding the potential of PV technology. Current Program goals call for 15% module efficiency and a 30-year module service life. Expressed in 1985 dollars, the price goals correspond to an energy cost of $0.17/kWh, making them much more demanding than the original values. It was the task of PA&I to interpret these revisions in the goal structure and to assess their effects on the FSA Project's technical goals.

In general, the impact of the revision of goals has been to shift the Program's research effort toward thin-film solar cell technologies. Although single-crystal silicon modules dominated commercial production during much of the Project's tenure, thin-film technology seems to offer the potential for lower costs in the long run.[5] Recent gains in solar cell efficiencies, however, have made single-crystal silicon a strong competitor for the future technology that ultimately will achieve market competitiveness.

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[4] This result was derived using a module efficiency of 10% and a 20-year module service life, as originally specified at Cherry Hill.

[5] The thin-film technology effort has been successful in adopting many of the cell-processing and encapsulation technologies developed for single-crystal silicon solar cells.

SECTION III

Planning Activities: 1975 to 1985

As a consequence of its role in defining Project goals and tracking progress, PA&I intimately was involved, usually as the lead organization, in the formulation of long-range Project plans and was a major contributor to most National Photovoltaics Program plans. The planning procedure typically was an iterative process between PA&I and other involved parties. Because PA&I included technically cognizant personnel aware of the status of the various involved technologies, first drafts of Project long-range plans were written by PA&I, based on requirements defined by Project management. The first draft tentatively would define cost goals for each major technical activity of the Project. Preliminary technical goals, schedules, and milestones were derived based on the cost goal, the status of the technology, and an assessment of the difficulty of work required to reach the goal. The various models and simulations described later in this document were extensively applied in this process. The draft plan then was reviewed by Project technical managers. Modifications in successive drafts were negotiated between PA&I, the technical managers, and the Project Office until the final plan was completed. Resource distributions based on the plan then were negotiated between the Project Manager and the technical area managers, with PA&I playing a supporting, but minor, role.

A. NATIONAL PHOTOVOLTAICS PROGRAM PLANNING: THE EARLY YEARS

Between 1975 and 1980, PA&I played a major part in formulation of National Photovoltaics Program plans. Prior to 1977, this Program was guided by the Proceedings of the Workshop on Photovoltaic Conversion of Solar Energy for Terrestrial Applications held at Cherry Hill, New Jersey, and a succession of Energy Research and Development Administration (ERDA) documents formalizing the Workshop results (References 1, and 3 through 7). The Workshop was funded by the National Science Foundation (NSF) and organized by JPL. At this workshop, goals for 1985 of \$0.50/W_p (1974 dollars), 10% conversion efficiency, 500 MW/year production, and 20-year lifetime were established for single-crystal silicon solar cell technology. Basic schedules were formed for the selection of processes for development and scale-up, and for large-scale plant construction. The prospects for CdS/Cu_2S and other thin-film materials were discussed, and schedules were set that were less definitive than for silicon. Solar thermal and satellite systems also were discussed. It was the silicon plans and schedules from Cherry Hill, however, that attained amazing longevity by becoming the foundation of the JPL FSA Project. During the period 1973 to 1977, the Cherry Hill report was the de facto Photovoltaics Program Plan, and the document that inspired the organization of the FSA Project.

By the summer of 1976, the Photovoltaics Program had grown considerably. It had been transferred from NSF to ERDA and was in need of a program plan that more accurately reflected what actually was happening. At the behest of ERDA, a Program Planning Group (PPG) was formed, consisting of representatives from JPL, SNL, Massachussetts Institute of Technology (MIT) Energy Lab, MIT Lincoln Lab, NASA Lewis Research Center, DOD, and the Aerospace Corp. During a period of a year, the PPG formulated a detailed plan that updated the Cherry Hill technology plans, moved the technology development goals to 1986, expanded them to explicitly include concentrators, described a detailed test and demonstration plan, and broadened the scope to include commercialization and industrialization goals. PA&I personnel were key participants and lead authors in the formulation of these plans, especially the Technology Development and Test and Demonstration Plans. The PPG Plan never was printed in final form. It was superseded by the ERDA Solar Division Director's Plan.

The foundation of the Director's Plan (Reference 8) was "market pull" involving large Government purchases of PV hardware through Program Research and Development Announcements (PRDAs) with early, large-scale utility experiments. The Director presented his plan to a congressional committee in August 1977. The plan was not well received because its thrust virtually ignored residential applications that had been identified in a Congressional Office of Technology Assessment (OTA) study as being especially attractive to photovoltaics. The Plan then was revised and reissued February 3, 1978, containing expanded residential applications, but retaining the market-pull program strategy. It was reissued again in March 1978 with minor changes.

There followed a period of progressively more organized concern in the PV community that questioned the viability of market pull as a device to attain Program goals. This culminated in a detailed examination of market pull in the SERI Venture Analysis issued in June 1978 (Reference 9). Its conclusions cast serious doubt on the fundamental assumptions of the Director's Plan. In addition, legislation by Congress, the "Solar Photovoltaics Energy Research, Development, and Demonstration Act of 1978," Public Law 95-590, called for a major, well-financed, 10-year program of PV R&D activities.

In 1977, ERDA was replaced by DOE. In 1978, DOE initiated the formation of a Photovoltaics Lead Center and identified the need for a new Multiyear Program Plan (MYPP). JPL, in its role of as yet unofficial Photovoltaics Lead Center, proposed to DOE that JPL should coordinate and integrate the MYPP. The content of the MYPP first draft issued in June 1979, and reissued in September 1980, differed from its predecessors in placing a heavy emphasis on "technology push" involving R&D of advanced materials. The draft also incorporated "fixed price buys" of hardware to supply the applications experiments. Program goals were redefined, for the first time since Cherry Hill, to be system-price goals rather than component price goals. Specific production quantity goals were deleted, through recognition of the fact that the National Photovoltaics Program had no direct control of markets.

B. FSA PROJECT PLANS

In all the Program plans, the most important intermediate milestone for FSA technology development was the attainment by the end of fiscal year (FY) 1982 of "Technical Readiness for \$0.70/W_p (1980 dollars) Technology." Technical readiness for a \$0.70/W_p PV technology implies that all processes required have been verified with prototype equipment and that the processes and equipment are ready for application to a scaled-up production level, sufficient in size to capture most economies of scale. In September 1979, PA&I completed a major detailed plan describing the path to technical readiness. This culminated in late 1982 with monitored physical demonstrations of the processes and equipment required to fabricate \$0.70/W_p (1980 dollars) PV modules.

A milestone such as "Technical Readiness" has meaning only in the context of a well-defined goal. Methods are required to gauge the relevance of the technology embodied in prototype processes to the stated goal, and to tell when the goal has been reached. Both of these conditions were present in the management of the JPL Photovoltaics Project and are discussed in more detail later in this document.

The "Technical Readiness 1982 Plan" (Reference 10) called for design and fabrication of experimental equipment for bulk polysilicon production, crystal growth, and cell and module fabrication. Some equipment was to be sub-scale, such as the polysilicon plant, but most were to be full-scale prototypes of production equipment. Provisions were made to experimentally ensure that the product of each process would be compatible with all following processes. This was considered to be especially important because PV manufacturers are very cautious about interrupting production to install new processes or equipment if there is any question about compatibility with adjacent processes in the fabrication sequence.

In addition to manufacturing-technology development, the Technical Readiness Plan called for extensive module design and testing activities to ensure that the fabrication technology produced fault-tolerant, long-lived modules for service in the field. It was deemed important for photovoltaics to avoid the damage to user and public perception that results from the kinds of costly, highly visible failures that had befallen some other renewable energy technologies because of insufficient quality control and testing prior to fielding the product.

From 1979 to mid-1981, the Technical Readiness Plan guided the JPL Photovoltaics Project. This was the period of maximum Project activity. More than 100 contracts were in force for all phases of flat-plate PV technology. The largest of the large-scale purchases of modules from manufacturers for testing and demonstration occurred during this time, and fabrication of prototype equipment for integrated prototype production lines was well underway.

In 1979, PA&I began to examine the question of what Project activities would be appropriate in the FY 83-to-FY 86 timeframe given that the objectives and goals of the Technical Readiness 1982 Plan were fulfilled. A rather lengthy planning and review process followed with the final plan undergoing formal JPL in-house review in the spring of 1981.

The FY-83-to-FY-86 Plan called for an active JPL role in the transfer and diffusion to private industry of the technology developed under the Technical Readiness 1982 Plan. Laboratories and prototype equipment were to be used for hands-on, industry-user familiarization; facilities were to be available for problem solving and troubleshooting to aid manufacturers adopting the technology developed in the DOE/JPL Project. The Plan also called for an active program in developing module standards for performance, reliability, and safety that would help prevent costly failures in the hands of PV users. The Project was to help in the establishment of independent testing laboratories for use by industry to certify their products.

In mid-1981, a series of events occurred that obviated many key features of both the Technical Readiness Plan and the FY 83-FY 86 Plan. Late in the fiscal year, budget recisions brought an abrupt halt to several development efforts and severely curtailed others. The DOE FY 82 budget specifically mandated the cancellation of the integrated prototype production lines known as Module Experimental Process Systems Development Units (MEPSDUs). Thus, it no longer was possible to demonstrate, end-to-end, the fabrication of PV modules and thereby ensure the industry that no undesirable effects occurred among the newly developed processes.

Fragmentation of the cell and module process and equipment development into small, widely scattered work packages resulted in heavier reliance on the analytical modeling performed in PA&I to assess the status of the technology. Because the modeling then had to be done using incomplete data, integration of the production line had to be done "on paper." In retrospect, the resulting analyses have held up well. At the time, however, the analyses seemed to lack credibility in the industry because there was little tangible evidence that the assumptions of the analyses could be realized in an actual integrated production line.

C. THE FIVE-YEAR RESEARCH PLAN: A NEW DIRECTION

In May 1983, the DOE Photovoltaics Energy Technology Division issued the *National Photovoltaics Program Five-Year Research Plan, 1984-1988*. It has guided the Project since then. Although PA&I had no role in development of that plan, subsequent analyses by PA&I led to modifications of certain key assumptions on which the goals in the Five-Year Plan are based. This left the Five-Year Plan goals unchanged, but provided more flexibility in how the goals could be attained.

The Five-Year Plan significantly altered the goals of the JPL Project for module price and efficiencies. The goal since the Cherry Hill Conference had been $0.50/$W_p$ (1974 dollars), equivalent to $1.07/$W_p$ in 1985 dollars. When this price is used in the Five-Year Plan energy-cost methodology, the result is $0.263/kWh. The Five-Year Plan, however, called for an energy cost of $0.17/kWh in 1985 dollars. To meet this goal, much more stringent requirements had to be placed on module costs and efficiencies. Based on PA&I studies, two principal avenues existed for meeting these goals. One was research to improve sunlight-to-electricity conversion efficiency, and the other was to reduce the cost of the silicon wafer. Barring a dramatic breakthrough in ingot growth and sawing, silicon ribbon became the only crystalline-silicon technology capable of achieving the new DOE goals.

The Project was re-oriented in these directions with an emphasis on basic cell characteristic improvements, high-efficiency module design, and enhancement of the dendritic web ribbon growth effort. A Project Implementation Plan (Reference 11) was drafted as an internal guide to implement the provisions of the Five-Year Plan. In February 1985, however, JPL was directed to terminate the Project at the end of FY 86.

SECTION IV
Analytical Model Development

One of the primary responsibilities of the PA&I team during the life of the FSA Project has been the development of models to support the decision-making and planning activities of Project management. From the beginning of the Project, a rapid flow of technical information was generated dealing with the status of alternative solar cell technologies. There was an immediate need for ways to convert this technical information into terms that would allow comparisons between technologies and assessments of progress being made toward the goals of the National Program.

Three of the most important models that were developed by PA&I for technology assessment work were:

(1) Solar Array Manufacturing Industry Costing Standards (SAMICS).

(2) SIMulation of Research ANd Development Projects (SIMRAND).

(3) Lifetime Cost and Performance Model (LCP).

Briefly, SAMICS is a methodology for the preparation of production cost estimates for PV modules. SIMRAND is a Monte Carlo simulation program that can analyze complex R&D decisions involving uncertain information. LCP is a simulation model for estimating the output, costs, and revenues of a PV system over its lifetime. These models have been implemented on the IBM-XT and are being made available to the public through NASA's Computer Software and Management Information Center (COSMIC) located in Athens, Georgia. Models also have been developed by PA&I for use in the design of solar cells and solar cell arrays.

All of these models, described in this section, have been successfully applied by PA&I in its supporting role to Project management. Examples of specific studies for which the models were used are presented in the next section. (See Section IX, Selected Bibliography, for documents describing these models.)

A. SAMICS

SAMICS was developed as a part of a fair, consistent, and reliable way to compare the various manufacturing processes developed by FSA Project subcontractors. The approach was that of an engineering-cost model that builds a company around detailed manufacturing process descriptions. Rule-of-thumb methods, using customary production-coefficients, were determined to be inappropriate because of the new nature of the processes involved. Because of the relatively unique nature of PV technology, reasonable cost estimates could not be expected from methods based on comparisons with existing manufacturing processes used in the production of other products.

Considerable emphasis was placed on standardization of the SAMICS methodology to ensure comparability of results between PV technologies and different time periods. The SAMICS model was constructed around a manufacturing facility designed specifically for the production of PV modules. The description of the PV facility included a description of indirect labor requirements including administrative and managerial personnel. This provided a standardized set of indirect requirements for plant and facilities that also is included in the standardized indirect requirements and cost descriptions of the SAMICS methodology. A standard set of financial parameters including rate of return on equity, interest rates, taxes, and insurance is built into the SAMICS model. As part of the program, a Cost Account Catalog, containing price information on a wide range of inputs used in PV module production, has been published.[6] The catalog has been updated periodically to reflect relative changes in the prices of inputs and changes in the expected rate of inflation. Figure 1 gives an overview of the SAMICS methodology.

Users of the Standard Assembly Line Manufacturing Industry Simulation (SAMIS) program, the computer implementation of the SAMICS methodology, can change any of the indirect input or financial parameters. Leaving these parameters at their initial settings, however, makes possible direct comparisons of manufacturing process technologies. SAMIS has been used by the FSA Project in comparing several technology options. It also has been used to track technical progress over extended periods of time.

SAMIS simulates the operation of a company, described by the user, to develop detailed estimates of input utilization, capital requirements, and financial flows of an operating business. Specifically, a hypothetical factory is "built," based on manufacturing process descriptions developed by the user. The manufacturing process description requires the user to specify process inputs. To simulate the facility's operation, an appropriate workforce, determined by SAMIS, consists of production workers, administrators, and managers. The cost of labor, along with materials, building space, and utilities are taken from a supporting cost-account catalog. A detailed financial model is applied to determine the costs of operation, including depreciation, taxes, insurance, and amortization of one-time startup costs.

The SAMIS computer program has extensive report-generating capabilities. Reports include individual process descriptions that indicate use of indi-

[6] See Appendix A, Aster, R.W., et al.

The SAMIS computer program implements this methodology by simulation:

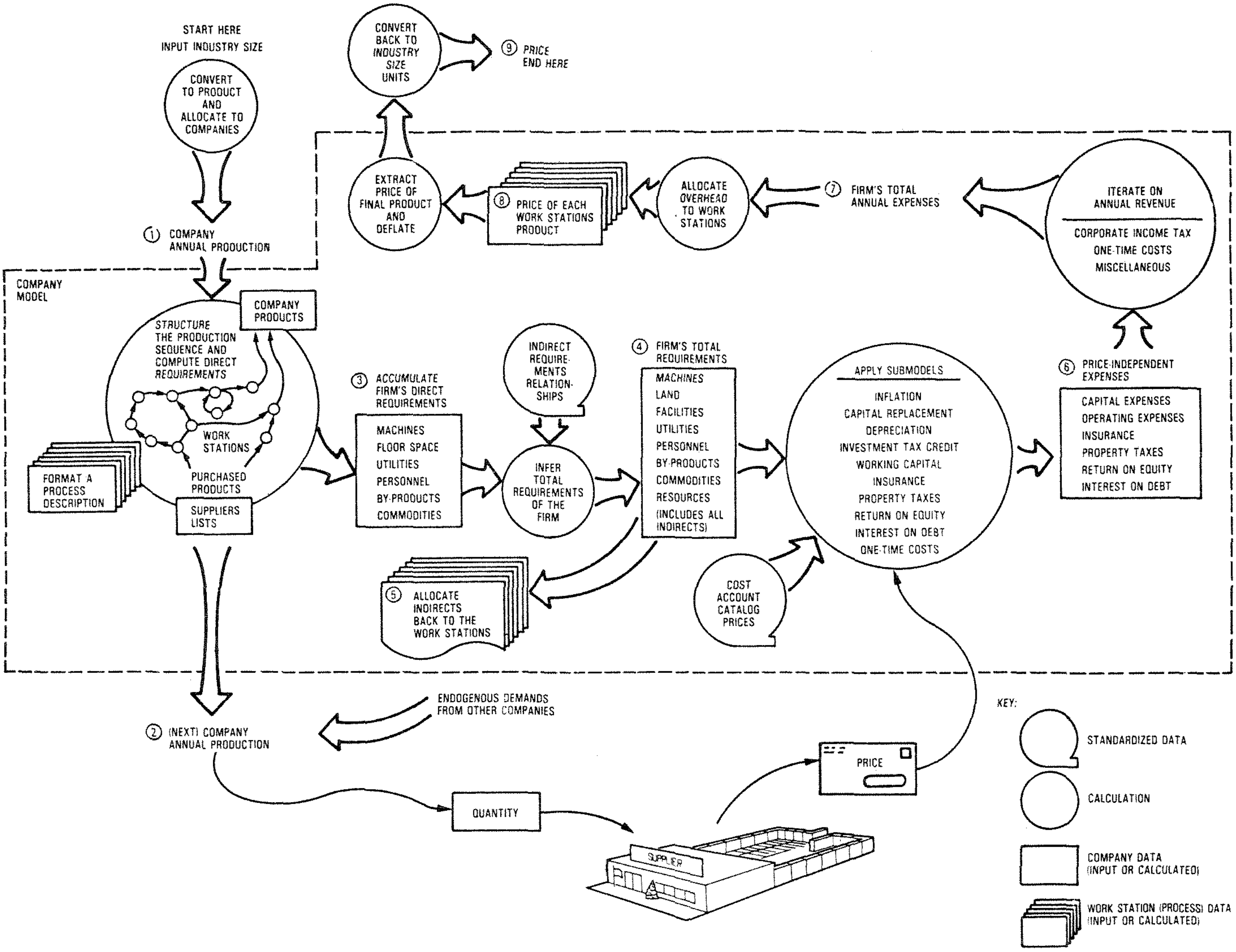

Figure 1. SAMICS Methodology Overview

vidual inputs and their cost, company-wide summaries of inputs, and a complete set of financial reports covering the operation of the company.

The recently developed personal-computer version of the SAMIS program has two additional modes of operation: Solar Array Manufacturing Price Estimation Guidelines (SAMPEG) and Improved Price Estimation Guidelines (IPEG). SAMPEG is expected to be used in most cases because it provides much quicker estimates of process costs (usually less than 5 min) than SAMIS with only a small sacrifice in accuracy.

SAMPEG was developed using a combination of SAMIS and the IPEG model. The latter is a much simpler linear approximation for SAMIS. SAMPEG employs the data-manager and manufacturing-process sequencing algorithms from SAMIS with factory construction, staffing approximations, and financial submodels of IPEG. These approximations and shorter run times dictate a limited reporting format. A table is produced that lists the value-added price of each process and the contribution of labor, materials, building space, equipment, and utilities to process cost.

IPEG, like SAMPEG, provides quick estimates of the results of a more detailed SAMIS simulation. IPEG calculates process cost from five overhead factors. The overhead factors usually are generated by a prior SAMIS simulation. These overhead factors convert direct inputs of equipment, labor, materials, utilities, and floor space into an estimate of product cost. IPEG users quickly and efficiently can explore effects of changes in each of these direct input categories. Essentially, the IPEG model has been constructed so that sensitivity studies can be made of the effect on costs if any one of a number of financial assumptions in the SAMIS model is changed. Ranges for a parameter can be specified, and the results of changing the parameter can be displayed in tabular form and/or plotted on the monitor.

B. SIMRAND

Program management for PV R&D involves complex choices among alternative research paths for technology development. To complicate matters further, the information available on elements of each research path is often relatively uncertain in nature. Thus, several outcomes are possible. SIMRAND was developed specifically to support decision-making in this uncertain environment. Under a given set of constraints, SIMRAND can estimate the probability that a specific research path will be the best from a network of possible paths. Using the opinions of experts, SIMRAND directly incorporates the uncertain outlook surrounding elements along each research path. Wherever possible, objective data are used as a guide in bounding the parameters in question. The result is an improved degree of consistency and objectivity in R&D decision-making.

SIMRAND is a generalized method for analysis of the information available for making decisions in a R&D environment. The first step in the process is to delineate the network of paths that are consistent with objectives of the R&D effort. For example, along the path to make low-cost silicon solar cells, several different methods have been proposed for growing crystalline silicon feedstock. Each of these techniques generates a new path that could be followed by a research program. An example of a test network for solar cell module production is shown in Figure 2.

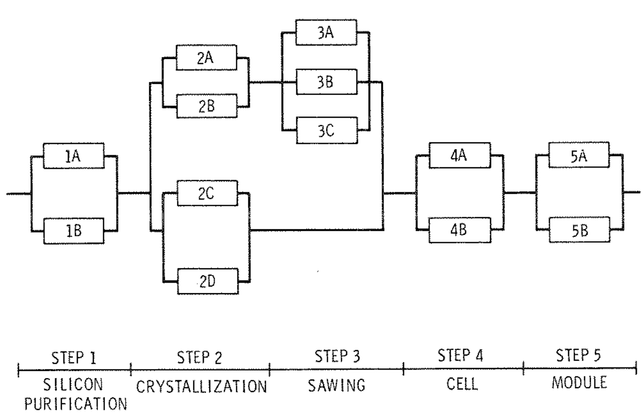

Figure 2. Task Network for Solar-Cell Module Production

The next step is to define the expected outcome of R&D work to improve each element in the network. To continue with our earlier example, experts would be asked to indicate what growth rates are likely to be achieved through additional R&D work on silicon ingot growth by the Czochralski (Cz) process. To capture the uncertainty in the outlook, experts would be asked to indicate a range of possible growth rates and how confident they were that each rate (or a better value) would be achieved. For example, the experts might believe there was a 50% chance of achieving a growth rate of 1.7 kg/h or better, and a 90% chance of achieving a growth rate of 1.4 kg/h or better. The result is a cumulative distribution that summarizes the probability that various growth rates will be achieved as shown in Figure 3. Similar distributions are developed to reflect the outcome of R&D work on other elements of the network.

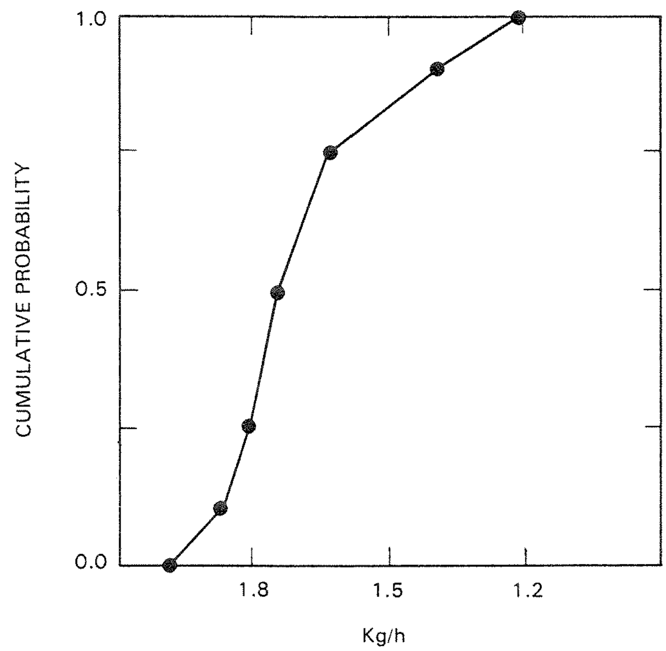

Figure 3. Example of a Cumulative Probability Distribution for Silicon Ingot Growth Rates

One other piece of information used by SIMRAND is a quantitative representation of how decision makers feel about the various possible outcomes of the research effort. For example, a decision maker may place a much greater value on achieving a goal of $1.00/$W_p$, in comparison to $1.20/$W_p$, because of the need to compete with alternative technologies for generating electricity. These preferences can be incorporated in a utility function and included in the SIMRAND evaluation process.

A Monte Carlo simulation method is used by SIMRAND to integrate all the information into a single result. Monte Carlo simulation corresponds to the process of throwing a pair of dice many times to estimate the probability that each outcome, 2 through 12, will occur. SIMRAND randomly selects a value for each element in the network. For this single trial, SIMRAND finds the optimal path through the network from the cumulative distributions generated by the cognizant experts. The outcome is tabulated just as one would record the result of rolling a pair of dice when estimating the probability of various outcomes. SIMRAND continues with these trials until sufficient information has been generated to accurately describe the range of possible outcomes.

Besides evaluation of the outcome of a specific R&D effort as described by a network, SIMRAND can be used to measure consequences of adding or eliminating elements from the network. The SIMRAND simulation simply is repeated with a new element or an element removed to see how results are affected. Entirely different research programs also can be compared with SIMRAND. Unlike similiar methods that focus on the most likely outcome of elements in a research program, SIMRAND shows the range of possible outcomes of carrying out each research program.

SIMRAND was used successfully to compare various technical options supported by the National Photovoltaics Research Program. The uncertainty in the minds of experts about the outcome of various research efforts were mirrored in the results as they reflected a wide range of possible outcomes. At times, the results vindicated support for what was viewed as less attractive research paths by showing that if these paths were successful, the payoff would be high for reaching the Program's goals, although the probability of success was less than perhaps a lower-payoff option.

C. LCP

The need to model PV systems in a specific application and under conditions of a specific geographic location led to the development of the LCP. LCP is a simulation program capable of modeling the lifetime performance of a PV array. The product of the LCP simulation is the electricity output, and cost and revenue streams from the systems operation. Input requirements of the LCP model and the output of a LCP simulation are shown in Figure 4.

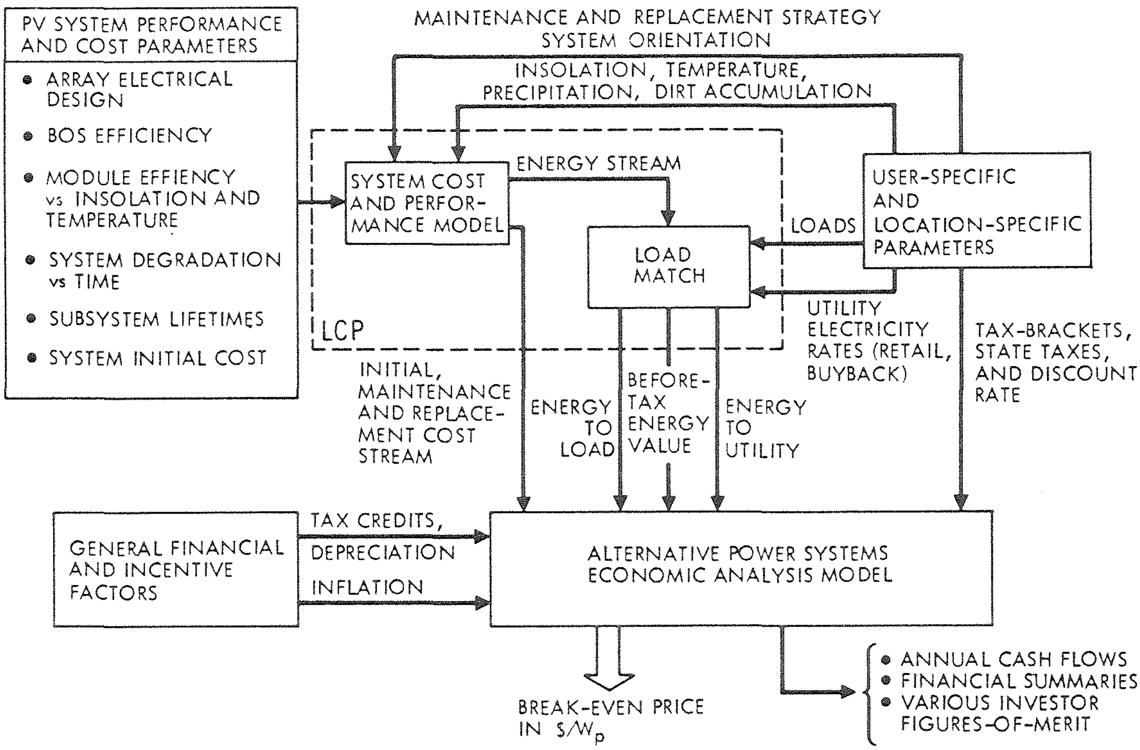

Figure 4. LCP's Role in the Analysis of the Performance of a Photovoltaic System

LCP's calculation of system-energy output is based on the system's electrical design, hourly weather conditions, and long-term variations in power output. Simulating the system's performance on an hourly basis makes it possible to calculate revenues under a time-of-day rate schedule or a block rate schedule. Figure 5 shows an example of how LCP simulates the load demand and energy output of a PV system, including the degradation of system output over time.

Provisions of the Public Utility Regulatory Policies Act (PURPA) of 1978, Public Law 95-617, require utilities to purchase electricity from qualifying, distributed, small-power producers at their net avoided costs. Owners of qualifying systems have the option to interconnect with

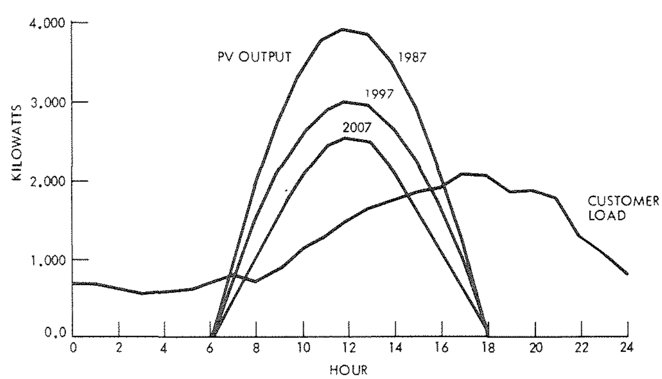

Figure 5. LCP Load and System Output Simulation Example

the utility in either of two ways: a parallel or a simultaneous mode. In the parallel mode, excess power generated is sold back to the utility at avoided costs. In the simultaneous mode, all electricity produced by the PV system is sold to the utility at the sell-back rate, while simultaneously purchasing all energy requirements from the utility at the normal rate for the customer class. Either situation can be simulated with the LCP model.

In combination with a financial model, LCP can be used to explore several important issues in the areas of system design and application. One example is the use of LCP in the selection of the best tracking option for a specific PV system application. Available insolation values and operating temperatures are fed to LCP for conversion to lifetime output, cost, and revenue streams. The supporting financial model then is able to calculate the economic value of the alternative systems.

A number of application issues can be handled effectively with the combination of LCP and the financial model. One issue is the operation and maintenance (O&M) schedule selected for a PV system application. Both alternative O&M policies can be evaluated in terms of their cost, incremental energy output, and dollar value. For example, evaluation of a cleaning program involves the input of the power gain resulting from each scheduled cleaning (based on the cleaning procedure, module cover material, and type of detergent), the number of cleanings for each month of the year, and the site-specific environmental conditions (i.e., the dirt-accumulation rates and the effects of precipitation). LCP has been used to show that the correct selection of an O&M schedule can lead to significant cost savings during a PV system's lifetime.

D. PVARRAY

PA&I developed the PVARRAY model to simulate array performance with the passage of time. The economic evaluation of solar cell technologies requires a technical assessment of their lifetime performance. PVARRAY can model the effect of random solar cell failure on system performance and adjust for various strategies of failed module replacement.

PVARRAY simulates the power output of a PV array during its lifetime. The PVARRAY model includes the ability to compare performance of different module designs, the capacity to consider alternative series-parallel wiring schemes, and the ability to evaluate alternative replacement strategies for different cell-failure rates and bypass-diode placements.

The combination of PVARRAY, SAMICS, and LCP has been used by PA&I to estimate the net present value of energy from a PV system during its useful lifetime. Manufacturing costs for the module-production sequence have been estimated using SAMICS, and the life-cycle cost and performance have been simulated using LCP in combination with PVARRAY. The three programs have allowed PA&I to calculate the cost of different module designs and to determine the time-dependent economic impact of design changes by simulating array performance and life-cycle cost (Figure 6).

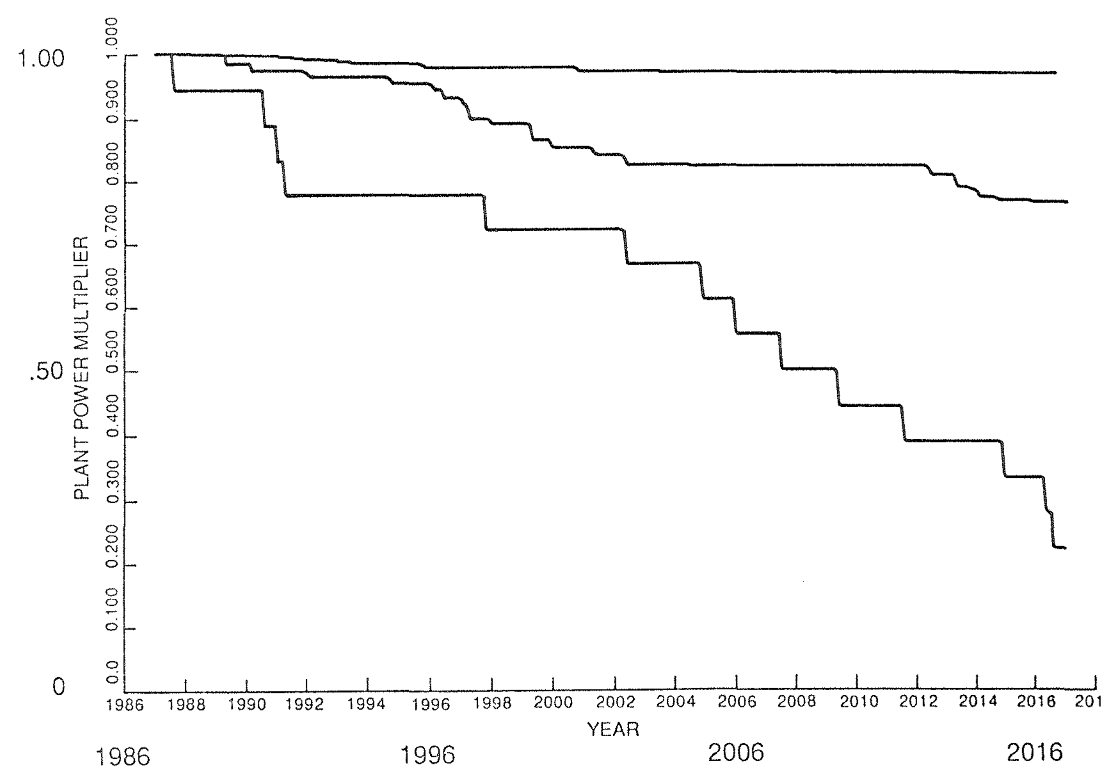

Figure 6. Example of Cell Degradation and Lifetime Performance for Three Different Module Designs

E. CELLOPT

The PA&I team periodically was called upon to apply operations research methods directly to technical problems. An example of this type of activity was the effort to optimize the metallization grid pattern on a PV cell. The problem had many interdependent attributes to consider: resistance losses in the metal grid and silicon, shadowing losses, metallization reliability and service life, and cost. An interactive computer program, Cell Optimization Model (CELLOPT), was developed to assist engineers in the design of current-collecting, metal-grid patterns for solar cells. Given a cell shape, silicon resistivity, metallization material, and metal application method, the methodology constructs a grid pattern to keep to a minimum the cell power loss that arises from the current-collecting mechanisms. The program does not directly incorporate cost considerations. The CELLOPT output, however, can be used by SAMICS to calculate manufacturing cost sensitivities. These, in turn, can be used in the LCP model to ascertain life-cycle cost effectiveness of a specific metallization pattern.

SECTION V

Major Studies

The charter of PA&I was to support the decision-making process of Project management. This was to be done with quantitative studies of the status and future prospects of a wide range of technical development options. The studies typically involved interactions with both technical areas of the Project and with industry to acquire the technical parameters necessary to estimate the economic characteristics of a piece of equipment, a process or sequence of processes, or a product. Technical information then was translated into economic information by exercising one or more of the models described in Section IV. Results were compiled and distributed to interested parties to aid the decision process.

The totality of studies performed by PA&I since 1975 is much too large for detailed listing since the analysis function has been essentially a continuous process. Many studies were "quick-look" estimates performed for DOE management and/or in response to some event occurring outside the JPL PV Project. A significant number of studies involved sensitive information held proprietary by industry. Although the proprietary information at times was very detailed and extensive, no proprietary concern ever was violated by PA&I.

In this section, the only studies mentioned are those that affected the course of the FSA Project, the DOE Program, or were milestone assessments. Quantitative results are limited to landmark studies. Generally, the studies are presented in chronological order and their effect on the direction of PV development is described. Note that quantitative results of studies reported are stated in different base-year dollars. This reflects the adjustment of Program goals and milestone statements to the changing value of the dollar over time.

A. GUIDELINES FOR PRICE ALLOCATION

The JPL PV Project was divided into several technical tasks involving the manufacture of PV modules: silicon feedstock, silicon wafer or sheet, cell and module fabrication, and encapsulation materials. The combined objective for these efforts was the Project goal to develop technology able to produce PV modules with a selling price of $0.50/W_p$ (1974 dollars), free on board (FOB) factory dock. To assist in management of the effort, the Project goal was subdivided or allocated among the various technical tasks. This was done on an "equal pain" basis, taking into account the difficulty of the problem, the maturity of the technology, and the industrial resources available to attack the problems at hand. The first PAGs were presented in the Second Project Integration Meeting (PIM) of the LSSA Project in April 1976. From that time, the PAG has been updated whenever it became apparent that any of the allocation criteria had changed. An example of a Guideline is shown in Table 2 from the 1978 PAG (Reference 12).

*Table 2. Example of 1978 Ingot Technology Price Allocation Guidelines (Reference 12)**

		1978	1980	1982	1984	1986
Encapsulated Cell Efficiency (%)		11.5	13	14	15	16.9
Module Efficiency (%)		8.6	10.1	11.2	12.8	14.4
			Guidelines			Goals
Silicon	$/kg	65	60	40	17	10
	$\$/W_p$	1.42	1.10	0.47	0.19	0.095
Sheet	$\$/m^2$sheet	214	129	90	54	18
(value added)	$\$/W_p$	2.33	1.24	0.72	0.38	0.112
Cells	$\$/m^2$cell	200	120	52	30	22
(value added)	$\$/W_p$	1.74	0.92	0.37	.20	0.130
Encapsulation	$\$/m^2$ module	30	25	15	10	8
materials	$\$/W_p$	0.35	0.25	0.13	0.08	0.055
Module	$\$/m^2$module	100	50	34	20	15.5
(value added)	$\$/W_p$	1.16	0.49	0.31	0.15	0.108
Totals	$\$/m^2$ module	602	404	224	128	72
	$\$/W_p$	7.00	4.00	2.00	1.00	0.50

*Although the stated goal at that time called for modules of at least 10% efficiency, the efficiency was traded off against module cost. It was realized at that time that module efficiencies considerably greater than 10% were highly probable.

The PAGs were the "top-down" statement of what would be necessary for each technical task to accomplish to reach the Project goal. The SAMICS methodology, described in Section IV, then was applied to examine the capability of various technical options to meet the task allocation goals and the overall Project price goal. During the years of the JPL Project, only four major issuances of the PAGs were made (1976, 1978, 1980, and 1984). The 1984 update was a major modification of the PAG because of the much more stringent requirements on manufacturing cost and module efficiency that were called for in the DOE Five-Year Research Plan of May 1983. Comparison of the 'top-down" allocation with the detailed "bottom-up" SAMICS analysis provided an extremely powerful procedure for sorting out the most promising cost-effective technical options.

B. CANDIDATE FACTORIES FOR $0.50/$W_p$ TECHNOLOGY (1977)

The first detailed, bottom-up SAMICS analysis of the cost of manufacturing PV modules occurred in 1977 with the publication of "Economic Analysis of a Candidate 50/W_p Flat-Plate Photovoltaic Manufacturing Technology" (Reference 13). The analysis assumed a large plant (250 MW/year) based on edge-defined, film-fed growth (EFG) silicon ribbon. For the first time, the study showed that ribbon technologies, if technically successful, had the economic capability to meet or exceed the Project price goal. A corollary study in 1978 examined a $2/$W_p$ candidate factory based on Cz silicon solar cells.

For the first time, these studies delineated in detail the requirements both for a long-range, large-scale PV factory and a near-term, moderate-scale factory. Quantitative sensitivities of final product price to various technical and economic factors were visible in an internally self-consistent format. The results of these studies formed the economic foundation that guided the long-term technical thrusts in silicon ribbon-based technology, and the near-term thrust in ingot-based technology.

C. NEAR-TERM COST-REDUCTION "TSONGAS" PROCUREMENT (1978 TO 1981)

In 1978, a congressional initiative was implemented for the "Near-Term Cost Reduction in Photovoltaics," known more commonly as the "Tsongas" procurement after the Congressman who initiated the enabling legislation. Some 55 proposals, ranging over the entire spectrum of PV technologies, were received for rapid evaluation. Because the purpose of the procurement was to solicit ideas for technological developments having an immediate (within 2 to 4 years) impact on the price of PV modules, a way was needed to quickly evaluate the numerous proposals. Proposals were evaluated on the basis of potential payoff, risk of failure, cost to the PV Program, cost of technology transfer, and timeliness of payoff if the proposed development were to prove successful. PA&I worked with FSA Project management, and JPL Procurement and Legal Counsel to develop an internally self-consistent methodology for ranking the proposals. The proposal evaluation process proved to be very effective. In several instances, when proposals that seemed very attractive technologically were examined using the methodology, it became apparent that some of the suggested innovations actually would have increased the cost of PV modules. From the 55 proposals submitted, 14 were selected for award.

At the conclusion of the "Near-Term Cost-Reduction" contracts in 1981, PA&I participated in an assessment of the results of the development effort and compared those results to the benefits predicted 3 years earlier during the proposal evaluation process. Of the 14 contracts, five failed technically and resulted in no cost reduction; four resulted in cost reductions, but somewhat less than predicted, and five resulted in cost reductions greater than predicted (Reference 14).

D. TECHNICAL READINESS ASSESSMENT FOR $2.80/$W_p$ MODULES (1980)

The first major milestone of the National Photovoltaics Program was achievement of technical readiness for a technology capable of producing PV modules for sale at $2.80/$W_p$ (1980 dollars) by the end of FY 82. In the summer of 1980, PA&I initiated a detailed assessment of the status of the developing technology to ascertain if there existed processes, equipment, and materials sufficient to meet this milestone.

The ground rules of this study were that all equipment must either have been in use in the industry or existed as tested prototypes to ensure that process parameters were well understood. Both equipment and processes had to be capable of being adopted by industry by the end of FY 82 and be capable of producing PV modules for sale at $2.80/$W_p$ (1980 dollars) or less.

A Cz ingot-based production sequence was chosen for analysis. Wherever possible, actual measured parameters were used to minimize assumptions. As with all such economic studies, there was no assurance that all the newly developed technology would be adopted by industry and collocated in a single factory.

The module fabrication sequence chosen represented the best technology ready for adoption at that time. The cell and module performance parameters chosen had been confirmed by laboratory and field tests for cells and modules using that fabrication sequence. The factory size was chosen large enough (30 MW/year) to capture most economies of scale. This was done to ensure that true economic capabilities of the technology were not obscured by scale inefficiencies associated with small manufacturing operations.

Results of the study are shown in Table 3 for the principal production steps. These results, presented at the 16th PIM, September 1980, indicated the technology had been developed to the point where the first major DOE PV Program milestone of $2.80/W_p$ technology had been met (Reference 15).

Table 3. Price Summary for Principal Manufacturing Steps for 1982 PV Crystalline-Silicon Technology

Technology Steps	$/W_p$*
Ingot Growth (including silicon feedstock)	$1.63
Wafering	0.37
Cell processing	0.36
Module assembly (including encapsulation material)	0.34
	$2.70

*1980 dollars.

In 1982, events of the preceding 2 years were reviewed to ascertain the extent to which the forecast of potential PV module cost reduction had been realized. Ground rules for this review were that all equipment and processes had to be in actual use in the PV industry, but not necessarily collocated in one manufacturer's plant.

Results of the review, shown in Table 4, were presented in January 1983 at the 21st PIM (Reference 16). In comparing the FOB factory dock required prices, the capabilities of the actual 1982 technology were slightly better than had been projected 2 years earlier. To see how the calculated price compared to actual market prices, some additional assumptions and adjustments had to be made. Marketing and distribution, which are not included in the SAMIS model, had to be added. Although manufacturers are reluctant to reveal marketing and distribution costs, PA&I was able to elicit from manufacturers that the range of 30 to 50% was reasonable. Inflation from 1980 to 1982, predicted in the 1980 study to be 14.5%, actually was 25.4%.

Table 4. Comparison of the $2.80/W_p$ Technical Readiness Projection Made in 1980 for 1982 with Actual 1982 Industrial Practices (Reference 16)

	Projection Made in 1980 for 1982[a] (1980$/W_p$)	1982 State of the Art[a] (1980$/W_p$)	
	30 MW/yr	30 MW/yr	2 MW/yr
Ingot growth (including silicon)	1.63	1.53	1.74
Wafering	0.37	0.42	0.77
Cell processing	0.36	0.31	0.84
Module assembly (including encapsulation material)	0.34	0.37	0.92
FOB factory dock required price	2.70	2.63	4.27
Marketing and distribution (30 to 50%)	0.81-1.35	0.79-1.31	1.28-2.13
Inflation (1980-1982) (14.5% estimated, 25.4% actual)	0.89-1.03	0.87-1.00	1.41-1.63
Required market price,[b] 1982$/W_p$	4.40-5.08	4.29-4.94	6.97-8.03

[a]Assumes 11.4% encapsulated-cell efficiency and a 0.78 packing factor.
[b]To convert to $/m^2$ of module, multiply by 89.4.

When these adjustments were made, the required market price of modules in 1982 dollars was in the range of $4.29 to $4.94/W_p$. In December 1982, 1 month after the completion of the study, the winning bid in a competitive procurement was submitted by a module manufacturer that had adopted most of the technology assumed in the study. The bid of $4.95/W_p$ was for a large number of modules to be used by a utility.

Also included in the study was a calculation of the required price of PV modules using the same technology, but produced on a much smaller scale of 2 MW/year. This scale was typical of most PV module manufacturers at that time. The results for 2 MW/year, shown in Table 4, were in the range of from $7 to $8/W_p$ (1982 dollars), including marketing and distribution. This corresponds very well to the typical selling prices for large purchases of PV modules at that time.

E. JPL/SERI JOINT ASSESSMENT OF CRYSTALLINE-SILICON SHEET (1981)

In the summer of 1981, the FSA PA&I was faced with an extremely difficult and delicate problem. At the request of the DOE PV Program Office, the various crystalline sheet options were to be listed in descending priority in anticipation of sharp reductions in the number of options being funded by DOE. A total of 11 different options were being pursued by JPL and SERI.

Each option had its vocal constituency both within and outside the institutions. Also, several sheet options had multiple options for ancillary requirements such as sawing or silicon feedstock. These affected the economic and technical viability of the sheet option. Eventually, 18 different paths were identified for silicon sheet, even when assuming commonality wherever possible in cell and module processing.

The task facing PA&I was to organize and conduct a joint JPL/SERI study and to arrive at a consensus between the two institutions on recommendations for which options should be continued and which should be terminated. At that time, for more than a year, PA&I had been developing SIMRAND, a decision-aid methodology for application to just such multiple-option problems as the silicon sheet study posed by DOE. It was decided to apply SIMRAND, described in Section IV of this report, to the problem. In part, SIMRAND had its origins in the "Tsongas" procurement, a problem similar to the priority-rating of silicon sheet options.

Several preliminary planning meetings were held at SERI and JPL to carefully develop the ground rules for the study and to familiarize all participants with a decision process that formally incorporated uncertainty with technical and economic point estimates. At the outset, the enthusiasm of the participants for the SIMRAND approach varied markedly. As the study progressed, however, the value of the process became apparent to most of those involved.

The bulk of the data discussions took place in two 2-day meetings at JPL chaired by the PA&I Area Manager and supported by PA&I analysts. Each variable was discussed for all sheet options. For example, cell efficiencies for cells fabricated from each sheet material were discussed. A consensus was reached that the efficiency distributions for each silicon sheet option was consistent with the knowledge of that material, and consistent relative to the efficiency distributions of other sheet options. The discussion then would move to the next variable, such as yield, for each of the sheet options. This ensured some measure of uniformity in the underlying assumptions across all sheet options. Proceeding in this manner, consensus was reached for each variable for all the sheet options. IPEG calculations were performed as needed to support the discussions.

Cumulative probability distributions were generated for each variable. These distributions were entered into the SIMRAND computer program. Through a Monte Carlo simulation, probability distributions for individual variables were combined into a single distribution for the cost of the module. Cumulative probability distributions were generated for each silicon sheet option. Although the discussions were highly spirited at times, the SIMRAND process, by formally excluding extraneous issues, provided an internal self consistency that permitted progress toward a consensus.

It is noteworthy that consensus was reached on all issues. The findings of the joint JPL/SERI team were presented to the DOE PV Program Office and subsequently almost all the team's recommendations were enacted by DOE. The results are summarized in an unpublished "white paper" report to DOE (Reference 17).

F. DEVELOPMENT OF "IDENTIFICATION AND COSTING OF BASIC PROCESSING UNITS" HANDBOOK (1981 TO 1982)

With the rapid emergence of new thin-film solar cell technologies, it became apparent that a new database of information would be needed to evaluate the progress and potential of these new technologies. The database would cover leading manufacturing processes for thin-film solar cell module production. Using the experience and database developed through many prior cost-assessments for silicon solar cell technology, it was shown that the large number of processes that might be used could be reduced to a much smaller and manageable list of "basic processing units." In 1981, JPL proposed to develop for SERI a simplified methodology and handbook for the rapid, rough estimation of process costs based on the use of basic processing units.

The handbook that resulted from this effort (Reference 18) consisted of descriptions and cost estimates for the basic processing units identified as representative of the manufacturing technology for thin-film solar cell modules. The process descriptions identified costs by principal categories, making it easy to adjust the description and estimate of cost to a specific production sequence and technology. The most sensitive parameters for individual process costs also were singled out, and sensitivity curves were generated showing the response of cost to variations in this input parameter. With this material, users of the handbook quickly can construct a cost estimate of both the processes in a PV module fabrication sequence and the total cost. Beginning with a process sequence description, process costs are taken from the handbook. If there are significant changes in the most sensitive parameter for the estimate of cost, the estimate can be read directly from the sensitivity curve for the process parameter. The handbook has proven itself useful in the study of manufacturing processes and the development of quick estimates of process costs.

The handbook of "basic processing units" was updated in 1986. It was extended to cover promising new manufacturing processes for thin-film technologies. The basic processing units are available as part of the SAMIS package of cost-estimating procedures that can be obtained through COSMIC.

G. SILICON COST ANALYSIS (1983)

By the fall of 1983, the polysilicon feedstock development task was being phased out of the FSA Project. Early in the Project, a contract had been issued to an academic institution (Lamar University, Beaumont, Texas) to estimate and track the costs of silicon from the numerous proposed production methods. Many point estimates had been made using standard industrial cost engineering technologies. In 1983, PA&I conducted a study of the surviving candidate silicon production methods to assess the capability for producing low-cost silicon. This study once again demonstrated the value and power of SIMRAND to produce internally consistent comparisons that are a requirement for sound management (Reference 19).

The silicon-cost study applied the SIMRAND technique, described in Section IV of this document, to a projection of the cost of silicon from future large production plants using technology developed during the FSA Project. Inputs to the SIMRAND model were based on updates of the Lamar University estimates. In SIMRAND, however, probabilities are assigned to the point estimates. An immediate result was the discovery that point estimates for different technologies, which previously had been used to compare cost of product, had very different probabilities of achievement in the opinion of a broad spectrum of experts in the field. When compared on an equal probability basis, the candidate silicon process in second place (the process developed by Hemlock Semiconductor, Inc.) became much more cost competitive with the Union Carbide leading-candidate process.

H. ECONOMIC COMPARISON OF FLOAT-ZONE AND CZOCHRALSKI TECHNOLOGY (1984)

In 1983, the reorientation of the National Photovoltaics Program toward high-efficiency modules (16% and above) prompted a reexamination of options for silicon material capable of the required cell efficiencies (Reference 20). Among the candidate sheet materials proven capable of producing high-efficiency cells was the float-zone (FZ) ingot material.

The FZ-ingot option was briefly examined early in the Project. Although it was known that very high crystal quality could be obtained with FZ, the state of crystal growing technology for Cz was more advanced. The semiconductor industry was moving toward large-diameter Cz ingots, a direction seemingly fortuitous in meeting the requirements for photovoltaics. At that early time, the goals of the National Photovoltaics Program required only a 10% efficient module that could be obtained by Cz technology without resorting to the less-developed FZ method. Restructuring of the Photovoltaics Program goals to 15% efficient modules, however, put stringent requirements on the bulk properties of the silicon wafer material before it starts into the cell processing sequence. With further development, Cz material probably would be able to meet these requirements, but FZ material could fulfill most of the bulk property requirements at that time. Although FZ material was acceptable, the crystal production methods require further technology development to be acceptable for large-scale manufacturing.

Under the assumption of equivalent cell efficiencies, results of the analysis indicated a slightly lower $\$/W_p$ and $\$/m^2$ cost for a FZ process when compared to a Cz-based process. If it is assumed for identical cell and module-fabrication sequences that FZ wafers will result in a higher cell efficiency than Cz wafers, the disparity in the results increase further in favor of FZ. A more conservative cost for the polysilicon feedstock was used for FZ because of the requirement for feedstock in rod form.

The principal difference between the assumptions for the two technologies was uncertainty in the crystal growth parameters. The assumptions for Cz were widely reviewed for more than a decade and, for the most part, demonstrated in practice. Conversely, FZ crystal growth is still very much an art, and technology development would be required, with all its attendent uncertainties, to fabricate production FZ-growers with the capabilities assumed in this study. The payoff for such a development effort could be an increase in the absolute efficiency of modules.

I. PARAMETER SENSITIVITY ANALYSIS OF PHOTOVOLTAIC SYSTEMS (1984 TO 1985)

By 1984, the network of models developed by PA&I had been completed. It was possible to trace analytically the life cycle of photovoltaics from the purification costs of the silicon feedstock through crystal growth, cell and module fabrication, installation and operation in the field and, ultimately, the decommissioning and salvaging of power plants at end-of-life. This powerful set of models allowed one to assess the sensitivity, of both life-cycle costs and cost per kWh, to changes in cost or performance at any point in the manufacture and operation of a PV power plant. By 1984, a considerable experimental database had been accumulated by module manufacturers and power plant operators. Based on these factors, PA&I initiated a major sensitivity study of flat-plate PV systems.

The purpose of the sensitivity study was to provide a guide for Program planning and technology assessments that would permit a user flexibility over a broad spectrum of PV system parameters. Using the relationship between lifetime cost and system performance parameters, analytical tests were made to see how overall PV system energy costs are affected by changes in the various goals set for module cost and efficiency, system component costs and efficiencies, O&M costs, and indirect costs.

An analysis was made of how the competitiveness of PV systems is affected by regional differences in competing energy costs and solar insolation levels. The sensitivity of competing energy costs (coal, combustion turbine, and combined cycle oil-fired generators) to escalation rates for capital and fuel was explored. Alternative tracking configurations (fixed, one-axis, and two-axis tracking) also were introduced into the sensitivity analysis.

Goal values for PV system parameters were reviewed on the basis of the most recent research findings. Sensitivity tests were made to see how research progress in areas such as power-related, BOS cost affected the combinations of module cost and module efficiency that meet Program goals for system energy costs (Reference 21). The results were an extensive set of tables that related the sensitivity of important system parameters to changes in other system parameters. This provides the system designer with insight into the effect a specific set of parameters will have on overall system economic performance.

J. FSA PROJECT ACCOMPLISHMENTS COMPARED TO CHERRY HILL GOALS (1985)

In 1985, nearing the end of the FSA Project, a study was undertaken to assess the economic consequences of the technical achievements of the Project from its inception. In an internally consistent process, these results were compared to the results envisioned by the Cherry Hill conferees in 1973. Three of the four PA&I managers who served during the life of the Project authored a paper presented at the 18th Institute of Electrical and Electronic Engineers, Inc. (IEEE) Photovoltaic Specialists Conference (Reference 22). The principal findings of this study are presented in detail in Section VI of this document.

SECTION VI

Progress in Crystalline-Silicon Technology

When the FSA Project was formed in January 1975, the PV industry was using some rather expensive materials for module manufacturing. The PV industry also was small and highly labor-intensive. The FSA Project planners envisioned a path that would lead to a dramatic decline in the price of terrestrial PV modules, from the range of \$70 to \$120/W_p (1985 dollars) in 1974, as shown in Figure 7, to the Cherry Hill goal of \$1.07/W_p (1985 dollars) in 1985.

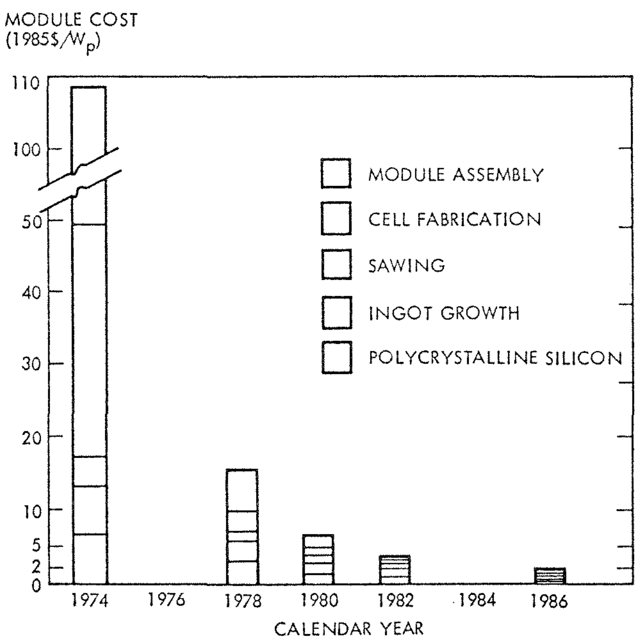

Figure 7. State-of-the-Art Projections for Czochralski Module Technology (1974 to 1985)

This section reviews the progress made in crystalline-silicon technology from 1974 to 1985. The reader should be cautioned that the numbers presented here reflect the potential of the technology in the limit of high production volume, and not the market prices at each point in time.[7]

A. CZOCHRALSKI TECHNOLOGY

Figure 7 displays state-of-the-art Cz technology at several points in time.[8] The major contributions to product cost are broken out by principal process category.[9]

The state-of-the-art factories of Figure 7 assume that the most advanced technology available to a manufacturer at that date is collocated in a single factory and scaled-up to a point where most economies-of-scale have been captured. This prevents differences attributable to scale economies from obscuring economic differences inherent in the technologies.

As shown in Figure 7, an astounding improvement in the state-of-the-art technology took place in the 4 years after 1974. By 1978, expensive materials such as silicone pottants and double-glass encapsulants were being replaced by polyvinyl butyral (PVB) and single-glass construction. Cz ingots (2- and 3-in. diameter) were replaced by 4-in.-diameter ingots. Module efficiency had improved substantially, and cell fabrication and module assembly, although still labor intensive, was done on a non-automated, assembly-line basis.

By 1980, prototype large-scale production equipment had been developed by contractors to the JPL Project. Notable among this equipment were automated, large-diameter, Cz-ingot growers along with new apparatus for cell processing, module assembly, and lamination. Yield and efficiency improvements reduced all manufacturing requirements for a given production level. New, long-life, inexpensive materials such as ethylene vinyl acetate (EVA) were being developed for encapsulation. A systematic test and failure analysis program at JPL allowed industry to avoid many costly failures in the field and to rectify quickly those that did occur. The engineering of the entire array as an integrated structure eliminated redundant structural material.

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[7] This section summarizes the principal findings of a silicon-crystalline study (Reference 22) that were presented at the 18th IEEE Photovoltaic Specialists Conference in October 1985. The results are not in strict agreement with the IEEE study because an estimate of inflation for 1985 (4%) was used in the study. Results presented here use the actual 1985 rate of inflation (3.7%).

[8] "State-of-the-art" refers to technology that has been developed, but is not necessarily used in production.

[9] The 1978 and later results are from state-of-the-art SAMICS analysis performed at JPL (References 15 and 16). The 1974 data are from the "Hearings Before the Subcomittee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974." The information is presented there as a manufacturing direct cost that is not in a form that permits a SAMICS analysis.

The cumulative effect of these developments, shown in Figure 7, shows how technical advances, combined with economies of scale, produce large reductions in manufacturing cost. Unfortunately, because of market conditions and shifting priorities in the National Photovoltaics Program, actual production levels were in the range of 1 to 5 MW/year, well below the level needed to capture full economies of scale. Technology transfer had also slowed appreciably in recent years. Consequently, market prices leveled off well above the price the technology was capable of reaching.

B. STATUS OF CRYSTALLINE-SILICON TECHNOLOGY IN 1985

A more detailed analysis of 1985 state-of-the art manufacturing using Cz technology is given in Tables 5 and 6. All assumed equipment and processes were in actual use or existed as production prototypes. Thus, if production were to start in 1988, more than 2 years would be required for today's state-of-the art technology to be installed in a 25-MW/year factory. Wafering parameters are assumed to continue their moderate improvement through 1988. The assumed cell and module fabrication processes already were individually proven in the production of modules. Results show that if modules of 13.5% efficiency [under standard test conditions (STC)][10] could be produced, then a price of $1.44/W_p$ (1985 dollars) or $0.68/W_p$ (1974 dollars) would be required for profitable operation. When this cost and efficiency are used to calculate energy price using the methodology and assumptions found in the current DOE Five-Year Research Plan, an energy price of $0.274/kWh (1985 dollars) is the result.

Table 5. Projected Price of Manufactured Module Using State-of-the-Art Czochralski Technology

Process	1985$
Silicon material	0.389
Ingot growth	0.367
Ingot wafering	0.303
Cell fabrication	0.207
Module assembly	0.178
Module price	$1.44/W_p$ (1985$)
Energy price (using baseline parameters of the National Photovoltaics Program)	$0.274/kWh

Table 6. Assumptions Used in Module Price Analysis: 1985 Czochralski Technology

Factory size	25 MW_p/yr
Year of production	1988
Silicon cost	$43/kg (1985$)
Crystallization rate	1.5 kg/h (Cz)
Ingot diameter	5 in.
Wafer thickness and kerf	19 mils
Sawing blade plunge rate	2.0 in./min
Sawing yield	95%
Cell size (modified square shape)	9.83 x 9.83 cm
Area per cell	94.6 cm^2
Packing factor (percentage of module as solar cells)	91.4%
Module size	122 x 61 cm (4 x 2 ft)
Module power	101 W_p
Encapsulated cell efficiency	14.8%
Module efficiency (STC)	13.5%

At the time of the Cherry Hill conference, little was known about BOS costs for large-scale PV electrical generation plants. It was the early 1980s before BOS parameters were defined adequately to allow a statement of the PV goals in more relevant terms of $/kWh energy price to the user.

As stated previously, when the Cherry Hill goals for PV modules are combined with the BOS costs and financial parameters used in the DOE Five-Year Research Plan, the selling price of the energy produced by the system is $0.263/kWh (1985 dollars). *Comparison of this number with previous calculations, shown in Tables 5 and 6, shows that Cz technology, for all intents and purposes, fulfilled the technology-development part of the Cherry Hill promise.*

C. FUTURE PROSPECTS FOR CRYSTALLINE-SILICON TECHNOLOGY

As shown in Table 5, more than 70% of the total required price for Cz modules in this projection is in the production of the unprocessed wafer. This technology area still is most in need of cost reduction. Silicon ribbon technologies show considerable promise of significantly reducing wafer costs because the sawing step is completely eliminated, and some ribbon technologies are quite conservative in usage of silicon material. Some ribbon materials also are capable of producing cells approximately equivalent to Cz in solar conversion efficiency.

[10]Measured at 25°C, Air Mass 1.5 spectrum, and 100-mW/cm^2 insolation.

The results of a SAMICS simulation of a possible future dendritic web ribbon-based PV factory are shown in Tables 7 and 8. The production year assumed is 1992, with production cost-estimates based on present state-of-the-art cell and module fabrication techniques, scaled up to 25 MW/year. The assumed web growth rates of 20 cm^2/min and module efficiency of 13.7% reflect projected developments in the technology. The resulting price required for profitable operation is \$1.02/W_p (1985 dollars) or \$0.49/W_p (1974 dollars). Because the efficiency actually is considerably higher, this cost easily beats the original Cherry Hill goal of \$0.50/W_p. To approach the current National Photovoltaics Program goals, however, ribbon growth-rates would have to increase significantly. The effect of dendritic web ribbon growth rates on module production cost is shown in Figure 8. As shown, some improvement in efficiency and a growth rate of more than 30 cm^2/min are required to meet the current goal.

Table 7. Projected Price of Manufactured Module Using 1992 Dendritic Web Technology

Process	1985$
Silicon material	0.153
Web growth	0.341
Cell formation	0.119
Metallization	0.162
Module assembly	0.244
Module price	\$1.02/W_p (1985$)
Energy price (using baseline parameters of the National Photovoltaics Program	\$0.220/kWh

Table 8. Assumptions Used in Module Price Analysis: 1992 Dendritic Web Technology

Factory size	25 MW/yr
Year of production	1992
Silicon cost	\$37/kg (1985$)
Web growth rate	20 cm^2/min
Growth machines/operator	18
Module area	4790 cm^2
Module power	68.2 W_p
Encapsulated cell efficiency	14.6 %
Packing factor	94%
Module efficiency (STC)	13.7%

Figure 8 shows the importance of improvements in silicon ribbon growth rates. The projected 20-cm^2/min growth rate for 1992 will allow dendritic web technology to exceed the original goals set at Cherry Hill. Additional research to improve efficiency and increase ribbon growth rates to the 30-cm^2/min range would bring module production costs close to current National Program goals.

Subsequent to the 1985 Cz and ribbon studies, significant progress has been made in laboratory, single-crystal cell efficiencies. This development is especially important because cell efficiencies greater than 20% were achieved in relatively large cells (4 cm^2). This indicates that efficiency assumptions for the 1985 study were unnecessarily conservative. If laboratory techniques for improving efficiency can be successfully adapted for industrial-scale cell production, then the price per watt for crystalline-silicon PV modules would be considerably less than indicated by the 1985 study. Because increases in module efficiency reduce total power-plant area-related costs, further increases in cell efficiencies would reduce the price per kilowatt-hour of electricity generated. *If both laboratory efficiencies can be approached in large-scale production, and ribbon growth rates improved, it is conceivable that the DOE goals can be surpassed by crystalline-silicon photovoltaics.*

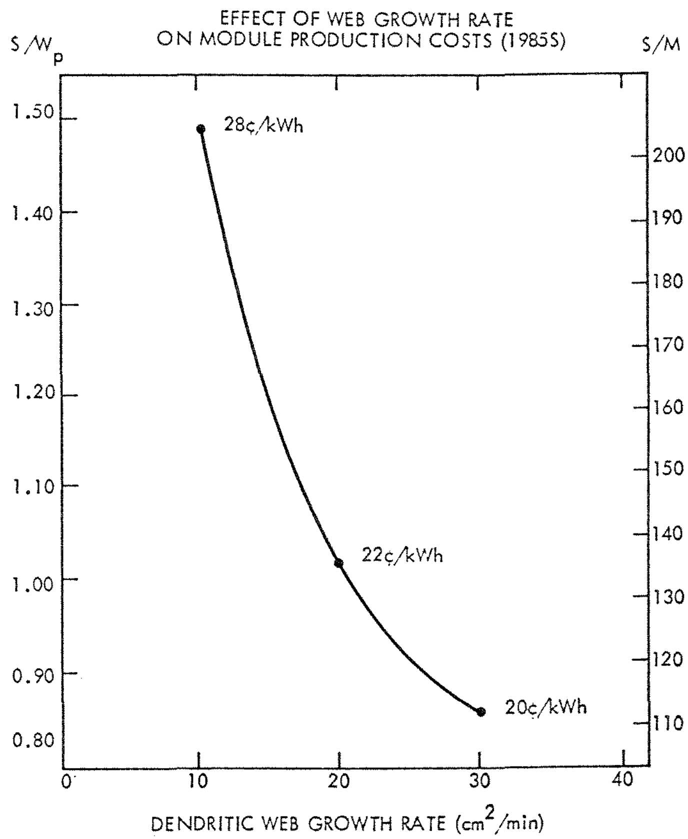

Figure 8. Effect of Web Growth-Rate on Module Production Costs (1985 dollars)

SECTION VII

Lessons and Legacies

The PA&I activity was the first of its kind at JPL. PA&I developed the depth, breadth, and autonomy to carry out the broad spectrum of activities involving model development, detailed technology assessment, and decision analysis required to support the FSA Project. PA&I assessment and analysis work provided Project management with a solid point of departure for folding in the diverse factors such as budgetary, organizational, and legislative constraints that influence a management decision. From this storehouse of experience, many lessons were learned that should help any future activity of a similar nature to avoid some of the pitfalls, failures, and false starts that at times befell FSA PA&I. Some of the most important lessons learned and the legacy left by PA&I are discussed in this section.

A. LESSONS LEARNED

Choose goals with great care. A properly structured project goal can be of great help in providing cohesiveness and direction to a project. Conversely, a poorly structured goal can be divisive, spawning inefficient use of resources and leading to external perceptions of poor progress or failure when, in fact, significant progress is being made.

Goals should be structured to include only those parameters over which the project has some control. The FSA Project was a joint Government-industry-university effort to develop technology that would later be used by a privately scaled-up industry. The extent to which that scale-up would occur was completely dependent on market and financial conditions in industry, over which the Project had no control. Consequently, the early-stated goal of a 500 MW/year production rate by 1985 was not an appropriate Project goal. Some criticism was heard that the Project was failing when the 500-MW/year goal appropriately was abandoned later. It was abandoned in part because analysis showed those production levels were not necessary to capture economies-of-scale, and because of the realization that the industry simply was not going to expand that fast. The corrollary lesson is that abandonment of an inappropriate or irrelevant goal will be interpreted in some quarters as failure.

The goal statement of a technology-development project, such as FSA, should contain limits of what can be accomplished. It was several years into the Project before the $\$0.50/W_p$ goal (later updated for inflation to $\$0.70/W_p$ in 1980 dollars) was consistently stated in the correct terms of "developing the technology that, if scaled up, would be capable of producing PV modules for the FOB price of $\$0.70/W_p$." The point is that the Project itself was never intended to actually produce $\$0.70/W_p$ modules. Complete success by the Project still would be only an *enabling* event toward private industry's implementation of the technology. Although the technology may be capable of producing $\$0.70/W_p$ modules, the actual market price charged by manufacturers for their product would be determined by market supply and demand conditions. Complete success by the Project in no way guaranteed that the private sector would implement the technology on a large scale.

The goal should be structured as a single "bottom-line" from which technical and economic sub-goals can be derived. Early in the Project, the goals were stated as $\$0.50/W_p$ and 10% efficient modules. Efficiency entered into the original Cherry Hill Conference estimates of what would be the necessary efficiency of polycrystalline silicon cell modules to achieve $\$0.50/W_p$. Efficiency is subsumed in any $\$/W_p$ calculation and at the outset should have been left as a free variable, as was $\$/m^2$ costs. This would permit maximum flexibility in how the $\$0.50/W_p$ goal was to be achieved.

The $\$0.50/W_p$ goal, along with the later $\$0.70/W_p$ goal, were themselves not especially good "bottom-line" goals. They did suffice, however, until 1983 when an appropriate goal stated in dollars/kilowatt-hour could be structured. By then, sufficient knowledge and agreement had been acquired regarding system parameters involved in the actual building and operation of large-scale PV electrical generating plants. This information permitted a reasonably well-stated dollars/kilowatt-hour goal to be made.

Credibility suffers when the audience has difficulty dealing with the complexities of a sophisticated analysis. During the FSA Project, PA&I developed several innovative and highly sophisticated models that were at the leading edge of their discipline. These models proved highly useful in the internal Project decision-making process. The same sophistication that made the models so useful, however, became a severe liability when attempts were made to convince those unfamiliar with rigorous and complex procedures of the discipline that the results of the model were valid.

The contrast between user-acceptance of the SAMIS computer model and the IPEG cost-estimation algorithm is instructive as an example of this problem. SAMIS required the use of a mainframe, time-sharing computer, and several days training for the operator to gain familiarity with the intricacies of the model's operation. Input data formulation was detailed and tedious. The payoff was extraordinary visibility and insight into the requirements and costs of the processes being examined. Errors in input values or assumptions also were readily apparent. The application of SAMIS to PV module costing, however, met with vigorous and lasting skepticism. (This remained true despite an extensive validation process to ensure the validity of the results under the input assumptions.)

IPEG is a linear algorithm that divides the cost into five categories and applies standarized coefficients that are fixed for each cost category. In fact, the IPEG coefficients are derived from the same methodology used in the SAMIS computer program. IPEG analysis requires virtually the same input data, but IPEG results are somewhat more subject to undetected input error than SAMIS. Still, the IPEG method achieved wide and virtually unquestioned acceptance in the industrial community. The method of multiplying direct costs by fixed coefficients is simple and widely used in industrial costing. Very few inquiries ever were received regarding the origin or validity of IPEG coefficients.

It is clear from the PA&I experience that great caution should be exercised when expecting the acceptance of innovative methodologies, especially by users whose principal interests are not directly associated with the methodology or its results. Packaging for ease of user accessibility and acceptance should rank just below validity in the criteria for any future model development. When disseminating a new and sophisticated methodology, much attention and time must be given to education of the users and others whose cooperation is needed to apply the methodology.

There can be problems in maintaining a first-class staff when most products are internally discreet. Because of the nature of the PA&I role in supporting Project management decision-making, many important PA&I products had only very limited circulation and were completely invisible to the external observer. This has the effect of limiting the future professional prospects of personnel in this position when one's resumé consists almost entirely of intangibles. The FSA Project was especially fortunate in dedication to the Project of some critical members of the PA&I staff. There may be no completely satisfactory solution to this problem. One possible approach is to periodically rotate personnel into more highly visible activities with more tangible products.

An independent assessment group having no stake in any specific outcome is highly valuable to project management. At the outset of the FSA Project, PA&I was created as a Project area on an equal plane with the other technical areas of the Project. Equally important, PA&I was not part of the Project Office and could interact as peers with other segments of the Project, not as representatives of the Project Office. Consequently, PA&I was highly successful in acting as the "honest broker" of information among various parties. The importance of this somewhat subtle point should not be underestimated as this seemingly minor organizational construct was probably the most enabling factor in the success of the PA&I activity.

B. LEGACIES

At the outset of the FSA Project in 1975, it became apparent that a very large number of technical options, in varying degrees of maturity, were available for development. One possible approach would have been to fund a broad spectrum of activities with only qualitative regard to nontechnical factors such as manufacturing cost. The FSA Project, however, chose a difficult, uncharted course. It set quantifiable, non-technical goals for the end result of a complex, long-range development effort where each technical option was to be judged on its contribution to meeting those goals. It was the task of PA&I to devise and implement the process by which the progress of the Project could be enhanced and measured.

Through the years of the Project, PA&I studies have documented the history of technical and economic progress toward meeting the objectives of the National Photovoltaics Program. A framework of goals and guide lines was established. A number of innovative and sophisticated analytical tools were developed to track overall progress and place individual research activities within the framework of the goals and guidelines. The analyses performed by PA&I provided the quantitative consistency required for informed management decisions.

Accomplishments of the PA&I activity, discussed in Sections III, IV, and V of this report, reflect only the most tangible of PA&I products. Not included is the aspect that PA&I became a clearing house for reliable information on a broad spectrum of subjects, responding frequently to inquiries from Government, industry, academia, and private parties. A significant proportion of PA&I resources was consumed by the demands of information transfer.

Not all the techniques, methodologies, and procedures of the PA&I activity will be applicable or appropriate to other technology-development projects. Indeed, not all technology-development efforts require a PA&I activity. *But an analysis and integration activity is essential in those cases where a number of competing development options must coalesce into an integrated technology, viable under both technical and non-technical constraints.* The legacy of the FSA PA&I activity will be the example it provided in enabling the orderly management of a very complex technology-development project.

SECTION VIII

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APPENDIX A

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APPENDIX B

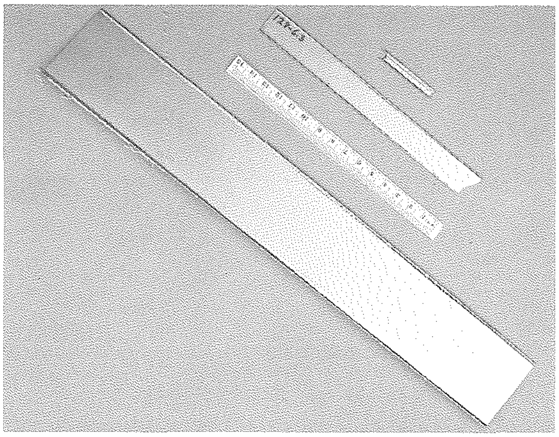
Glossary

BOS	balance of system (non-array elements of a PV system)
CELLOPT	Cell Optimization Model
COSMIC	Computer Software Management Information Center
Cz	Czochralski (classical silicon-crystal growth method)
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EFG	edge-defined film-fed growth (silicon-ribbon growth method)
ERDA	Energy Research and Development Administration
EVA	ethylene vinyl acetate
FOB	free on board
FSA	Flat-Plate Solar Array Project
FY	fiscal year
FZ	float-zone (silicon sheet growth method)
GNP	Gross National Product
IBM-XT	International Business Machines, XT computer model
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IPEG	Improved Price Estimation Guidelines
JPL	Jet Propulsion Laboratory
LCP	Lifetime Cost and Performance
LSA	Low-Cost Solar Array (Project)
LSSA	Low-Cost Silicon Solar Array (Project)
MEPSDU	module experimental process system development unit
MIT	Massachusetts Institute of Technology
MYPP	Multiyear Program Plan
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
O&M	operation and maintenance
OTA	Congressional Office of Technology Assessment
PAG	Price Allocation Guidelines
PA&I	Project Analysis and Integration Area (of FSA)
PC	personal computer
PIM	Project Integration Meeting
PPG	Program Planning Group
PRDA	Program Research and Development Announcement
PURPA	Public Utilities Regulatory Policies Act of 1978, PL95-617
PV	photovoltaic(s)
PVB	polyvinyl butyral
RANN	Research Applied to National Needs
R&D	research and development
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SAMPEG	Solar Array Manufacturing Price Estimation Guidelines
SERI	Solar Energy Research Institute
SIMRAND	SIMulation of Research ANd Development Projects
SNL	Sandia National Laboratory
STC	standard test conditions

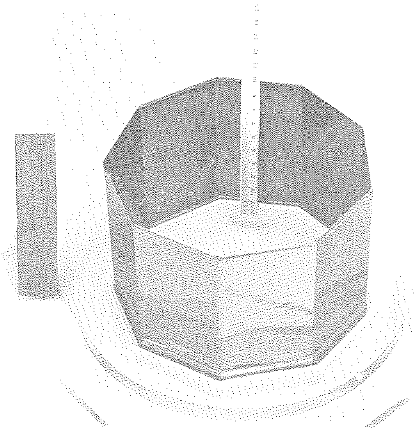
Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

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.

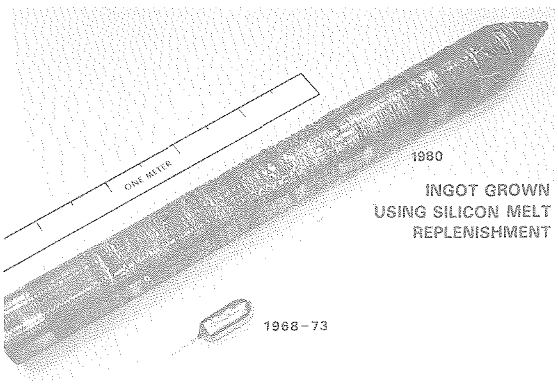
More Technology Advancements



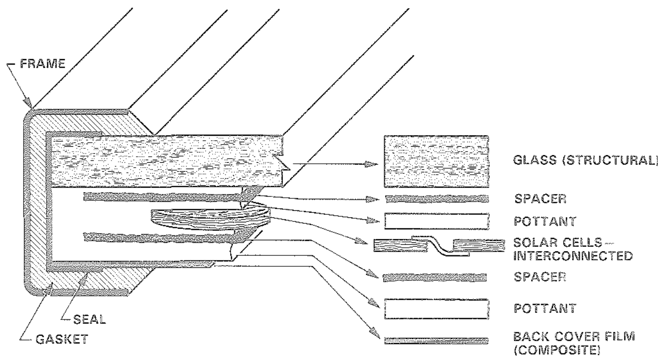
Dendritic web silicon ribbons are grown to solar-cell thickness. Progress is shown by experimental ribbons grown in 1976 and 1978 and a ribbon grown in a Westinghouse Electric Corporation pilot plant.



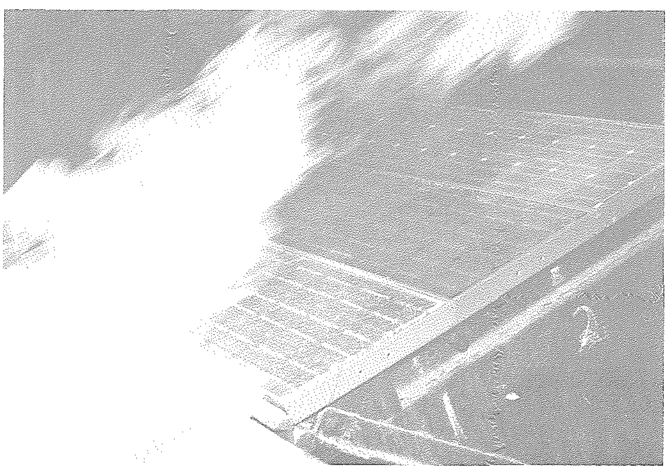
The edge-defined film-fed growth silicon ribbons are grown to solar-cell thickness. A DOE/FSA-sponsored research ribbon grown in 1976 is shown next to a nine-sided ribbon grown in a Mobil Solar Energy Corporation funded configuration.



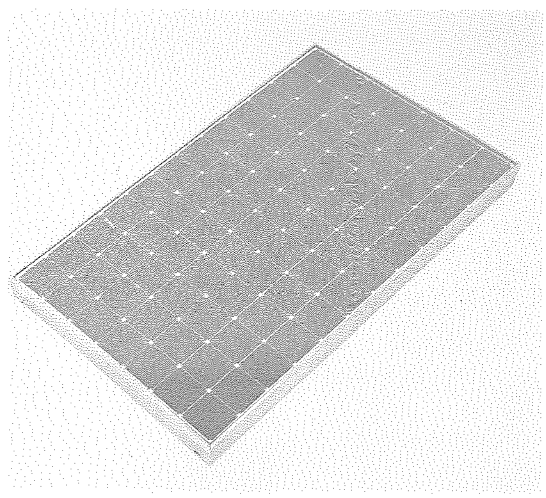
Czochralski silicon crystals as grown are sawed into thin circular wafers. (Support for this effort was completed in 1981.)



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.



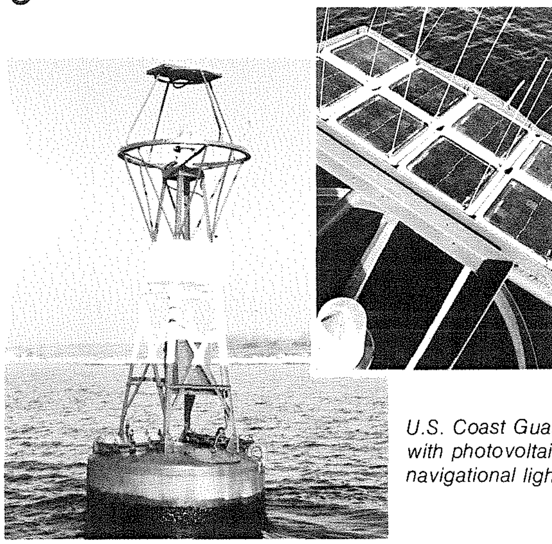
Prototype modules have passed UL 790 Class A burning brand tests which are more severe than this spread of flame test.



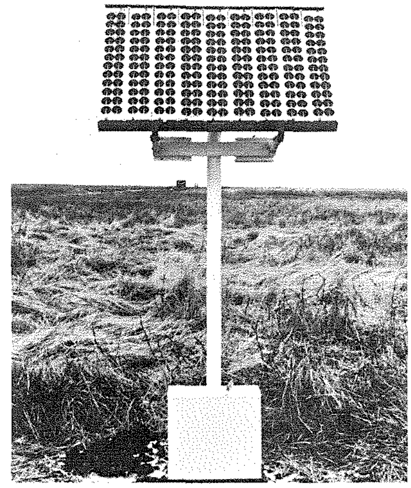
A 15.2% efficiency prototype module (21 x 36 in.) was made by Spire Corp. using float-zone silicon wafers. Recently, similarly efficient modules were fabricated from Czochralski silicon wafers.

Photovoltaic Applications

1975

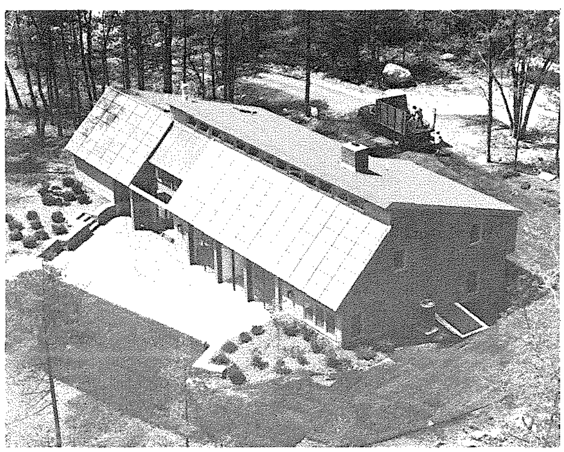


U.S. Coast Guard buoy with photovoltaic-powered navigational light.

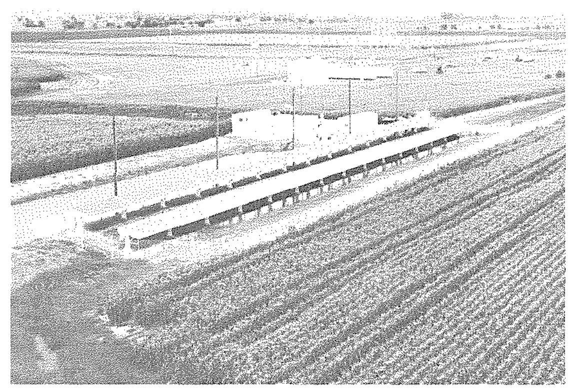


Photovoltaic-powered corrosion protection of underground pipes and wells.

Later...

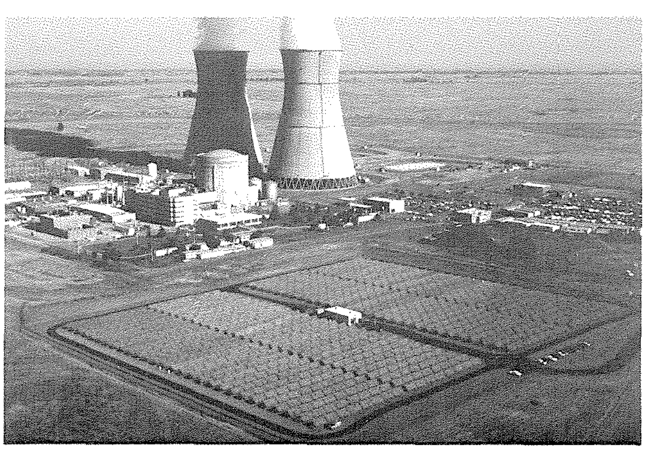


House in Carlisle, Massachusetts, with a 7.3-kW photovoltaic rooftop array. Excess photovoltaic-generated power is sold to the utility. Power is automatically supplied by the utility as needed.



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.)