NASA-TM-58229 19810009004

NASA Technical Memorandum 58229

The Development and Utilization of Solar Photovoltaic Cells: An Assessment of the Potential for a New Energy Technology

Kelley J. Cyr

January 1981

NASA
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

NASA Technical Memorandum 58229

The Development and Utilization of Solar Photovoltaic Cells: An Assessment of the Potential for a New Energy Technology

Kelley J. Cyr
Lyndon B. Johnson Space Center
Houston, Texas

NASA
National Aeronautics and
Space Administration

Scientific and Technical
Information Branch

1981

N81-17526 #

CONTENTS

TABLES

FIGURES

Figure | Page

INTRODUCTION

> If you have built castles in the air, your work need not be lost; that is where they should be. Now, put the foundations under them.
>
> --Henry David Thoreau, Walden

Within the last decade, the United States has experienced two "energy crises," and the efforts to overcome America's energy problems have become "the moral equivalent of war." Yet, each year there is enough solar radiation striking the surface of the country to supply America's energy needs 500 times over (ref. 1). While the Sun has provided almost all of the world's energy throughout history, the world now runs primarily on fossil fuels. This is a form of "energy capital" that is limited in quantity and unevenly distributed around the globe. Since energy consumption is inexorably linked to economic growth, the world will eventually run out of this capital unless other, renewable sources are developed.

One renewable source of energy is the Sun's daily radiation. Solar cells (also called photovoltaics or just PV) are able to capture the Sun's radiation and convert it into electricity, a very useful form of energy. The photovoltaic principle has been known for over 100 years, but only since the discovery of semiconductors in the 1950's have solar cells been a practical means of producing electricity. Silicon, one of the most abundant minerals on Earth, is the principal semiconductor material used in cells to date. Since the principles are the same for all materials, this discussion will be limited to the construction and operation of silicon solar cells.

Alexander Becquerel discovered, in 1839, that the illumination of an electrolytic cell caused a change in the electromotive force of the cell. In 1873, Willoughby Smith observed a change in the resistance of selenium when exposed to light. By 1900, Philip Lenard had proved that electrons were ejected from the surface of a metal under radiation, and in 1902, he showed that the maximum kinetic energy of the electrons was proportional to the frequency of the incident radiation. Three years later, Albert Einstein proposed the theory that the photoelectric effect was the result of photons colliding with electrons. The kinetic energy of the resulting photoelectron, according to Einstein's equation, was equal to the difference between the energy absorbed by the electron and the work required to escape the forces binding it to the atom. Einstein's theory, for which he won the Nobel Prize in physics, was verified by 1916, largely through the work of Robert Millikan.

Meanwhile, in 1914, the photovoltaic effect was connected by Goldman and Brodsky with the existence of a barrier layer. But it was not until 1941 that the first single crystal silicon photovoltaic device was created with a "grown p-n junction" barrier. The device was impractical, however, and it was another

12 years before the impurity diffusion method of p-n junction formation produced a practical cell. After that, things began to move rapidly. In 1954, a solar array was placed on a telephone pole in Georgia by Bell Telephone researchers to test the application of the device for converting terrestrial solar energy. Two years later, two semiconductor firms, Hoffman (now Applied Solar Energy Corporation) and International Rectifier, opened production lines for silicon solar cells, but the terrestrial market was not yet ready for the device.

In 1957, the beginning of the space age introduced a significant new market for photovoltaic devices. The first spacecraft were powered with chemical batteries, but in 1958, Vanguard I was launched with a small solar array to power its backup transmitter. By 1960, virtually all spacecraft with a mission duration of more than a few weeks were equipped with solar arrays.

The spacecraft industry, with an annual demand of about 50 kilowatts, was the major market for solar cells until about 1973 when the Arab oil embargo, high energy prices, and lower cell prices combined to open up the terrestrial market for solar cells. Cell prices are still too high to be competitive with many conventional electricity sources, but the Department of Energy has initiated a research and development program designed to bring cell prices down to $0.50/watt by 1988. At that time, solar cells will be competitive with conventional electric power sources and a market of up to 500 billion watts will be available.

In compliance with the NASA's publication policy, the original units of measure have been converted to the equivalent value in the Systēme International d'Unites (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

SILICON SOLAR CELLS FOR TERRESTRIAL APPLICATIONS: TECHNOLOGY AND POLICY ISSUES

Photovoltaic Principles

The outermost electron orbit of a silicon atom contains four valence electrons. When a silicon crystal is formed, each atom is surrounded by and bound to four equidistant neighboring atoms. Each of the valence electrons is shared with a neighboring atom in a covalent bond. At absolute zero, the valence electrons are inexorably bound, and no current can flow. For any temperature above absolute zero, there is enough thermal energy to free some of the electrons. When an electron leaves the valence band, a hole is created which can be filled by an electron from a neighboring atom, creating a hole in another location. The motion of valence electrons is the basic mechanism for electrical conduction (ref. 2).

If photons of sufficient energy (approximately 1.1 electronvolts in silicon) strike a crystal, free electrons and holes are created. If the crystal is left to itself, the electrons will "fall" back into the holes, releasing the original energy in the form of heat. In order to prevent this recombination of the charge carriers, a solar cell is equipped with an intrinsic voltage barrier called a junction which separates the holes and electrons, forcing the electrons to travel through an external circuit and perform useful work before recombining with the holes.

Because solar radiation is diffuse, and the cost of a PV system is directly related to the size of the array, the efficiency of the PV device is an important consideration. Conversion efficiency is defined as the ratio of electrical energy produced to the amount of solar energy available. In theory, the maximum efficiency for a silicon cell is about 22 percent, but the best silicon cells produced today are only about 15 percent efficient. About 73 percent of the energy in sunlight is lost due to factors intrinsic to the cell itself, and another 7 to 12 percent is lost due to fabrication techniques. With improved fabrication techniques, the latter loss may be reduced to about 5 percent (ref. 2). A summary of efficiency losses is shown in figure 1.

Since the present costs of silicon cells are too high to allow the penetration of major markets, a number of research efforts are underway to reduce the costs of PV. One approach is to reduce the required amount and quality of silicon by utilizing thin films and polycrystalline or amorphous (lacking a crystalline structure) silicon materials. Polycrystalline and amorphous materials are cheaper to produce than the traditional single crystal silicon, but the conversion efficiencies of these materials are significantly lower at the present time. Laboratory research may improve the actual efficiency of thin-film devices to 14 to 15 percent, and research in this area is proceeding rapidly, but commercial availability is not expected until the 1990's (ref. 4).

Another area where costs can be substantially reduced is in the manufacturing process. The most common process for growing silicon crystals is the Czochralski method. A rotating seed crystal is dipped into a counterrotating crucible of molten silicon and then slowly withdrawn. The result is a cylindrical crystal 7.6 or 10 centimeters (3 or 4 inches) in diameter and several feet long. The cylinder is then sawed into round wafers for further processing. About 20 percent of the molten silicon remains in the bottom of the crucible and is wasted. The sawing also wastes about 60 percent of the silicon. An estimated 40 percent of the available surface of the resulting array is unused because of the shape of the round wafers. A number of techniques are being developed to reduce this waste, but the best approach may be to eliminate ingots entirely and grow crystalline sheets from molten silicon. Efficiencies as high as 14 percent have been achieved with cells fabricated from silicon sheets. The Czochralski method and three alternative processes are compared in figure 2.

If a suitable quantity of boron is added to the molten silicon, the result is a p-type wafer. Exposing one surface of the wafer to phosphorus at a high temperature creates a thin layer of n-type silicon. Then the electrical contacts are attached to the front and back of the wafer, an antireflection coating is applied, and the entire cell is encapsulated in a protective material. Because of the small volume of production and the complexity involved, most of these steps are performed manually. The equipment exists to automate much of the production process, but manufacturers are hesitant to invest in capital equipment because the technology is developing so rapidly that they could be stuck with economically obsolete equipment before they recoup their investments (ref. 5).

Current R&D Projects

The Department of Energy has established a program to accelerate the commercialization of photovoltaics with a combination of market-pull and technology-push actions. Figure 3 shows the developments that are necessary to achieve commercial readiness. The purpose of the PV program is summarized in the following excerpt from the multiyear program plan (ref. 6).

> The objective of the Department of Energy (DOE) Photovoltaic Program is to reduce system costs to a competitive level in both distributed and centralized grid connected applications. Equally important, the Program will also resolve the technical, institutional, legal, environmental, and social issues involved in fostering widespread adaptation of photovoltaic energy systems.... The Photovoltaic Program strategy is to achieve major system cost reductions to meet the market requirement for a competitive life-cycle cost of electricity through the aggressive pursuit of Advanced Research and Technology Development. In addition, real world testing will be pursued to support the accelerated transfer of the technology to the market place.

In order to meet these goals, the Photovoltaic Program has been divided into six subprograms, which are briefly described in figure 4(a). Figure 4(b) illustrates the relationship between the subprograms and the development phases.

The overall management of the program is the responsibility of DOE Headquarters and falls under the Assistant Secretary for Conservation and Solar Applications. Day-to-day management of the program activities is delegated to field organizations as much as possible (ref. 6).

The lead center for Technology Development and Tests and Applications is the Jet Propulsion Laboratory (JPL) in Pasadena, California. JPL manages the Low-cost Solar Array (LSA) Project for the DOE Photovoltaics Branch under a contract with the National Aeronautics and Space Administration (NASA). Field organizations that participate in the LSA Project include the Aerospace Corporation, MIT's Energy Laboratory, and Lincoln Laboratory, NASA's Lewis Research Center, the Sandia Laboratories, and the Solar Energy Research Institute (SERI).

The SERI in Golden, Colorado, is also the lead center for Advanced Research and Development. The main thrust of this effort is to develop advanced PV materials, concepts, and devices such as thin films and electrochemical cells. Most of the research at SERI is conducted through externally contracted research, but a small portion is conducted in-house by the Photovoltaics Research Branch (ref. 7). SERI also operates the Solar Energy Information Data Bank, which collects and distributes information about solar energy technologies.

A third branch of the program, which has not been officially established yet, is the commercialization subprogram. The objectives of this tentative division will be to facilitate technology transfer, coordinate Federal procurement, identify and develop commercial markets, and accelerate the growth of a competitive PV industry (ref. 8). Although photovoltaics will not reach the stage of commercial readiness until around 1988, it is appropriate to develop the strategies and policy options now. These functions are currently being performed by the Planning, Assessment, and Integration subprogram.

Political Environment

The National Photovoltaic Program was established by the Energy Research and Development Administration (ERDA) as a result of the Federal Non-Nuclear Energy Research and Development Act of 1974 (Public Law 93-577), which states that Federal involvement in a particular research and development undertaking is appropriate when "the urgency of public need for the potential results of the research, development, or demonstration effort is high, and it is unlikely that similar results would be achieved in a timely manner in the absence of Federal assistance" (ref. 9).

The program was specifically mandated in 1978 when Congress passed the Solar Photovoltaic Energy Research Development and Demonstration Act of 1978 (Public Law 95-590, hereafter referred to as the RD&D Act). The purpose of the RD&D Act is to

> Establish during the next decade an aggressive research, development, and demonstration program involving solar photovoltaic energy systems and in the long term, to have as an objective the production of electricity from photovoltaic systems cost competitive with utility-generated electricity from conventional sources (ref. 10).

Furthermore, the RD&D Act establishes the following objectives for the development effort:

> Double the production of PV systems each year to approximately two million peak kilowatts by Fiscal Year 1988
>
> Reduce the average costs of installed PV systems to $1 per peak watt by Fiscal Year 1988
>
> Stimulate the purchase by private buyers of at least 90 percent of all PV systems produced in the United States during Fiscal Year 1988

Funding for the RD&D Act will amount to $1.5 billion over 10 years, with private industry expected to invest an additional $2.5 million (ref. 11).

The legislative history of the RD&D Act goes back to September 1977 when the House Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration held oversight hearings to review the progress of DOE's PV research efforts. After the hearing, subcommittee staffer Henry Eaton held extensive meetings with industry representatives to determine the potential for solar cells. As a result, the RD&D bill was introduced in February 1978 by Representatives Mike McCormack, Barry Goldwater, Jr., and Olin Teague, of the House Committee on Science and Technology. Co-author Goldwater said, "I firmly believe that we are going to see significant cost reductions in the use of photovoltaics, and that this bill will hasten and increase the likelihood of that occurrence."

One of the cornerstones of the original RD&D bill was a provision authorizing the Government to make substantial purchases of PV cells in order to stimulate low cost, mass production (ref. 12). The bill allowed these purchases to decrease over time because, as Gordon Woodcock of Boeing said, "the Government stimulation....should have the capability and provision to fade away softly...to allow the commercial market to take over" (ref. 11). However, when President Carter signed the bill, on November 4, 1978, he refused to authorize the purchase saying that

> It is still too early to concentrate on commercialization of photovoltaics. Photovoltaic systems hold great promise; but in the short run, we must emphasize research and development, including fundamental work on the physical properties of these systems, so that this promise can be realized (ref. 13).

Apparently the President was forced to give up that position on November 9, 1978, when he approved the National Energy Conservation Policy Act, a package of bills that included the Federal Photovoltaic Utilization Act (Public Law 95-619, Title II, Part 4), which establishes a $98 million "photovoltaic energy commercialization program for the accelerated procurement and installation of photovoltaic solar electric systems for electric production in Federal facilities" (ref. 14). The history of the Federal Photovoltaic Utilization Program (FPUP) is long, but it offers useful insights into the political environment surrounding PV so the story will be repeated here.

The origin of solar energy as a national policy objective can be traced back to a little-noticed hearing of the Senate Select Committee on Small Business, chaired by Senator Gaylord Nelson of Wisconsin, on the opportunities for small business in solar energy research. The hearings were held on May 13 and 24, 1975. During the testimony, Donald B. Craven, Acting Assistant Administrator, Federal Energy Administration (FEA), said that the FEA was developing programs to "facilitate the accelerated utilization and widespread commercial application of proven solar energy technologies." But, at that time, only about $200 000 and two full-time staff members were allocated to the FEA's Solar Energy Branch. Craven's testimony led to the introduction of legislation, by Representative Richard Ottinger of New York, that would require the FEA to establish detailed action plans for the commercialization of solar energy. The Ottinger bill failed, but Senators Gary Hart and Charles Percy managed to attach a similar provision to the Energy Conservation and Production Act of August 1976. The FEA immediately established a Task Force on

Solar Energy Commercialization and, within 6 months, the Task Force produced several reports that showed how solar technologies could be commercialized. One of these reports was the "Preliminary Analysis of an Option for the Federal Photovoltaic Utilization Program" (ref. 15). The traditional approach for such a report is to examine the technology itself and determine the research and development breakthroughs needed to produce a marketable device. Instead, the FEA Task Force assumed that a viable solar cell existed and then went on to examine the market for the device.

They found that, although solar cells could provide a silent, environmentally safe source of electricity, the demand for cells was low because the initial purchase price was too high to be competitive and the price was high because the demand was too low to support an efficient scale of production. Government intervention in the form of a large purchase was therefore needed to encourage economies of scale. The study concluded that a $440-million purchase spread over 5 years would bring the price of cells down to $0.50 a peak watt ($0.50/Wp), low enough to begin competing with conventional residential power systems. In addition, the plan would save the Government $500 million to $1.5 billion in direct fuel and maintenance costs over an expected 20-year lifespan. Once the penetration of commercial power grids had begun, it was estimated that the potential market for solar cells would be 500 billion watts. Although the White House opposed the purchase plan, it was included in the National Energy Conservation Policy Act. However, the funding was reduced from $440 million to $98 million. At the lower funding level, it is expected to take 8 years, rather than 5, to reach the $0.50/Wp goal.

Another report that has influenced the political climate is the American Physical Society (APS) Study on Solar Photovoltaic Energy Conversion. The APS study was begun in 1977 when the White House Office of Science and Technology Policy asked Herman Feshbach, Chairman of the MIT Physics Department, to form a study group to examine the potential for photovoltaics as a significant source of electrical energy generation and to outline an optimal program for research and development. A panel of distinguished scientists, chaired by Harvard physicist Henry Ehrenreich, began the first phase of the study in November 1977. The panel looked only at terrestrial applications of PV and, in particular, examined the economic feasibility of PV for centralized utility applications. In February 1979, the study group published its findings in a document titled "The Principal Conclusions of the American Physical Society Study Group on Solar Photovoltaic Energy Conversion" (ref. 16). Some of the major conclusions and recommendations are summarized below:

> There are no fundamental problems that will prevent PV from becoming a significant source of electricity in the United States.
>
> Significant advances in solar cell technology will have to be made before PV will be competitive with coal and nuclear powerplants.
>
> It is unlikely that PV will contribute more than 1 percent of the U.S. electric production by the year 2000.
>
> It is premature for the Government to stimulate a large-scale, low-cost solar cell industry.

The Government should encourage a diversity of approaches to research and development efforts.

High-efficiency silicon cells combined with low-cost plastic concentrators could just compete with coal at the high end of projected coal-generated electricity prices (refs. 17 and 18).

While it is probably too early to assess the APS study's effect on policy, it has been pointed out that President Carter's FY 1980 budget proposal asked for increased spending on PV research and development but requested reduced funding in the area of accelerated industrialization. Of course, the study was immediately attacked by the proponents of solar energy. One organization, the Solar Lobby, said the report was "distorted" and criticized the APS for releasing the report at a time of intense Federal budget activity (ref. 18). Barry Commoner points out that

> In a list of 175 references, the study fails to include the FEA commercialization study. Indeed, the study makes no comparisons of the conventional electrical system with decentralized photovoltaic designs. By choosing to saddle the photovoltaic approach with precisely the wrong sort of design, it becomes relatively easy to demonstrate that "It is unlikely that photovoltaics will contribute more than 1% of the U.S. electrical energy produced near the end of the century" (ref. 12, pp. 44-45).

To which Ehrenreich replies,

> The existing electric generation system and the reluctance of homeowners to incur high capital expenses, particularly in a period of rapidly rising house prices, favor the use of photovoltaic systems in central power generation, but local conditions may exist that make purely residential deployment advantageous (ref. 3).

The debate over centralization is an important one which may take years to resolve.

Legal Environment

There are two other legal issues that will have an impact on the commercialization of photovoltaic cells as well as solar energy in general. The first issue is the problem of three-dimensional zoning or "Sun rights." The second issue is the legal aspects of industrial property (i.e., patents, trade secrets or know-how, and licensing).

A PV array produces significant amounts of energy only when exposed to direct sunlight. If the array is shaded by a tree or a neighboring building, it may not produce enough electricity to recover the initial investment. Zoning regulations need to be rewritten to prevent shading or at least to permit only a small amount of shading. Since zoning regulations are usually written by local authorities, it has been suggested that the Federal or state governments should establish zoning guidelines to avoid a confusing disparity of regulations (ref. 19).

The legal questions regarding patents and licensing of industrial property are too complex to be fairly treated here, but one issue does stand out. "A patent is a device to prevent the diffusion of new methods before the original investor has recovered profit adequate to induce the requisite investment" (ref. 20). Thus, the existence of patents may tend to slow the diffusion of PV technology. However, in an unpublished study for JPL, Bill Gates suggests that this effect will be mitigated by three factors:

1. Government-funded technology developments are considered public property and are available on a nonexclusive basis.

2. In competitive industries characterized by rapid technological change, firms tend to establish liberal licensing policies.

3. The PV industry is similar to the semiconductor industry where the mobility of scientists and engineers tends to reduce the impact of patents and proprietary knowledge.

Gates concludes that "limitations to the widespread adaptation of new technology due to barriers in the flow of knowledge between inventors and eventual users are not expected in the photovoltaic industry."

Project Selection

Texas Instruments (TI) is one of the major companies that has become involved in PV research and development. Using $10 million of corporate money, TI has come up with a new silicon solar cell that may solve the problem of simultaneous conversion and storage of solar energy. A review of TI's management system provides some useful insights into the management of R&D projects with long-term payoffs.

The TI system is similar to "management by objectives" (MBO), but TI managers call it "objectives, strategies, and tactics" (OST). The principal elements of the system are

The Objectives - Establish long-range goals, 10 years with several intermediate points, for each of the major businesses.

The Strategies - Focus on an intermediate set of the goals relating to a product line and define the course or direction to be pursued to attain these goals.

The Tactics - Fund action programs oriented to realization of short-term goals (ref. 21).

The Corporate Development Committee, made up of the President, Executive Vice-President, Group Vice-Presidents, and several staff members, is the principal decisionmaking body for initiating new ventures and strategic planning.

One of the tools that can be used to select projects is the decision tree. Figure 5 is a decision tree developed by TRW for a diversified solar cell company in a market environment where a Government incentive program has established a fixed, high price schedule. The diagram shows net present values for several options, identifies uncertain events, and shows where further information is needed. Decision trees could also be used by Government planners to determine the optimum price schedule to encourage development of the industry (ref. 22).

In addition to the standard decisionmaking techniques, there are a couple of decision models that have been developed specifically for the solar cell industry. One such model is the Photovoltaic Energy Conversion Analysis (PECAN) simulation model developed by IBM. PECAN "is a deterministic simulator, which translates present and future manufacturing technology into economic and financial terms, using the production unit concept. It guides solar cell development in three areas: Technical decision making; strategic planning; and the formulation of alternative options." It is an interactive system that allows the decisionmaker to evaluate the impact of different production-unit parameters and processes. In addition, PECAN can be used by Government policymakers to determine the optimal processes for meeting the DOE price goals (ref. 23).

Another software system that was developed for JPL by Theodore Barry and Associates, Inc., is the Solar Array Manufacturing Industry Costing Standards (SAMICS). Now known as Standard Assembly Manufacturing Industry System (SAMIS), SAMICS was developed to provide a consistent, reliable method of comparing manufacturing processes developed by dozens of LSA project contractors. The SAMICS method combines standard direct and indirect costs with a model similar to PECAN to develop annual cost and price data. With both PECAN and SAMICS, the detailed process descriptions are provided by the user (ref. 24).

Benefits and Impacts

What are the expected benefits and costs of PV technology? Since the issues involved in an impact assessment of PV are numerous and very broad, this discussion will be limited to a few of the more important issues. These issues can be divided into three general categories: micro- and macroeconomic considerations; environmental, health, and safety issues; and social and institutional impacts.

Microeconomic issues revolve mainly around the question of PV energy costs. While the variable costs of generating electricity from solar cells are negligible, the fixed costs (i.e., the initial investment) are quite substantial. The usual method of comparing PV costs to alternate sources of energy involves calculating a break-even cost for the PV system. This is done by calculating the net present value of the energy displaced by the PV system and comparing that to the capital cost of the system. The capital cost of a PV system is made up of the cost of the cell array itself plus the balance of system costs, including power conditioning, storage capacity, and backup capacity. It should be noted that, since solar arrays are inherently modular, small additions to capacity can be made over a period of years. This reduces the risk and high initial cost of investing in a coal or nuclear plant that would not provide any power for several years.

The APS study group has estimated that solar cell costs in the range of 10-40¢/Wp in 1975 dollars are necessary for photovoltaics to be competitive with coal-generated electricity. Current cell prices are about $6/Wp so a reduction by an order of magnitude is required (ref. 3). In the past, solar cell costs have exhibited learning curve behavior with prices dropping about 10 percent (90-percent learning) each time cumulative production experience doubles. The RD&D program is expected to put solar cells on a 70-percent learning curve while the balance of system costs remain at 90-percent learning. The DOE price goals for solar cells are 70¢/Wp by 1988 and 50¢/Wp by 1990 (see fig. 6), but the APS study group believes these goals cannot be met without significant technological breakthroughs.

The other economic question that needs to be answered is "What are the macroeconomic benefits of a widespread PV technology?" Because of the uncertainties involved in estimating future energy prices and diffusion rates of solar technologies, it is impossible to quantify the macroeconomic impacts of PV energy. It is possible to say qualitatively that photovoltaics will increase both GNP and employment if it is assumed that PV systems will be net additions to the nation's power grid (refs. 25 and 26).

Government decisions regarding the level of RD&D expenditures and other subsidies must be based on the broader interests of society. Photovoltaics are a promising part of the long-term solution to the nation's energy problems. One way of measuring the social value of photovoltaic energy is to estimate its value as an insurance policy against foreign curtailment of fuel for electricity. A Spectrolab study concludes that "the nation should be willing to pay between $100.00 to $300.00/kW more for PEPS (photovoltaic energy) than for a conventional power plant that uses imported energy sources" (ref. 26). In addition, the social value of photovoltaic energy is significantly enhanced when the following impacts are taken into consideration:

PV can reduce the nation's dependence on foreign energy sources, thereby influencing the nation's foreign policy and international relationships.

PV technology can be exported to third world countries with positive effects on the nation's balance of trade.

Decentralized applications will help reduce energy losses due to long transmission lines.

The scientific knowledge gained from PV research may be transferrable to other activities.

Decentralized utilization will reduce the effect of sabotage or disasters such as Three Mile Island nuclear powerplant breakdown.

Many military applications can use the logistical advantage of not requiring a fuel supply (refs. 12, 19, and 26).

Photovoltaics have the added benefit of being virtually pollution free compared to coal, the burning of which pours carbon monoxide into the atmosphere and may eventually cause a "greenhouse effect," and nuclear energy, the production of which entails the disposal of radioactive materials, a problem that has not been solved after 40 years of research. On the other hand, silicon solar cells do present some hazards to the workers making cells and to the potential users. The most important hazards are inhalation of silicon dust, which is an established cause of respiratory disease, and offgassing of toxic products in a fire.

The final area of analysis concerns the institutional impacts of widespread implementation of PV systems. Because of the intermittent nature of solar radiation, decentralized systems may require backup power from a commercial utility. The availability of backup power and the cost of providing backup power on standby will significantly affect the viability of PV power. Another area of concern is the legislation requiring utilities to buy back excess power generated by solar customers. The issue is not whether utilities should be required to purchase excess power but at what price. "Determination of appropriate rates to be paid to excess power producers would require careful consideration of utilities' variable costs and the extent to which prices should reflect incentives to use photovoltaics" (ref. 27).

THE LONG-RANGE MARKET FOR PHOTOVOLTAICS

Purpose of the Market Study

Solar cells must compete with alternative sources of energy for research and development funds as well as for consumer dollars. Figure 3 showed that a sustained market demand was necessary for a technology to reach commercial readiness. Therefore, it is essential for planners in government and industry to have some knowledge of what the demand for photovoltaics will be. This section will examine the potential demand for solar cells using three different forecasting techniques: time trend, judgmental, and econometric.

Time Trend Analysis

A trend extrapolation model uses a curve, fitted to historical data, to predict the future. The problem with this method is that the forecast is only as good as the historical data and, so far, no effort has been made to collect "statistically meaningful" data on solar cells. The data shown in figure 7 were taken from Martin Wolf (ref. 28) and supplemented for the last few years with information the author received from conversations with DOE officials. Wolf notes that the estimated figures may vary as much as ±33 percent from the actual sales. The figures Wolf gave were actually for production, but since the demand for solar cells exceeds the production capacity, it was assumed that production equals sales.

Figure 8 shows the results of an exponential curve fitted to the historical data and projected to the year 2000.

Since the structure of the market changed dramatically in 1973, only the last few years of data were used to calibrate the model. Figure 8 shows the time trend forecast using data from 1972 to 1978 and from 1973 to 1978. The resulting forecasts for the year 2000 were 57 and 340 gigawatts, respectively.

An exponential forecast using so few data points is highly dependent on the first and last values, as is demonstrated by the order of magnitude difference in the two projections. Therefore, the forecast using only six points is very suspicious despite an R^2 of 98 percent. The projected annual sales of 340 GWp is more than double the estimated annual additions to electric generating capacity for the year 2000. This means that photovoltaics would have to replace existing capacity in addition to displacing 100 percent of incremental capacity within 20 years. Technological and institutional barriers will make this virtually impossible, so the high forecast should be rejected a posteriori.

Judgmental Model

An extensive review of published literature revealed a number of medium-range and long-range forecasts of the market for solar cells (refs. 19 and 29 to 32). Most of the forecasts used market research techniques to examine individual product markets and then added the individual markets to produce aggregated forecasts. Six predictions from four different reports were chosen to be incorporated in a judgmental model. The reasoning behind a judgmental approach was that each forecast represented the opinion of an expert forecaster based on a variety of assumptions about the market. Table 1 lists the forecast sources, time frames, and methods used. Figure 9 shows the data from individual forecasts.

The line shown in figure 10 was fitted to the data using a simple two-point method. The diagram shows a negative bias in the residuals up to 1982, followed by a positive bias up to the year 2000. To correct this, a two-part curve was constructed (fig. 11).

The use of a two-part curve can be economically justified if one notes from table 2 that the near-term and long-term markets are substantially different. The lesser slope after 1985 indicates saturation of near-term markets and a slower penetration of the long-term market. The latter assumption may be valid based on the characteristics of long-term users and the relatively high initial cost of large-scale PV systems.

Figure 12 compares the single and two-part curves with the historical data. Clearly, the two-part method gives a better projection of the slope of the historical data. If the economic assumptions regarding the turning point are valid, the two-part method gives a superior forecast.

Econometric Model

The procedure for estimating PV demand on the basis of economic factors is shown in figure 13. First, forecasts of annual incremental installed electric generating capacity were obtained from existing sources. The next step was to calculate the portion of incremental capacity that could be taken over by solar cells. It was assumed that 20 percent of the incremental capacity would be available to solar cells. This is defined to be the maximum total market available to solar cells. The actual market share for solar cells at any given time is some portion of the maximum available market. Market share, in percentage terms, was projected using an S-curve or logistics curve.

The market penetration model used here is a version of the Fischer-Pry model (ref. 33). The substitution curve was calibrated using the historical data from 1972 to 1978 and the DOE market goals for 1988. Thus, the forecast is conditional on the Government's RD&D program. Multiplying the percentage market share by the maximum available market gives the forecast shown in figure 14. Three different curves were produced using three different forecasts of incremental capacity. For curve A, incremental capacity was estimated by extrapolating the most recent data from the Statistical Abstract at 6.5 percent annual growth, the average growth for the last 20 years. Curve B was calculated the same way but with a 5.4-percent annual growth, the average for the last 6 years. Finally, curve C was developed from a forecast of incremental capacity by the Oak Ridge National Laboratory (ref. 34).

The Oak Ridge forecast, done in 1976, tends to underestimate actual data, so curve C is a conservative estimate. Curve A was estimated with an average growth rate of incremental capacity over the last 20 years but actual growth rates have declined since 1973, so curve A is probably optimistic. Curve B is the most realistic of the three because it assumes an average growth rate taken from the post-oil-embargo years.

Once again, the projections show a slowdown in the exponential growth of demand occurring around 1990. This is due to saturation of the market. Since the econometric forecast is conditional on meeting the DOE price and production goals, the inflection point could be moved up or delayed by changes in the RD&D program.

Final Analysis

The three modeling techniques described - trend extrapolation, judgmental, and econometric - have resulted in widely varying forecasts, from a low of 0.76 GWp to a high of 340 GWp in the year 2000. Any one of the models can be justified using different assumptions, but even with the best forecast from each method, the spread is still more than two orders of magnitude. In order to refine the forecast further, an eclectic model was developed.

One forecast was selected from each method on the basis of the author's judgment. Table 3 summarizes the various forecasts, and figure 15 plots the three that were chosen for final analysis. A weighted average of these three forecasts was calculated using 50 percent of the econometric results plus 30 percent of the judgmental results plus 20 percent of the time trend results for an amalgamated prediction. The final results are plotted in figure 16 along with estimated dollar sales. The dashed lines indicate a range of a factor of 3. The range indicates possible variations due to changes in the RD&D program or changes in the demand for electricity.

The demand for solar cells is a derived demand, not a final demand, because it is the need for electricity that motivates the production of solar cells. Anything that affects the demand for electricity will have a dramatic impact on the sale of photovoltaic arrays. Widespread use of electric cars is one example of a structural change that would significantly change the outlook for solar cells. In addition to providing utility power, photovoltaics might be incorporated into the automobiles themselves or even into the roads as a means of supplementing the electric car's batteries. This is only one of a number of potential scenarios that would alter the model of demand presented here, since only the most probable scenario was considered.

CONCLUDING REMARKS

President Carter has said, "Photovoltaics...hold significant promise as a solar technology for the future....There is no question about our technical ability to use photovoltaics to generate electricity....The main issue now is how to reduce the costs of photovoltaics for grid-related applications...over the next five to ten years" (ref. 35).

In reviewing the prospects for energy in general and photovoltaics in particular, four policy issues become apparent. First, the need to shift the nation's dependence on expendable fossil fuels to renewable sources of energy is almost universally accepted. This transition will require an unprecedented level of long-range planning and consideration of indirect impacts by the nation's decisionmakers. Finally, the road to a renewable energy future is not a clear-cut choice of technological options. The future will require a diversity of approaches, and a variety of options are needed to get there.

In principle, the future of energy and resources can be viewed in three stages. The first stage is a continuation of our present patterns of consumption of nonrenewable resources. During the second stage, people will begin to turn away from widespread use of limited resources. Finally, in the third stage - the "Age of Substitutability" - society will be based on resources that are virtually inexhaustible (ref. 36). The transition will be caused mainly by economic forces. As the price of scarce resources, such as oil, goes up, it creates an incentive to develop other sources. The problem is that substitutes usually require better technology than traditional methods. It takes time to develop new technology; therefore, the solution of a shortage problem must begin years before the actual shortage occurs.

Unfortunately, the kind of long-range planning that is needed to solve the nation's energy problem is a rarity in a democratic society. What is needed is a plan that determines objectives and then outlines the policy changes that will achieve them. This "teleological" approach is not uncommon in the business world where "management by objectives" is widely accepted.

Long-range planning does not imply exclusivity. While Amory Lovins argues that we are at a crossroads, faced with a mutually exclusive choice between a "hard" technology and a "soft" technology, the choice is not that simple. Even the so-called "soft" solar technologies will require large-scale industries and high technology to make them cost-competitive. There is no guarantee that a specific technology, like photovoltaics, will be available at a reasonable price when it is needed. Therefore, the government must pursue - and encourage private industry to follow - a diverse strategy until the time comes when the final decisions must be made.

The recently released report of the Committee on Nuclear and Alternative Energy Sources (CONAES) calls for an extensive risk assessment that goes beyond the usual cost-benefit analysis to analyze the "factors that determine public perceptions of the health and environment risks of energy systems and their acceptance by different subgroups within the public" (ref. 37). This is the beginning of a more comprehensive viability assessment. Viable is defined by Webster's as "capable of existence and development as an independent unit." Such a viability assessment would examine the political and social feasibility of an energy project as well as the economic and technical aspects. This is important in an era where public opposition has virtually halted nuclear powerplants, delayed the Trans-Alaskan Pipeline, and prevented offshore drilling in some regions. Viability assessment could prevent the wasteful expenditure of development money on projects that have little chance of succeeding.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, January 23, 1981
073-36-00-00-72

REFERENCES

1. Chambers, Bruce: The Photovoltaic Generation of Electricity. Scientific American, vol. 235, no. 4, Oct. 1976, pp. 34-43.

2. Fan, John C. C.: Solar Cells: Plugging Into the Sun. Technology Rev., vol. 80, no. 8, Aug./Sept. 1978, pp. 14-36.

3. Ehrenreich, Henry; and Martin, John H.: Solar Photovoltaic Energy. Physics Today, vol. 32, no. 9, Sept. 1979, pp. 25-32.

4. Moore, Robert M.: Cost Predictions for Photovoltaic Energy Sources. Solar Energy, vol. 18, 1976, pp. 225-234.

5. Sherman-Willis, Mary: Photovoltaic Cost Blitz Spawn New Silicon Processes. High Technology, Feb. 1980, pp. 78-85.

6. National Photovoltaic Program, Multi-Year Program Plan (draft only). U.S. Department of Energy (Washington, D.C.), June 6, 1979.

7. Feucht, Donald L.: Advanced Research and Development Status. Proceedings of the U.S. DOE Photovoltaic Technology Development and Applications Program Review, 1978, pp. 2-92 to 2-102.

8. Jet Propulsion Laboratory: Photovoltaics Program, Subprograms, and Applications. Paper presented at 14th IEEE PV Specialists Conference (San Diego, Calif.), Jan. 7-10, 1980.

9. Federal Non-Nuclear Energy Research and Development Act of 1974. Public Law 93-577, 93rd Congress, Dec. 31, 1974.

10. Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978. Public Law 95-590, 95th Congress, Nov. 4, 1978.

11. Solar Photovoltaic Research, Development, and Demonstration Act of 1978. Hearings Before the Subcommittee on Advanced Energy Technologies and Energy Conservation Research, Development, and Demonstration, 95th Congress, Apr. 11, 12, May 17, 18, 1978, p. 2.

12. Commoner, Barry: The Politics of Energy. Alfred A. Knopf, 1979, pp. 33-38.

13. Carter, Jimmy: Statement by the President on signing H.R. 12874, November 4, 1978. Office of the White House Press Secretary (Washington, D.C.), Nov. 6, 1978.

14. Federal Photovoltaic Utilization Act, included in the National Energy Conservation Policy Act. Public Law 95-619, 95th Congress, Nov. 9, 1978.

15. Merrill, A.; et al. (BDM Corp.): Preliminary Analysis of an Option for the Federal Photovoltaics Utilization Program. U.S. Department of Energy (Washington, D.C.), 1977, pp. 1-15.

16. Principal Conclusions of the American Physical Society Study Group on Solar Photovoltaic Energy Conversion. The American Physical Society, Feb. 1979.

17. Photovoltaic Study Findings. Physics Today, vol. 32, no. 3, Mar. 1979, p. 87.

18. Robinson, Arthur L.: American Physical Society Panel Gives a Long-Term Yes to Electricity From the Sun. Science, vol. 203, no. 4381, Feb. 16, 1979, p. 629.

19. Westinghouse Electric Corporation: Conceptual Design and Systems Analysis of Photovoltaic Systems. U.S. Energy Research and Development Administration (Washington, D.C.), 1977.

20. Robinson, Joan: The Accumulation of Capital. McMillan Press, June 1956, p. 87.

21. Phipps, Charles: Management of Innovation: The OST System. Paper presented at the Business Week Strategic Planning Conference (New York), Oct. 5, 1978.

22. TRW, Inc.: Analysis of Investment Alternatives to Stimulate Development of Technology Transfer for Energy Technologies: Solar Photovoltaics - A Case Study. U.S. Department of Energy (Washington, D.C.), 1978, pp. 3-1 to 3-7.

23. Kran, A.: Contribution to Solving the Energy Crisis: Simulating the Prospects for Low Cost Energy Through Silicon Solar Cells. Proceedings, 11th Annual Simulation Symposium, 1978, pp. 1-19.

24. Chamberlain, Robert G.: Product Pricing in the Solar Array Manufacturing Industry: An Executive Summary of SAMICS. Proceedings, 13th IEEE Photovoltaic Specialists Conference, 1978, pp. 904-907.

25. Domestic Policy Review of Solar Energy: A Response Memorandum to the President of the United States. Rep. TID-28834, U.S. Department of Energy (Washington, D.C.), Feb. 1979.

26. Spectrolab, Inc.: Photovoltaic Systems Concept Study. U.S. Energy Research and Development Administration (Washington, D.C.), 1977.

27. Environmental Development Plan: Photovoltaics. Rep. DOE/EDP-0031, U.S. Department of Energy (Washington, D.C.), 1979.

28. Wolf, Martin: The Near-Term Prospectives for Photovoltaic Solar Energy Conversion. Acta Electron., vol. 20, no. 2, 1977, pp. 205-215.

29. Intertechnology/Solar Corp.: Photovoltaic Power Systems Market Identification and Analysis. U.S. Department of Energy (Washington, D.C.), May 1979.

30. Rattin, E. J.: Overview of Photovoltaic Market Studies. U.S. Department of Energy (Washington, D.C.), May 1978.

31. General Electric Corp.: Conceptual Design and Systems Analysis of Photovoltaic Systems. U.S. Energy Research and Development Administration (Washington, D.C.), Apr. 1977.

32. BDM Corp.: Photovoltaic Power Systems Market Identification and Analysis, Vol. 2. U.S. Department of Energy (Washington, D.C.), Nov. 1978.

33. Fischer, J. C.; and Pry, R. H.: A Simple Substitution Model of Technological Change. Industrial Applications of Technological Forecasting, M. J. Cetron and C. A. Ralph, eds., Wiley-Interscience (New York), 1971.

34. Lane, J. A.: Consensus Forecast of U.S. Electricity Supply and Demand to the Year 2000. U.S. Energy Research and Development Administration (Washington, D.C.), May 1977.

35. Carter, Jimmy: Solar Energy, Message to the Congress. Weekly Compilation of Presidential Documents, June 20, 1979, pp. 1097-1107.

36. Goeller, H. E.; and Weinberg, A. M.: The Age of Substitutability or What Do We Do When the Mercury Runs Out? Science, vol. 191, no. 4227, Feb. 20, 1976, pp. 683-689.

37. Will the Political Arena Survive the Decision Process? Government Executive, Mar. 1980, pp. 17-20.

TABLE 1.- SUMMARY OF MARKET RESEARCH FORECASTS

Source	Method	Forecast period	Final annual demand, GWp
Near-term			
BDM Corp.	Market penetration substitution model	1977-86	0.048
BDM Corp.	Judgmental method	1977-86	.043
Intertechnology/ Solar Corp.	Market penetration substitution model	1980-85	.276
Mid-term			
General Electric Corp.	Regional competitive-cost analysis; residential market; new construction only	1990-2000	10
General Electric Corp.	Substitution model; new residential construction plus retrofit with 5-yr delay	1986-2000	.7
Westinghouse Electric Corp.	Judgmental method; residential, intermediate, and central station; new construction only	1985-2000	6

TABLE 2.- MARKETS FOR SOLAR CELLS

Past (1956-73)	Present (1974-84)	Future (1985-)
Spacecraft	Cathodic protection	Central power stations
Research	Remote repeaters	Intermediate stations
Warning devices	Navigation aids	Residential
	Telemetry	Shopping centers
	Federal buildings	DOD generators
	Consumer products	Village power
	Intrusion detection	Recreational vehicles
	Low-lift pumping	Industrial power
	Smoke detectors	Medium-lift pumping
	Weather stations	Outdoor lighting
	Drip irrigation	Call boxes
		Highway signs
		Railroad crossings

TABLE 3.- SUMMARY OF VARIOUS FORECASTS

Model	Description	Annual demand in 2000, GWp	Subjective validity
Trend extrapolation	Exponential; last 6 data points (fig. 8)	340	Low
Trend extrapolation	Exponential; last 7 data points (fig. 8)	[a]57.6	Medium
Judgmental	Log-linear (fig. 10)	7.8	Medium
Judgmental	Two-part log-linear (fig. 11)	[a]4.3	High
Judgmental	Second-degree log polynomial (not shown)	.76	Low
Econometric	High asymptote (fig. 14, line A)	29.1	Medium
Econometric	Medium asymptote (fig. 14, line B)	[a]19.4	High
Econometric	Low asymptote (fig. 14, line C)	9.8	Medium
Eclectic	Unweighted (not shown)	66.8	Low
Eclectic	Weighted (fig. 16)	22.5	High

[a]Used in weighted eclectic model, Figure 15

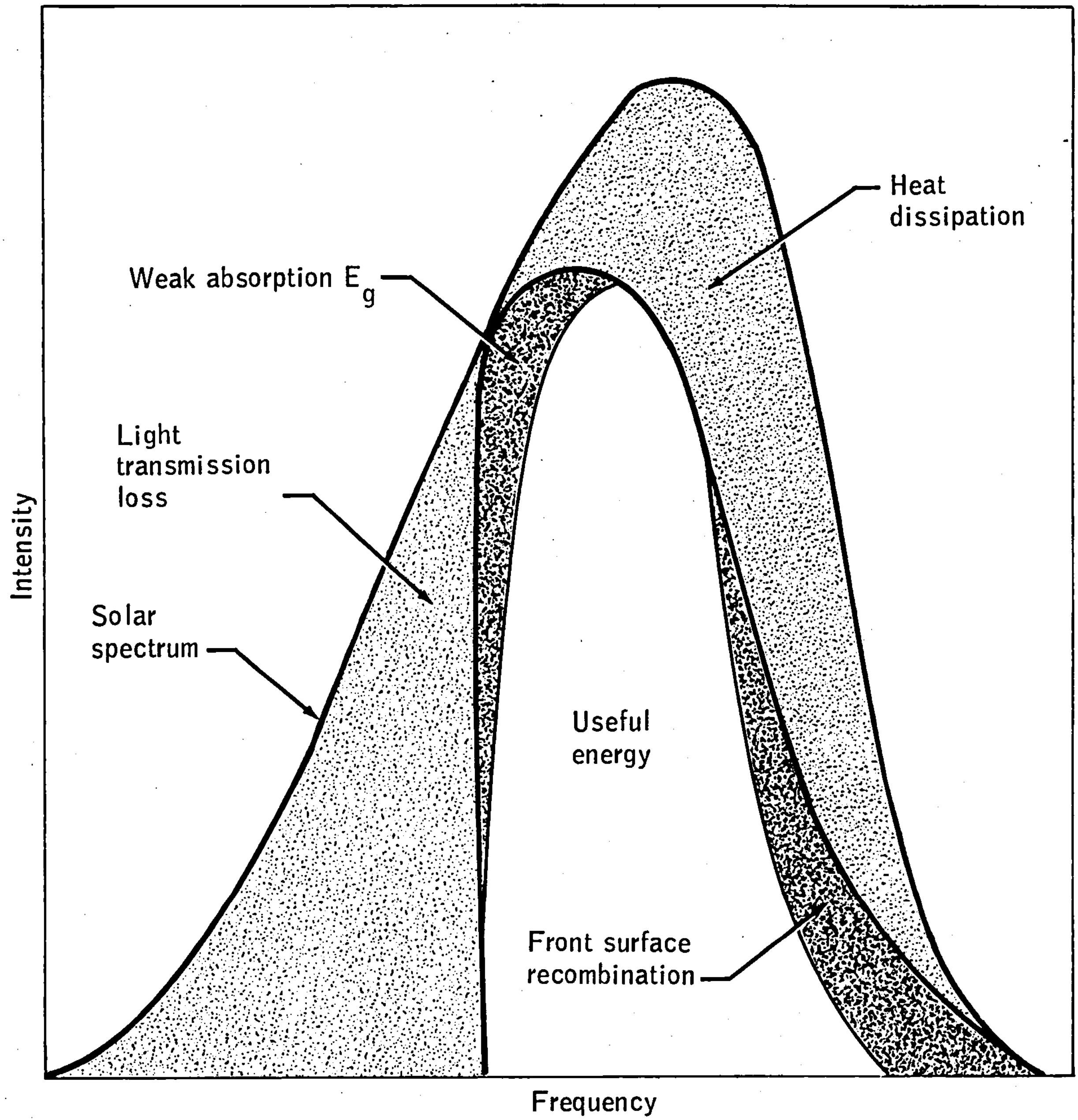
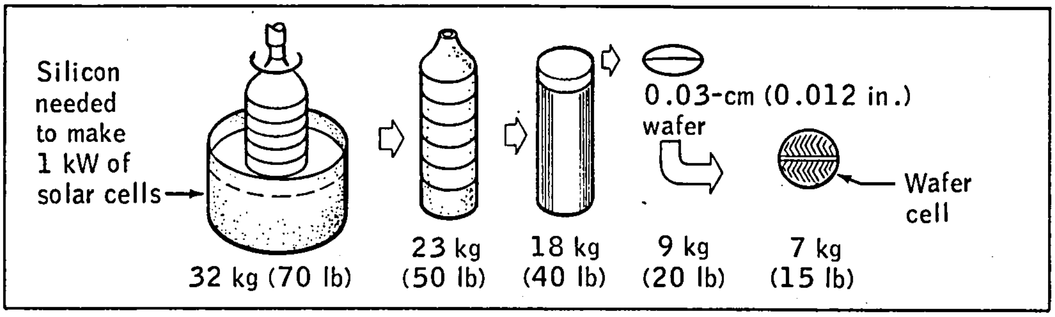
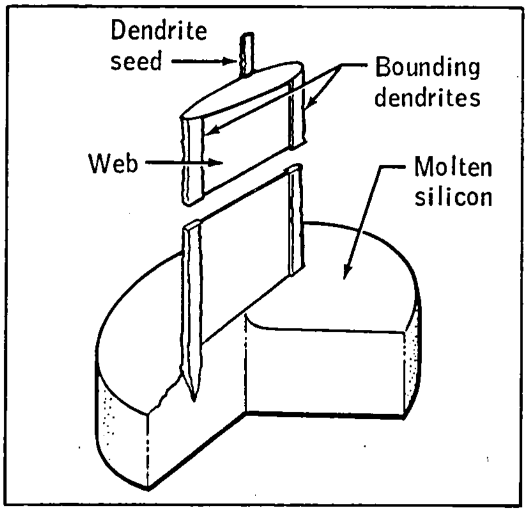
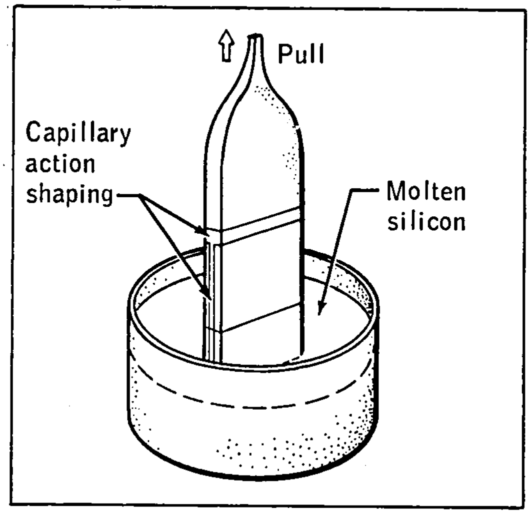


Figure 1.- Solar cell collection efficiency (ref. 3). The outer curve represents solar power as a function of frequency (or, equivalently, the number of photons as a function of their energy). The lightly shaded region represents inherent losses in any solar cell based on a semiconductor with band-gap energy E_g, so that the inner curve marks the performance of an ideal single-junction cell. The heavily shaded region represents two additional loss mechanisms present in a real cell. The unshaded area in the center is the remaining useful energy available from the cell.

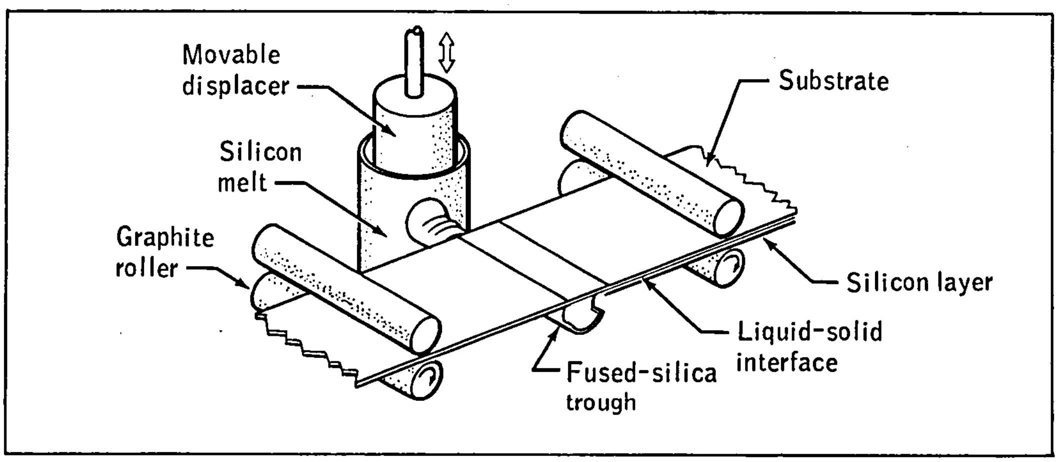


(a) Traditional Siemens/Czochralski method.





(b) Westinghouse dendritic web. (c) Mobil-Tyco EFG technique.



(d) Honeywell coated-ceramic approach.

Figure 2.- Crystal growth processes (ref. 5).

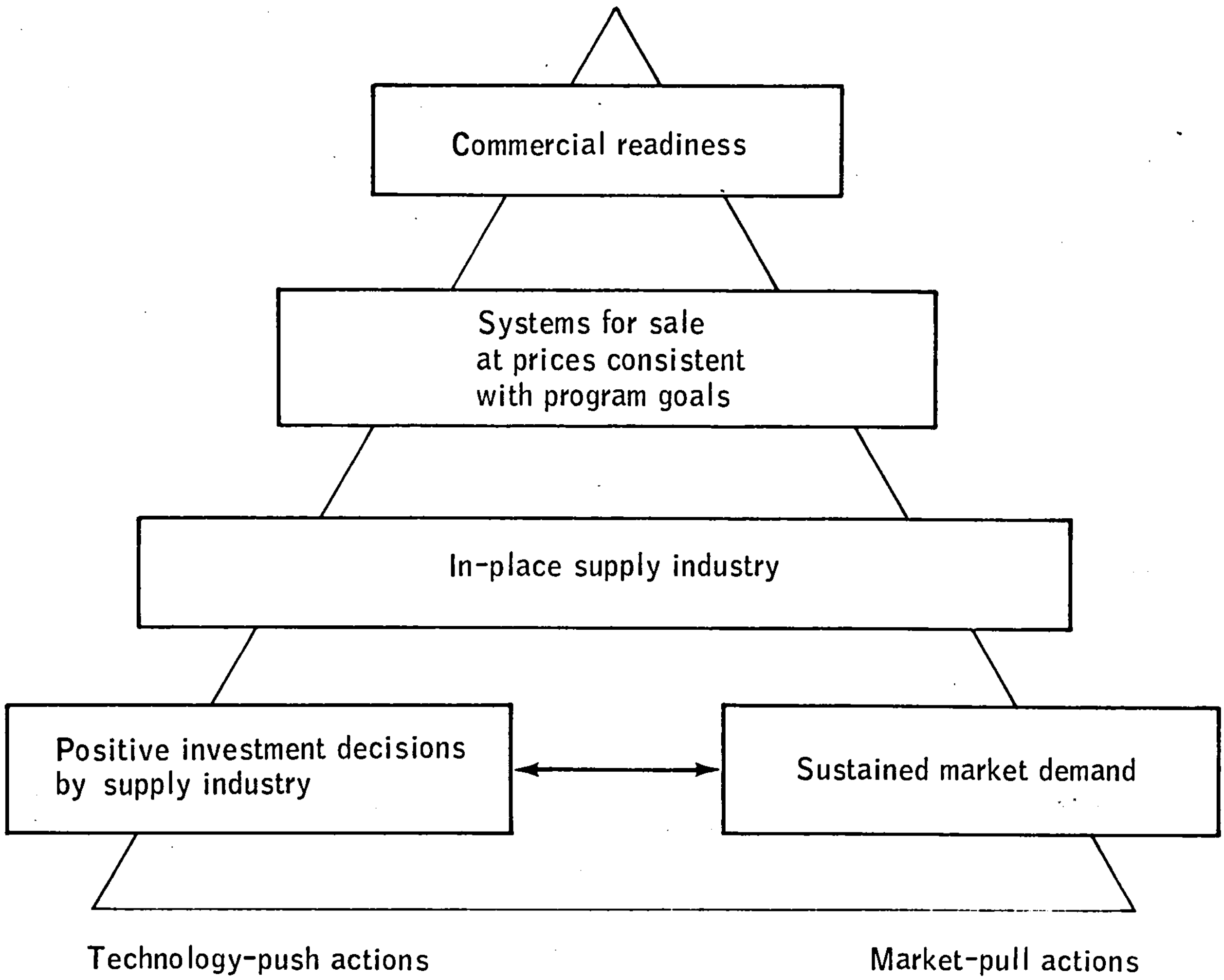
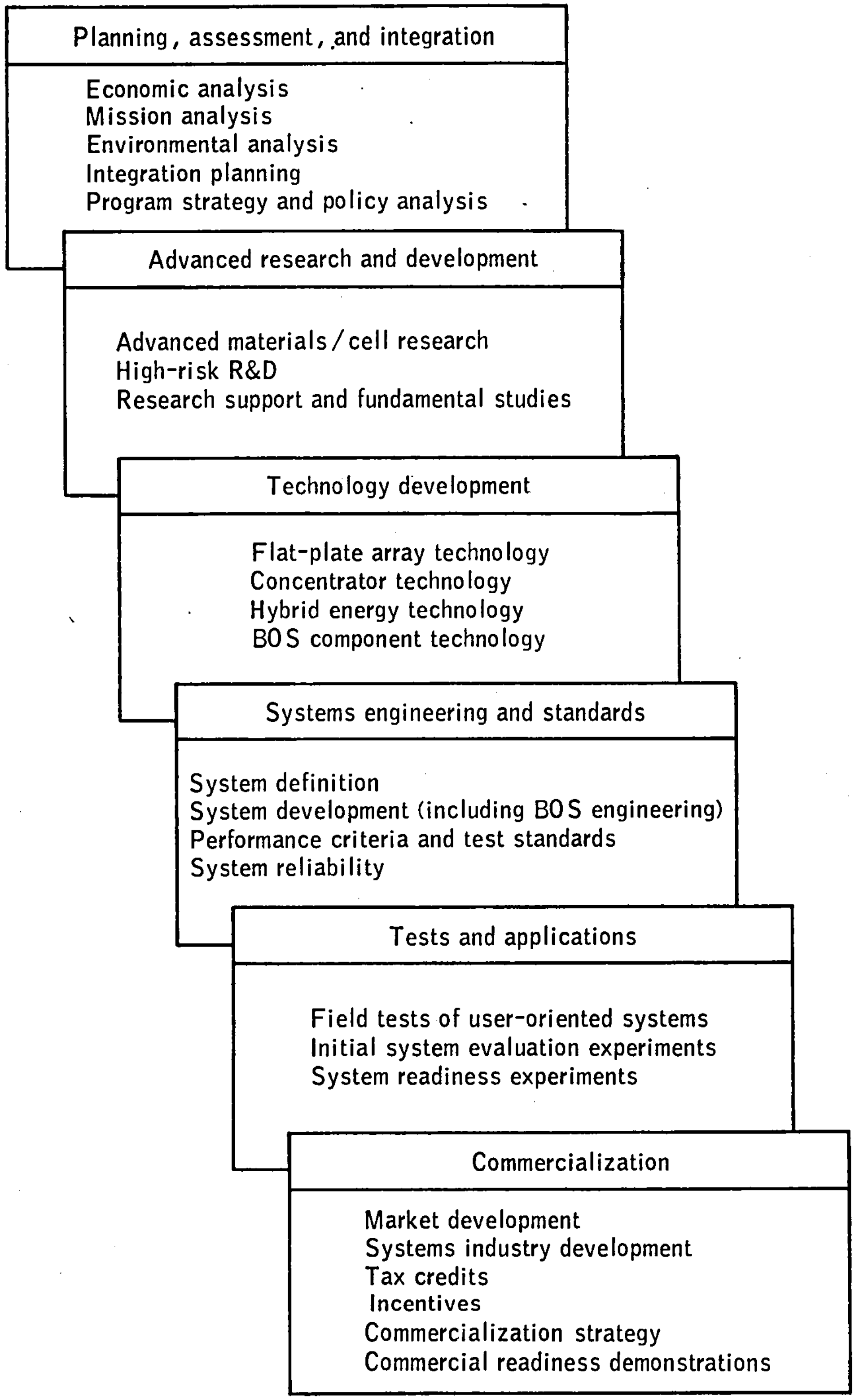
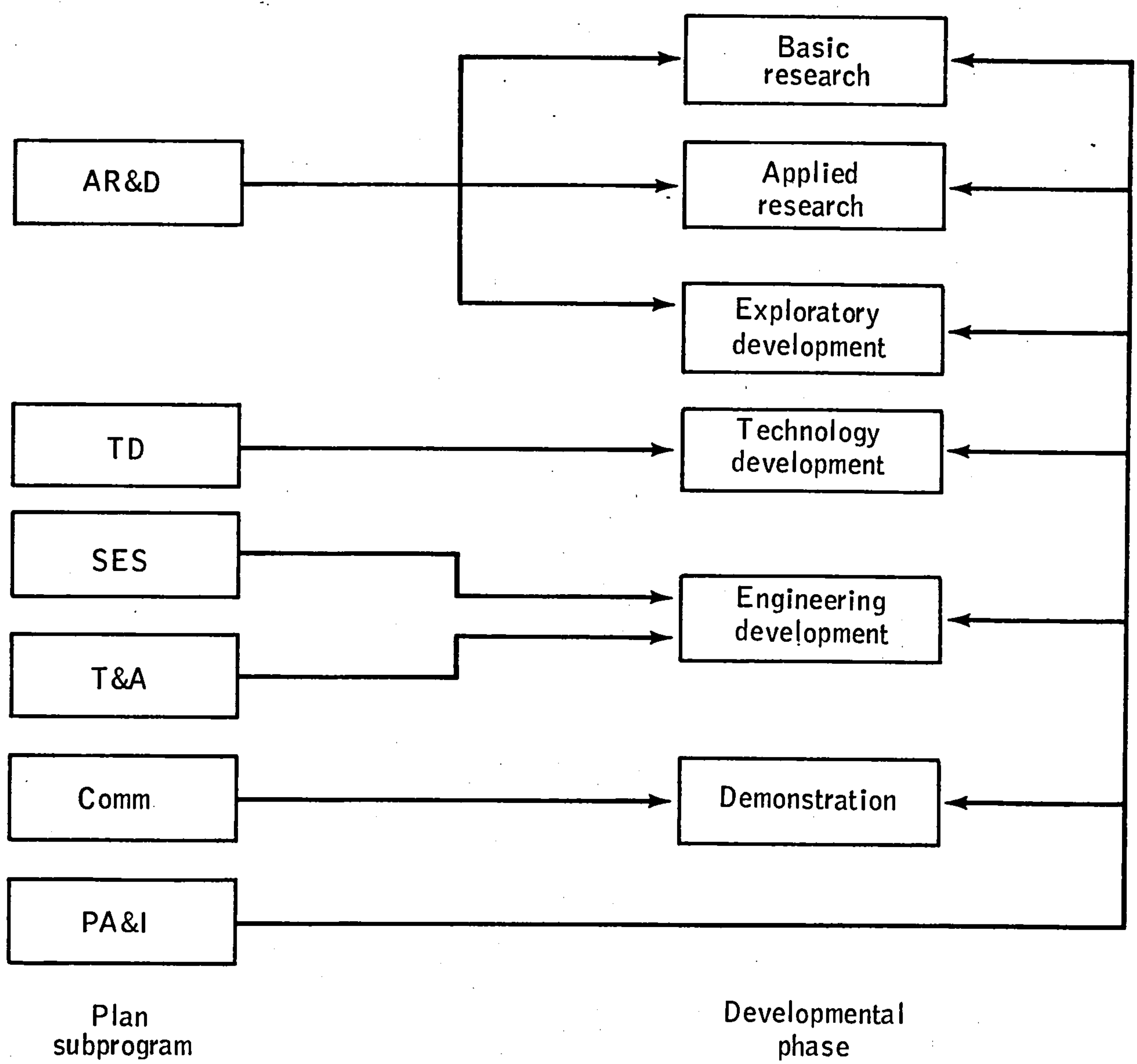


Figure 3.- Commercial readiness pyramid (ref. 6).



(a) Subprogram functions.

Figure 4.- Photovoltaic plan subprogram (ref. 6).



(b) Subprogram mapping into developmental phases.

Figure 4.- Concluded.

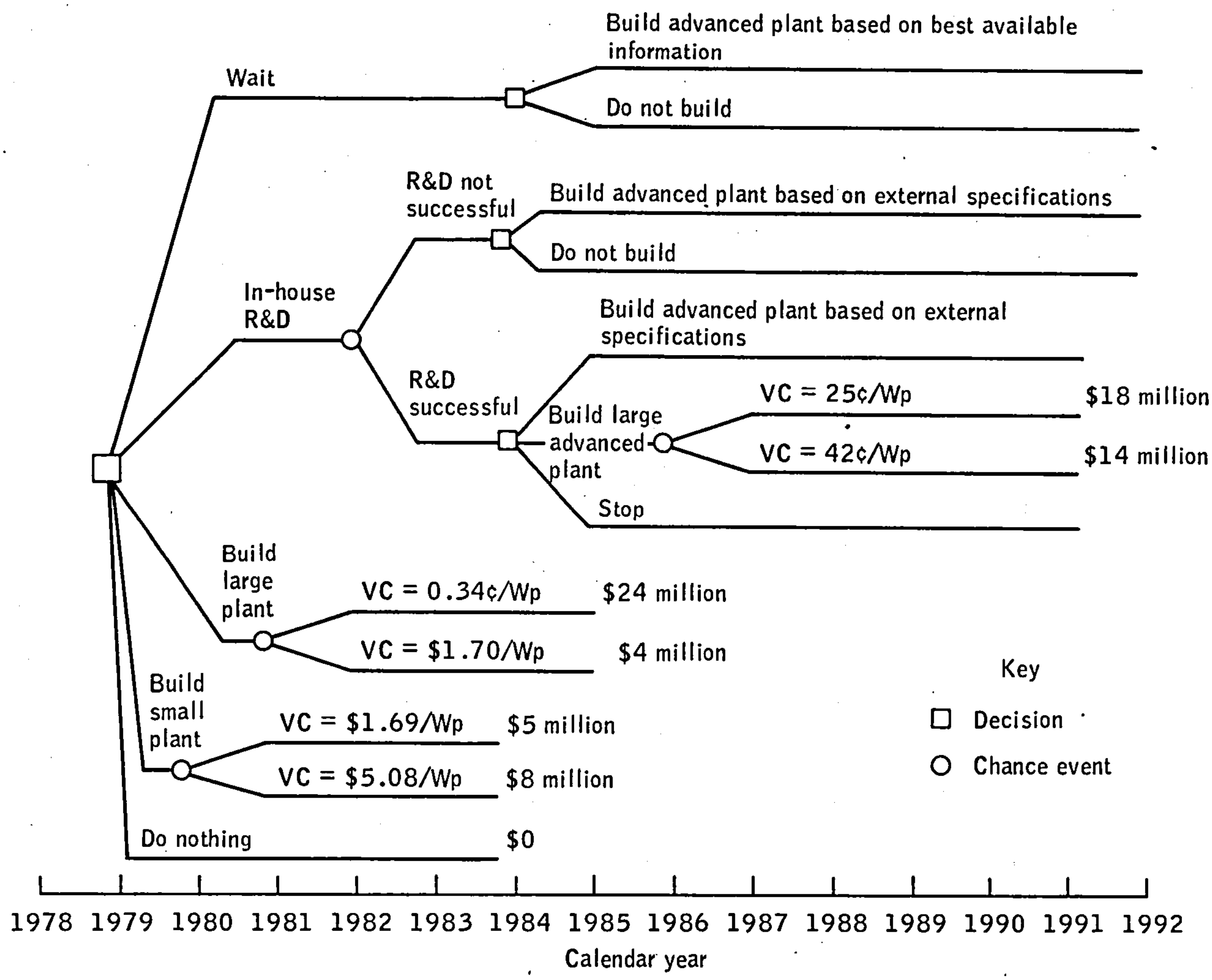


Figure 5.- Company decision tree. (Adapted from ref. 22.)

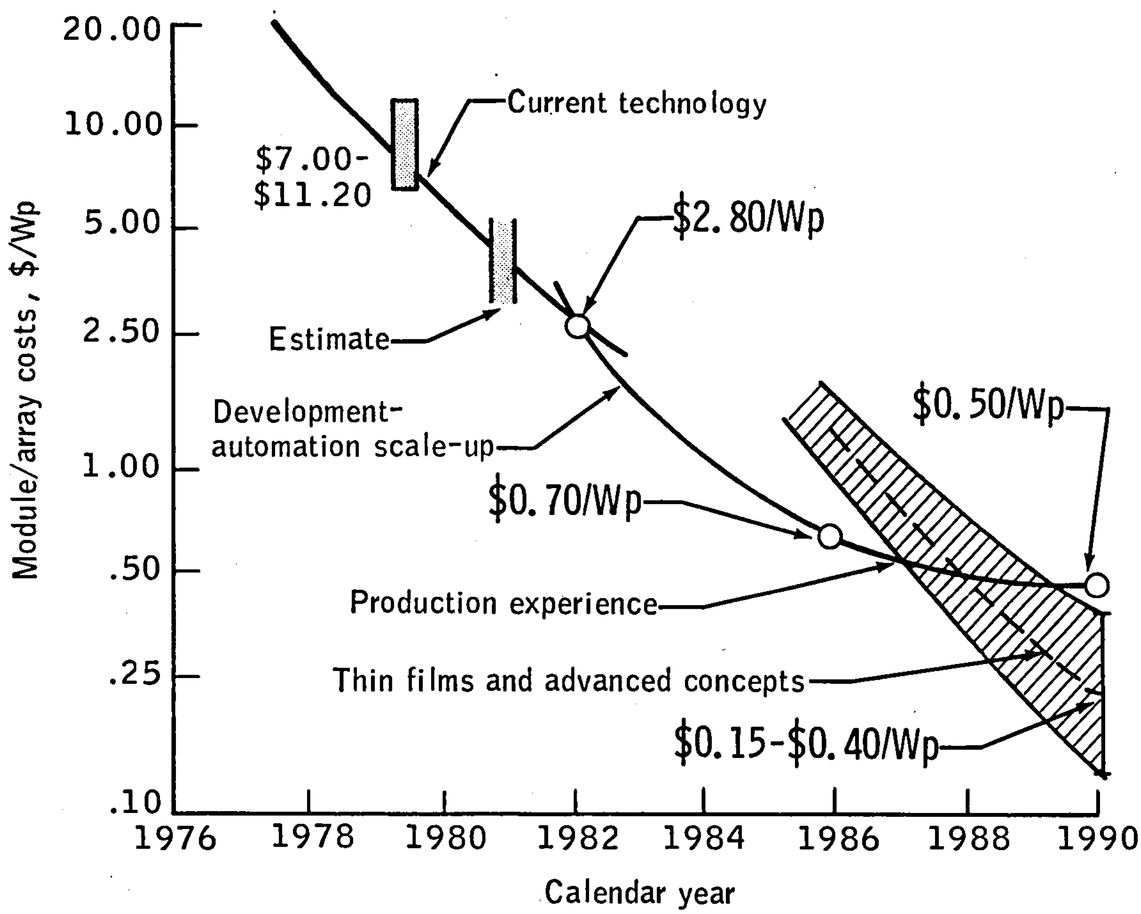


Figure 6.- DOE Photovoltaics Program price goals and history (1980 dollars). (Adapted from ref. 8.)

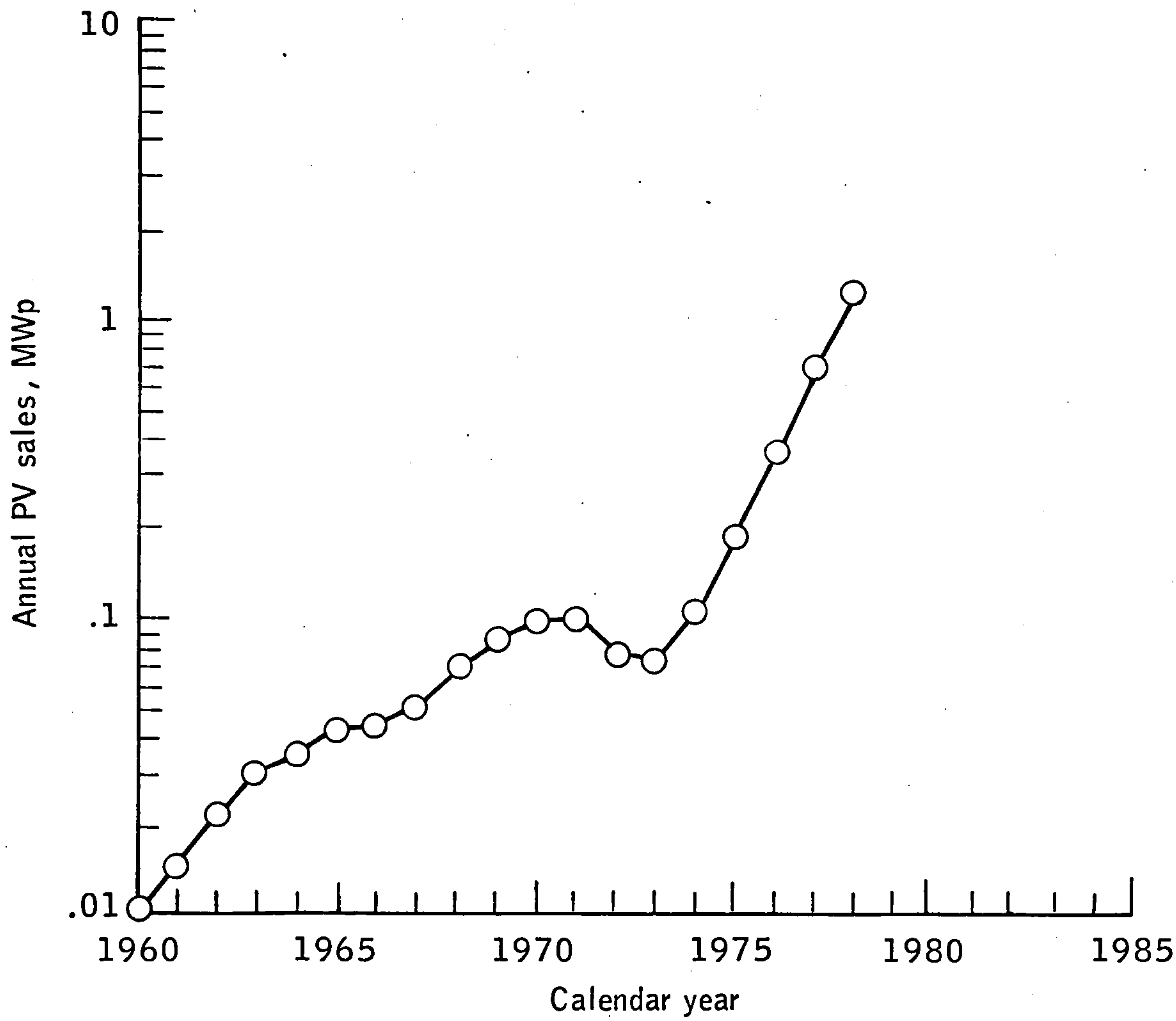


Figure 7.- Estimated historical PV production in the United States (ref. 28).

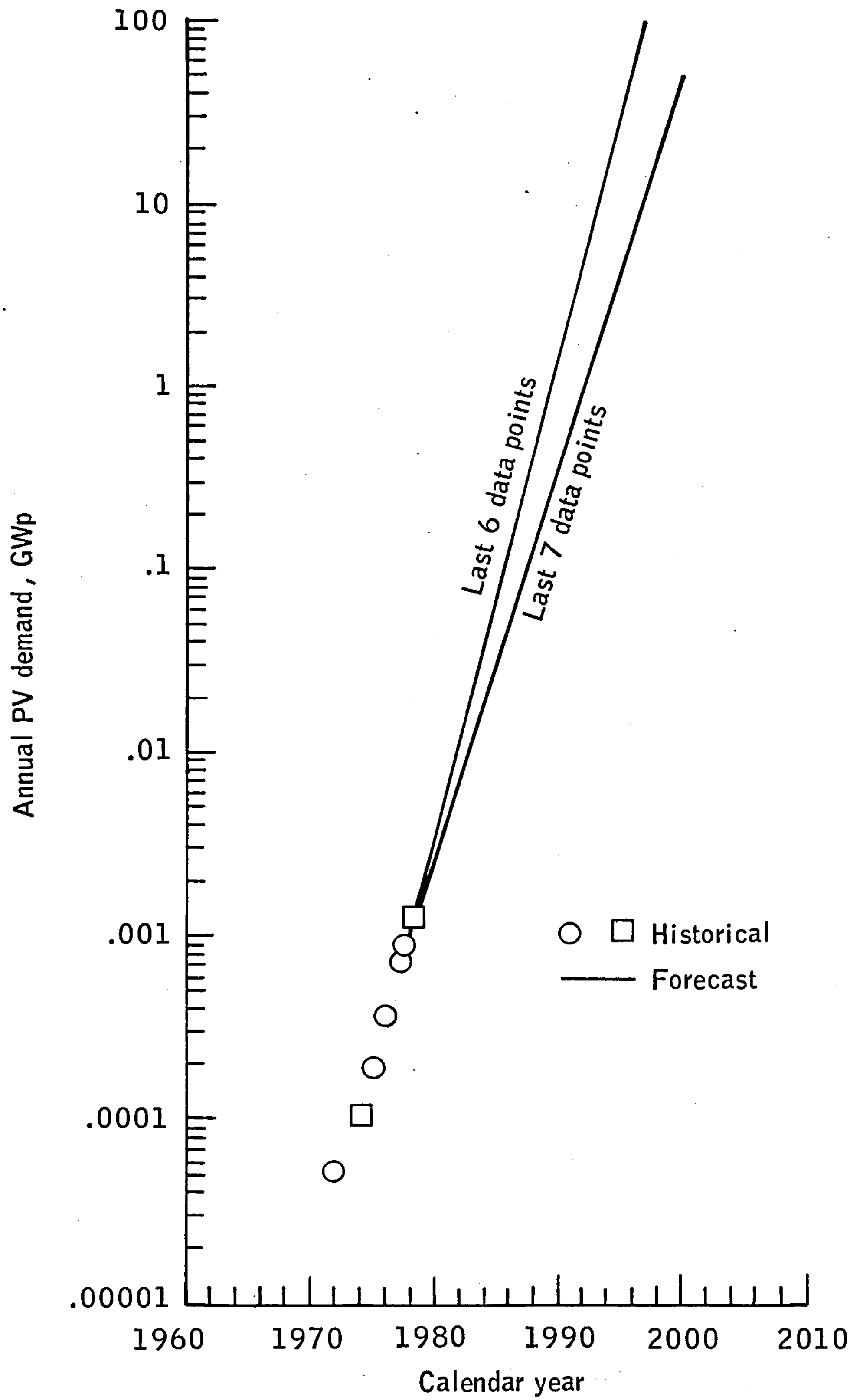


Figure 8.- PV sales - exponential extrapolation method.

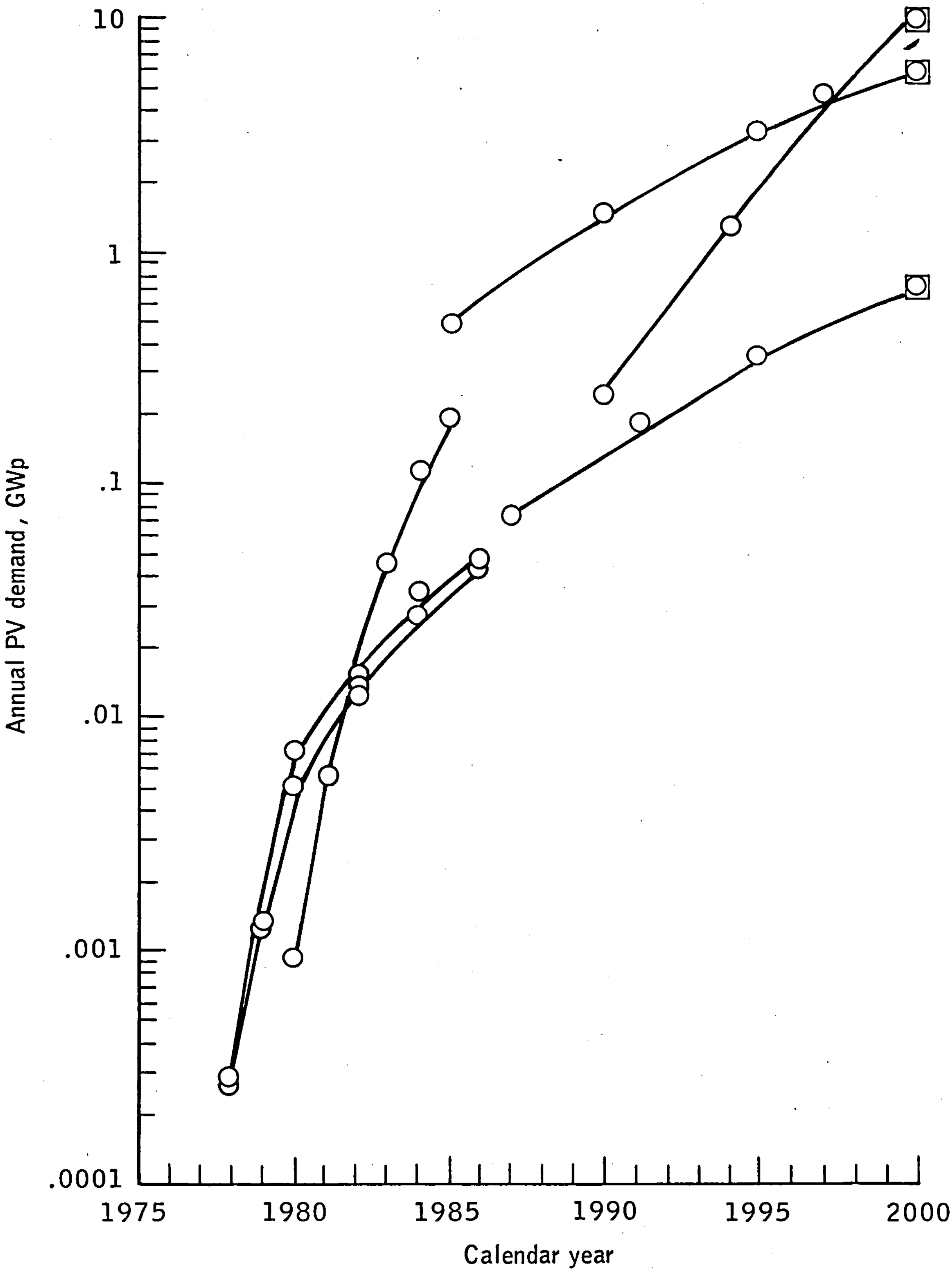


Figure 9.- PV sales - scattergram of market research forecasts.

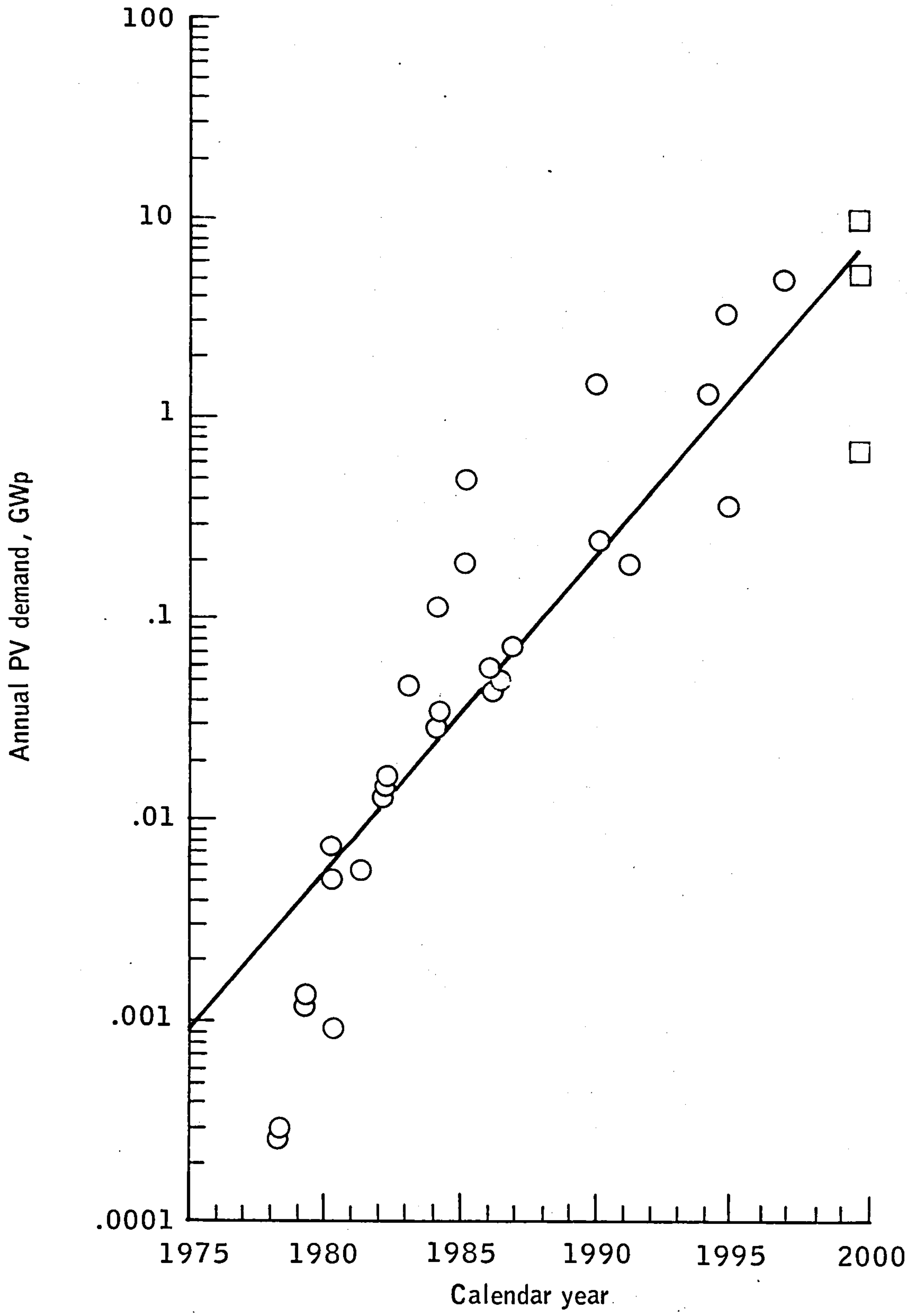


Figure 10.- PV sales - two-point log-linear judgmental method.

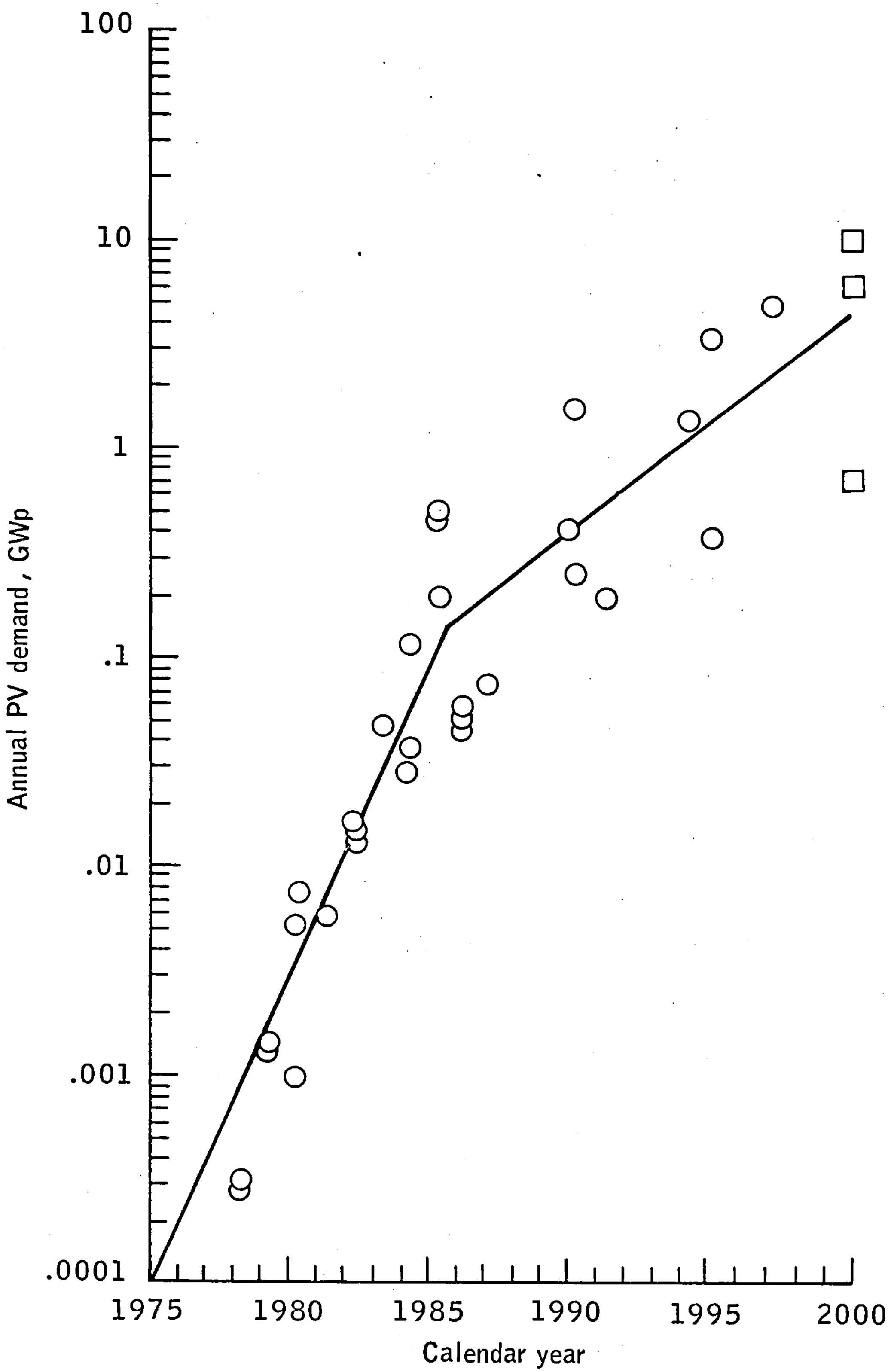


Figure 11.- PV sales - two-part log-linear judgmental method.

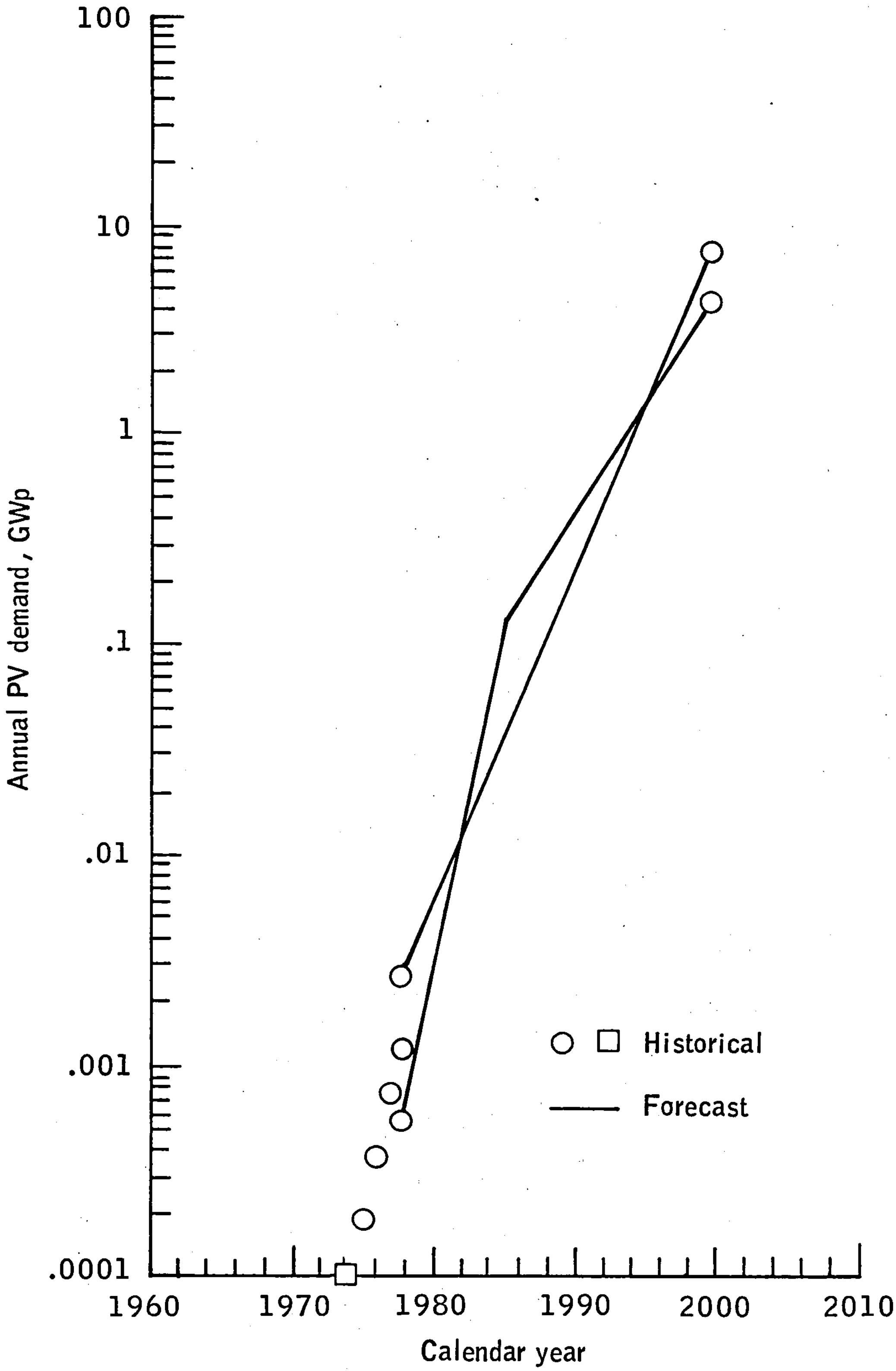


Figure 12.- PV sales - single log-linear and two-part log-linear forecasts compared with historical data.

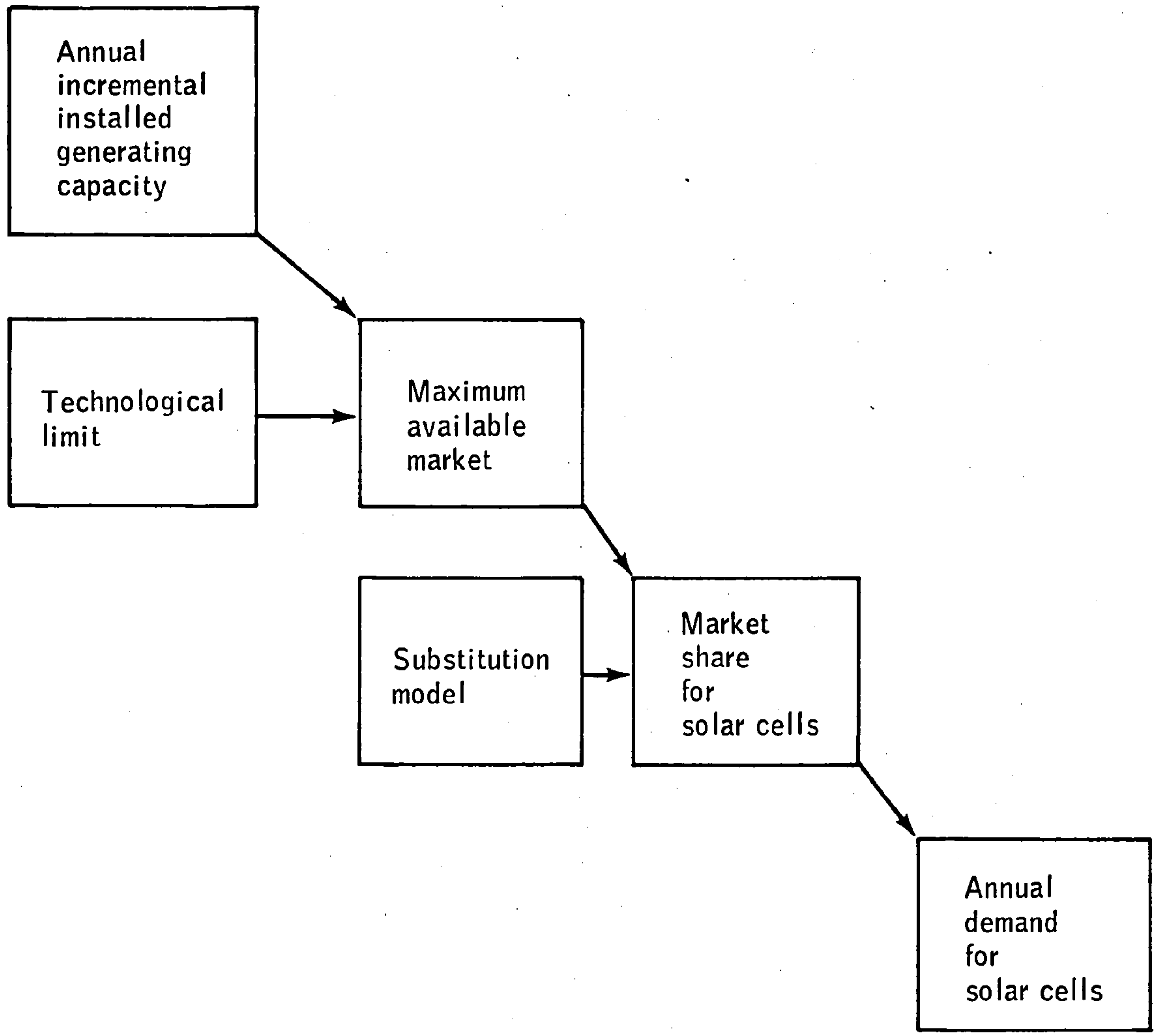


Figure 13.- Econometric method for estimating PV cell demand.

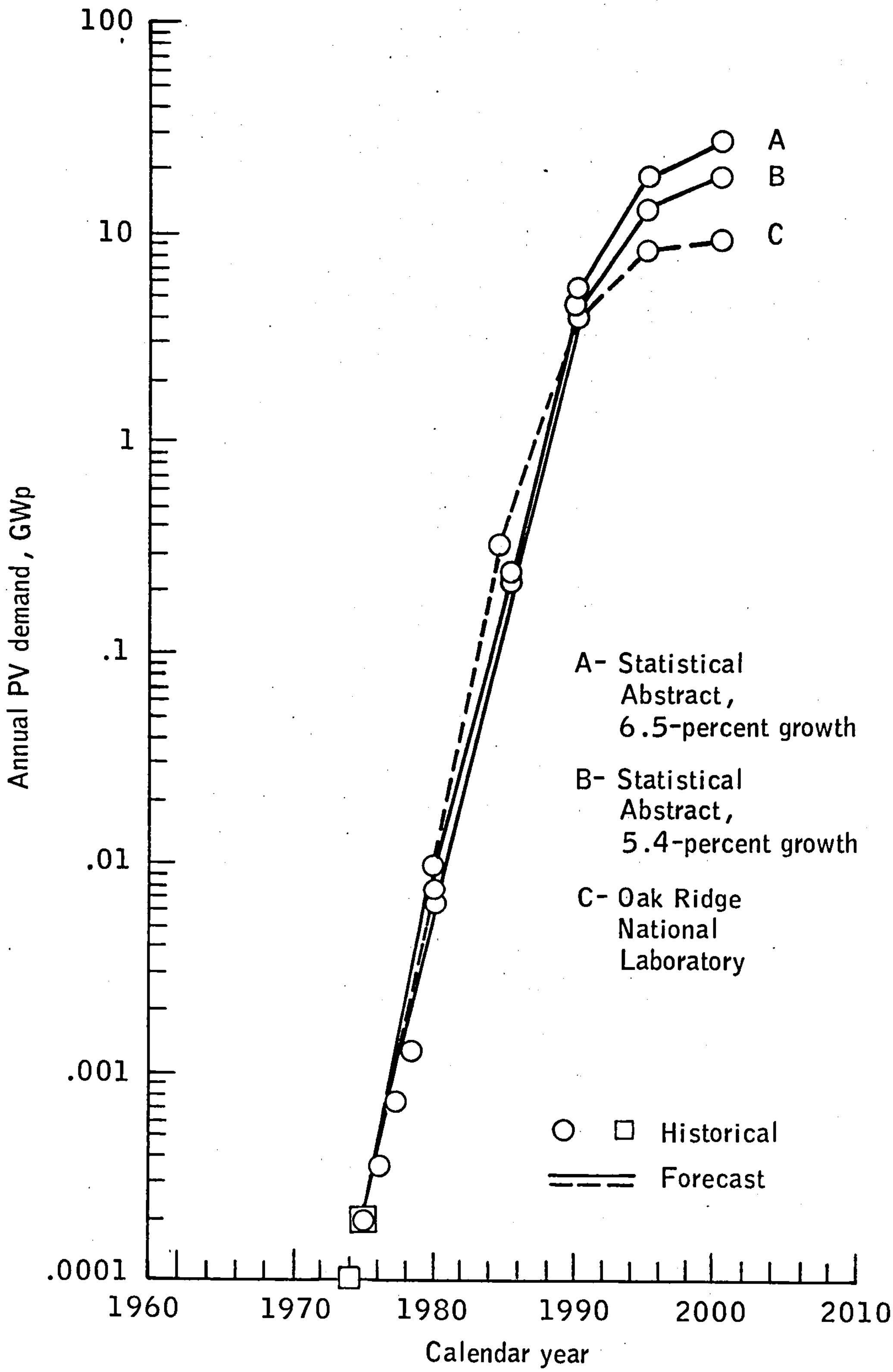


Figure 14.- PV sales - Fischer-Pry substitution model.

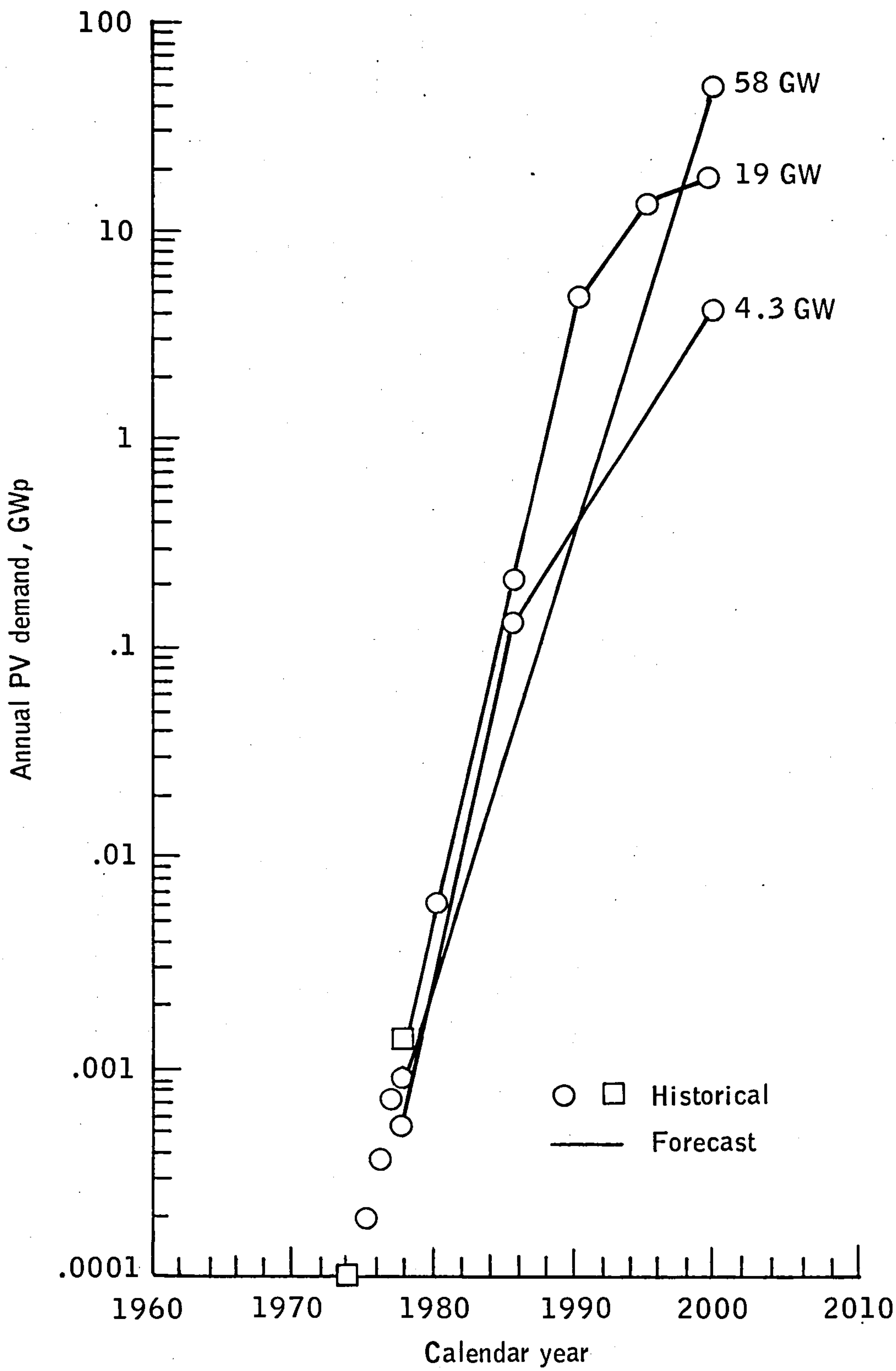


Figure 15.- PV sales - three selected forecasts.

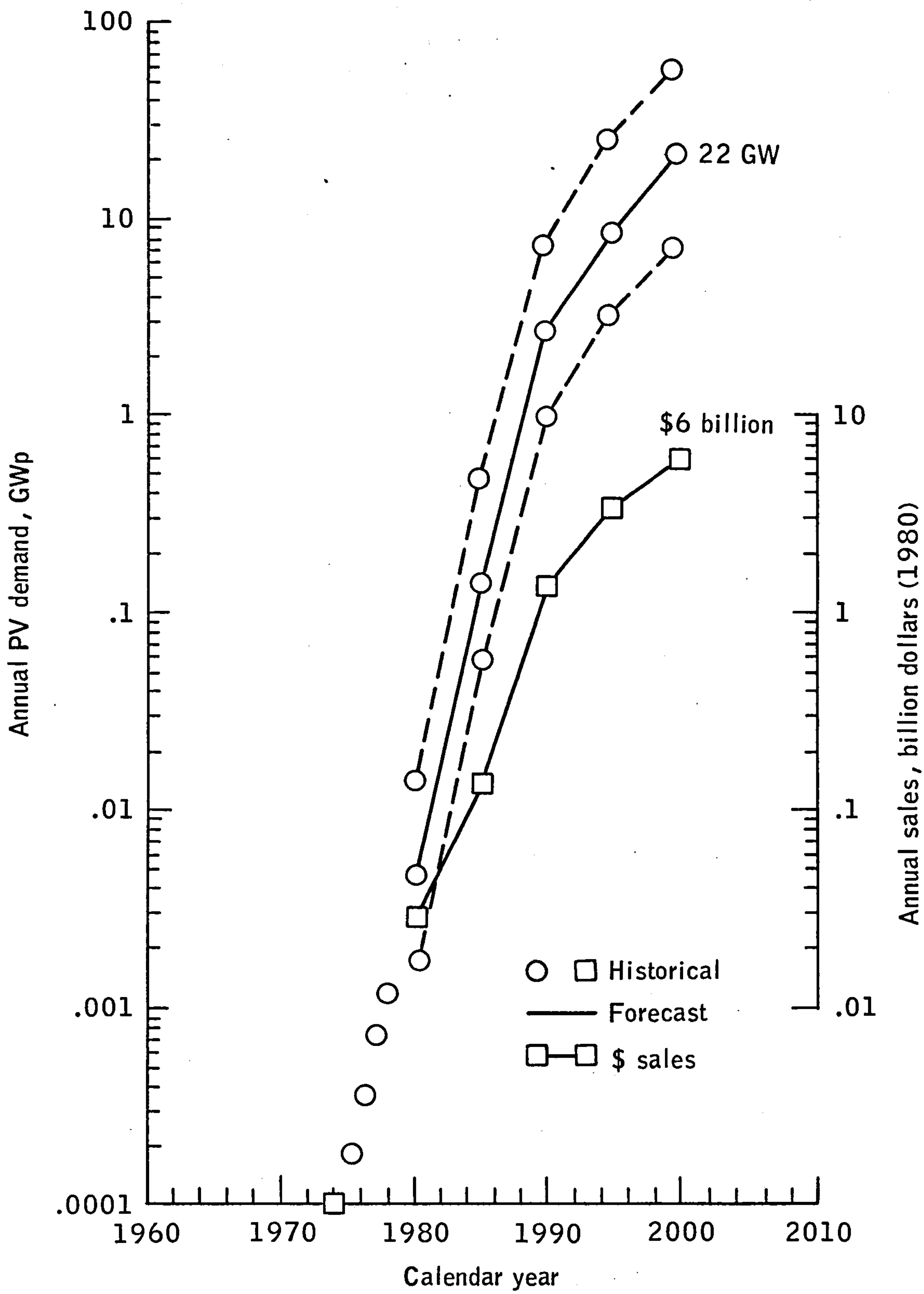


Figure 16.- PV sales - weighted amalgamated final forecast.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-58229		

4. Title and Subtitle	
THE DEVELOPMENT AND UTILIZATION OF SOLAR PHOTOVOLTAIC CELLS: AN ASSESSMENT OF THE POTENTIAL FOR A NEW ENERGY TECHNOLOGY	5. Report Date January 1981
	6. Performing Organization Code
7. Author(s) Kelley J. Cyr	8. Performing Organization Report No.
9. Performing Organization Name and Address Lyndon B. Johnson Space Center Houston, Texas 77058	10. Work Unit No. 073-36-00-00-72
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	13. Type of Report and Period Covered Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

President Carter, in his 1979 energy message, established a goal of meeting 20 percent of America's energy needs with solar energy by the year 2000. Photovoltaics are an important potential energy source for meeting that goal. The present high cost of solar cells and public resistance to the new technology are significant barriers to the widespread diffusion of this energy source. The Government has set the goal of accelerating the adaptation of photovoltaics by reducing system costs to a competitive level and overcoming the technical, institutional, legal, environmental, and social barriers impeding the diffusion of photovoltaic technology. This paper examines the utilization of photovoltaic technology in two parts. The first part examines the technology of silicon solar arrays and reviews the current status of development efforts. The political, legal, economic, social, and environmental issues are discussed, and several methods for selecting development projects are described. The second part deals with the commercialization of photovoltaic technology. A number of market forecasting techniques - including time trend, judgmental, and econometric methods - are reviewed, and the results of these models are analyzed.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Photovoltaic cells Energy policy Economic analysis Demand (economics) Forecasting Market research	STAR Subject Category: 44 (Energy Production and Conversion) 83 (Economics and Cost Analysis)

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	45	$4.00

*For sale by the National Technical Information Service, Springfield, Virginia 22161