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Lead Center

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Photovoltaics as a Terrestrial Energy Source: Volume I, An Introduction

Jeffrey L. Smith

October 1980

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
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ABSTRACT

This volume is the first in a series of Jet Propulsion Laboratory (JPL) examinations of photovoltaic (PV) systems, their potential for terrestrial application, and JPL's role in their development and application. It begins with an overview of the subject to put subsequent detailed discussions in context. Additional major sections review photovoltaic technology, existing and potential photovoltaic applications, and the National Photovoltaics Program. The competitive environment for any new electrical source, including PV, is fundamentally affected by the presence or absence of utility supplied power. In developed countries, PV must compete with utility power, necessitating an order-of-magnitude reduction in PV system prices. The price goals of the PV Program are discussed, and the roles of technological breakthroughs, directed research and technology development, learning curves, and commercial demonstrations in the National Program are introduced. The potential for photovoltaics to displace oil consumption is examined, as are the potential benefits of employing PV as a significant source of electrical power, fully interconnected with existing utility grids in either central-station or non-utility owned, small, distributed systems. Such systems will probably not include significant quantities of electrical storage, using the grid as a backup source instead.

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FOREWORD

This is the first in a series of documents discussing the use of photovoltaic (PV) systems for terrestrial applications. The purpose of the series was to provide a forum for discussion of Jet Propulsion Laboratory (JPL) policy on the conduct of its photovoltaic projects, within the charter granted JPL by the Department of Energy Photovoltaics Program. These photovoltaic projects constitute a major part of JPL's Utilitarian Program. This Program applies skills developed in space exploration to problems of high national priority. JPL believes that its technical competence and success at managing complex research and development projects have wide applicability to many pressing issues of national scope.

While the overall intent of JPL's Utilitarian Program is straightforward, important questions surround the specific purposes, limitations, strategies and status of the individual projects, including the PV projects. It is hoped that the information presented here aids policy formulation with respect to these questions.

The purpose of this volume is to introduce major considerations and issues that arise in an evaluation of photovoltaics for terrestrial application. Its Introduction is a survey of the subject that serves to put subsequent detailed discussions in context. It reviews photovoltaic technology, existing and potential photovoltaic applications and the National Photovoltaics Program as formulated and initiated by the Carter Administration. Each of the following volumes will address specific topics of importance to an evaluation of the potential for advantageous use of PV systems.

ACKNOWLEDGMENTS

This paper has benefited considerably from extensive discussions and written comments from many of my JPL colleagues, including Bud Schurmeier, Tom Hamilton, Bob Forney, Rich O'Toole, Mickey Alper, Kris Koliwad, Don Ebbeler, Chet Borden, Bob Easter, Bob Chamberlain, Paul Sutton and Bob Aster. In addition, discourses held with the JPL Advisory Council PV discussion group have proven invaluable. Finally, I would like to thank my editor E. E. Sloman, my assistant Karen Hughes, and my secretary Arlene Calvert.

CONTENTS

Tables

SECTION I

INTRODUCTION

A PV system employs semiconductor materials to convert energy contained in a portion of the electromagnetic spectrum (typically a small portion of the visible spectrum)* into dc electrical energy through a mechanism known as the "photovoltaic effect." Pioneering research on the photovoltaic effect was conducted by Bell Laboratories in the early 1950s. Later in that decade photovoltaic systems saw their first important practical applications**--powering spacecraft with sunlight. Spacecraft designers continue to use photovoltaic systems as a major source of spacecraft power.

Terrestrial applications of photovoltaic systems began to grow as a fraction of total PV sales in the early 1970s. Solarex, the first PV manufacturer dedicated exclusively to terrestrial applications, was formed in 1973. Mountaintop radio and microwave repeaters, ocean signal buoys and pipeline corrosion protection systems are typical of the applications for which PV systems are presently commercially attractive. Power requirements are small and the systems are usually remote from electric grids and human habitation. A small, highly competitive industry has sprung up to supply PV systems for this worldwide market; it produced approximately 4 peak megawatts (MW_p)*** of generating capacity during 1980. This generated a total sales revenue of approximately $40 million, about a fourth of the current annual federal PV Program budget (about $157 million in FY80). French, German, and Japanese competition is challenging the early lead held by U.S. companies in this fledgling industry.

Figures 1, 2, and 3 show typical terrestrial photovoltaic systems.

Competitive application of photovoltaic systems is presently limited to this tiny market because of two partly related major drawbacks: PV systems are very expensive, and the power output of PV systems is intermittent, owing to the nature of the solar resource. Photovoltaic systems can be purchased

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*Most commercial PV systems exhibit an efficiency of slightly less than 10% (10% of the total solar flux is converted to electrical energy). Efficiencies range from less than 1% to more than 30% in experimental collectors.

**The first application of photovoltaics was made in 1955: a telephone repeater system installed in Americus, Georgia. The first PV-powered spacecraft was Vanguard 1, in March of 1958.

***PV systems are rated at their power output under standard illumination (insolation) and weather conditions that correspond roughly to ideal conditions. Thus the rating corresponds to peak output level. In favorable conditions, PV systems have capacity factors of approximately 0.20 depending on location, PV technology, sun-tracking capability, etc. Hence a 1000 MW conventional electricity plant with a capacity factor of 0.60 produces approximately three times as much electrical energy as a 1000 MW_p PV facility (capacity factor equals average output/year divided by rated output).

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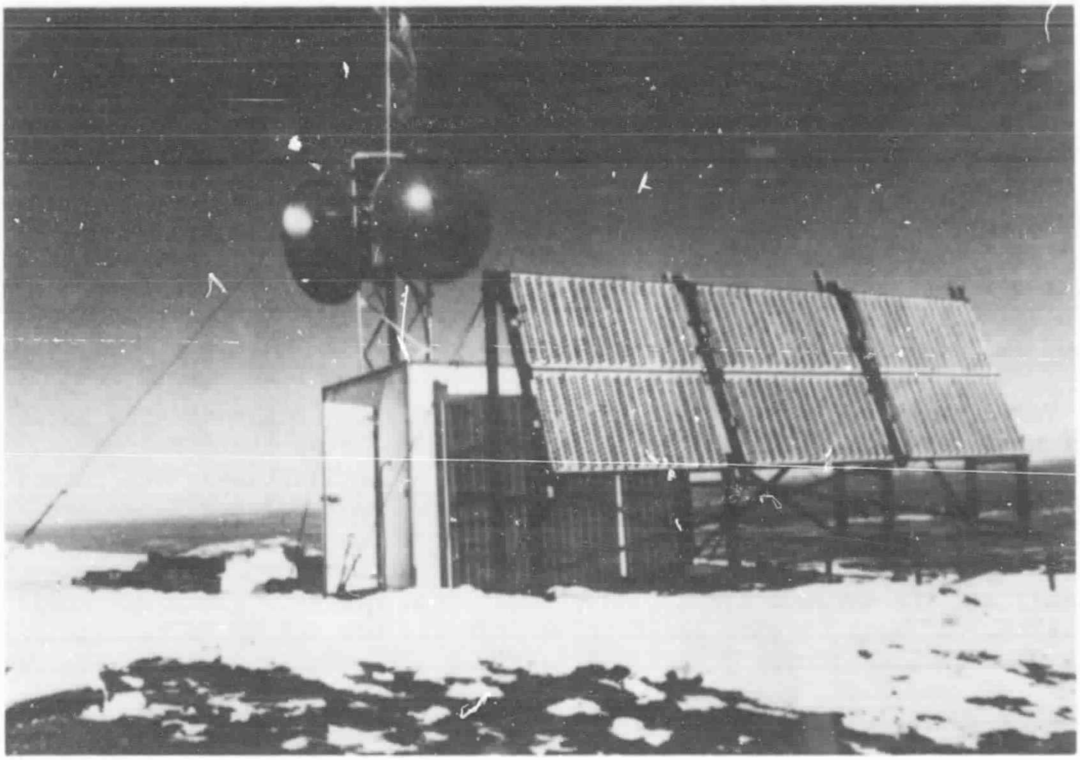

Figure 1. Microwave Repeater Station in Alaska (Courtesy of Spectrolab, Inc.)

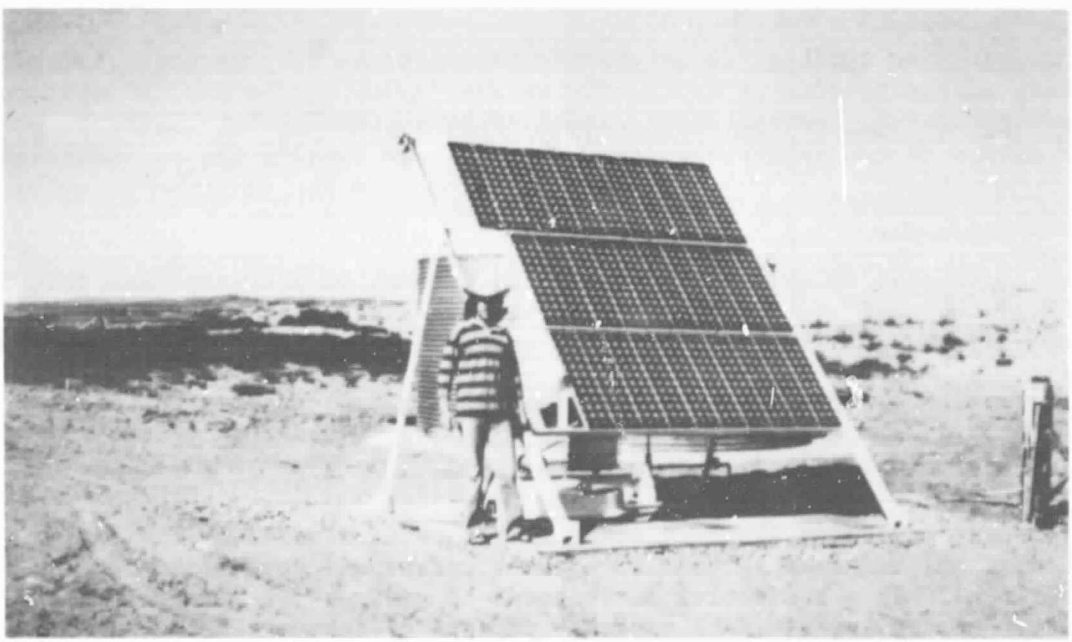

Figure 2. Livestock Watering on Indian Reservation in New Mexico; Water is Pumped from a 300-foot Well into a Storage Tank (Courtesy of Arco Solar, Inc.)

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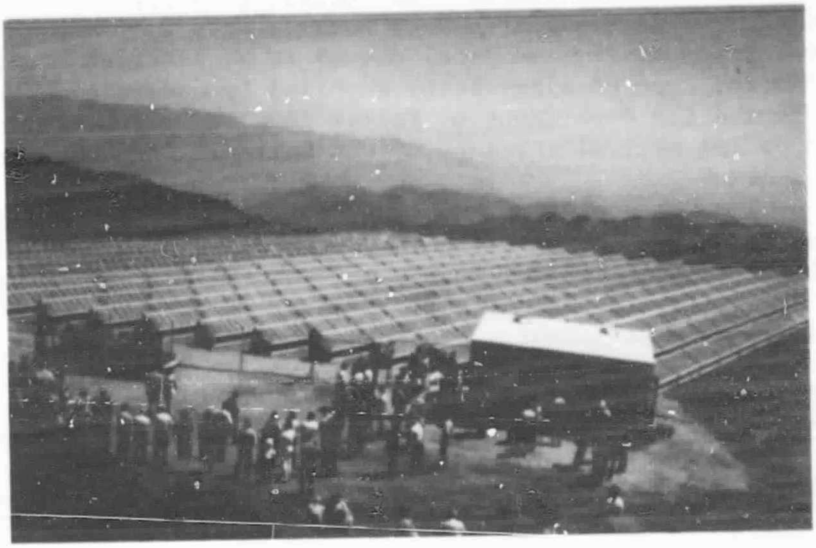

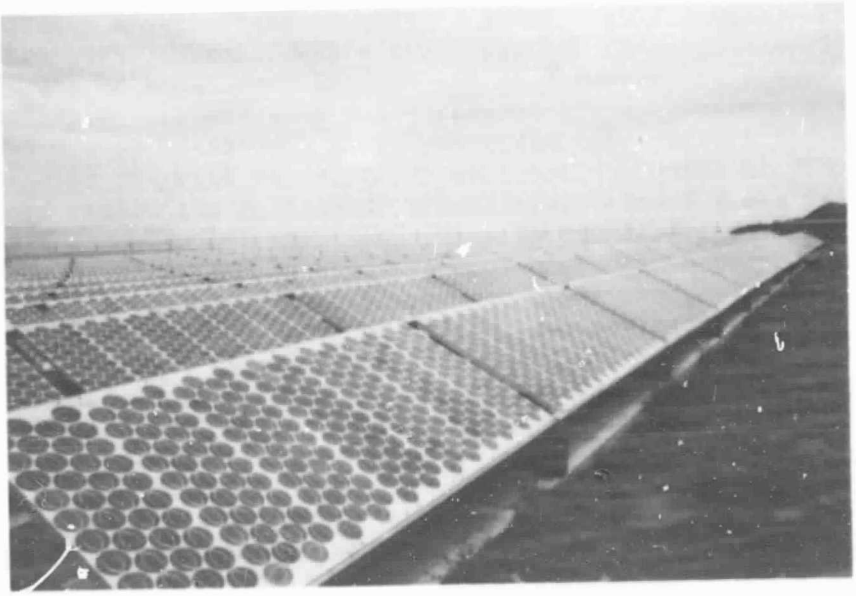

Figure 3. 60 kW Experimental PV Installation
Mt. Laguna AFB, California

today for between $15/$W_p$ and $30/$W_p$, depending on application and system configuration. This translates very roughly into $.50/kWh to $2.00/kWh. Thus the current price of PV electrical energy is at least an order of magnitude higher than the cost of electricity supplied by modern electric grids. This has led JPL and the Department of Energy (DOE) to emphasize cost (price) reduction as the central strategy of the National Photovoltaics Program:

> The Photovoltaics 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, systems engineering and market development.... (Reference 1.)

Specific numerical price targets or goals have been adopted that, if achieved, may permit photovoltaic systems to compete with conventionally generated bulk power. In addition, the National PV Program agenda has been organized to increase the probability that these price goals will be achieved by the selected time, 1986.

Probably the most critical uncertainty concerning the potential for successful introduction of large quantities of privately supplied and purchased PV systems is that of achieving the required tenfold reduction in current PV system prices. Among PV Program participants, including many of the 100 private research and development (R&D) contractors, and within the PV industry, there is consensus on the central importance of cost reductions (although the exact amounts necessary are questioned). Significant cost reduction has already been achieved,* with flat-plate module prices falling from $200/$W_p$ in space applications to as low as $7/$W_p$ to $8/$W_p$ today for terrestrial use. Further significant reductions are widely expected. Judgments on the likelihood of sufficient cost reduction to make PV systems widely attractive depend upon consideration of many interrelated factors, to be discussed throughout these papers. No simple or automatic gauges of the probability of sufficient cost reduction exist. Clearly of major importance are assumptions concerning the future availability and cost of nuclear, coal, oil and gas as sources of electricity. The explicit pursuit of technological change by the PV Program and industry also necessitates inherently uncertain and complex production cost (PV supply price) forecasts.

A second major drawback of PV and other solar systems and a contributor to the high cost of present systems is the intermittent nature of sunshine. This has led many observers to conclude that electrical storage must become an integral part of PV systems and PV research. For example, the Ford Foundation-sponsored Energy Study Group concluded in its discussion of PV potential:

> Unfortunately, the technology works best during the daytime and often not then because of clouds. Thus, an integral part of a solar photovoltaic approach must be the storage of the energy in electrical form.... (Reference 2.)

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*The reader is cautioned against confusing price quotations for photovoltaic collectors (modules) with those for photovoltaic systems. As a rough rule of thumb, PV system costs are about twice the module costs.

This conclusion cannot be disputed for most PV applications remote from electric grids. However, it is not correct if grid interconnection is possible. In this configuration, PV systems become one of many generating sources supplying power to the electric grid. In many utility districts, PV systems generate primarily during periods of high electrical demand (daytime). Often, when PV systems are not operating (e.g., at night), enough excess generation capacity exists in the grid to meet all demands. An interconnected arrangement can prove beneficial to both the electric utility and its customers. The value of this arrangement depends partially on the correlation between utility system peak and shoulder demand periods and PV system output on both daily and yearly bases.

Under favorable circumstances, the addition of PV systems to electric grids may result in a significant capacity credit for photovoltaics. That is, additions of conventional capacity to electric grids may, to some extent, be deferred if PV systems are added. At worst, all capacity additions required without photovoltaics may still be required, although the optimal configuration (generation mix) of grid generating sources may still be altered in PV's presence.

Possibly more surprising, in grid-interconnected configurations, photovoltaic systems and electrical storage systems are often substitutes--that is, the presence of one in an electric grid may reduce the value of additions of the other to the same grid. This results because, even in the presence of significant PV capacity, PV systems and storage systems will both be producing electricity at the same time. The optimal dispatch* strategy for large, grid-connected electrical storage systems will charge the storage systems at low marginal-cost periods (e.g., at night) and discharge them during high marginal-cost periods (daytime).** On the other hand, it is easy to imagine utilities in which PV and system storage would be complementary almost immediately (i.e., utilities whose peak and shoulder periods occur primarily after dark). With very large penetrations of PV into any grid they would undoubtedly become highly complementary. Nevertheless, this does not mean that system storage is required in any of these situations. On the contrary, it appears that a number of alternative arrangements of sources of generation in a grid may beneficially include significant quantities of PV systems without including electrical storage.

Figure 4 shows the effect of including 800 MW_p of PV on the net load seen by conventional generators in a typical Southwestern utility. PV produces 3% to 4% of the total electrical energy of this utility. Note the high

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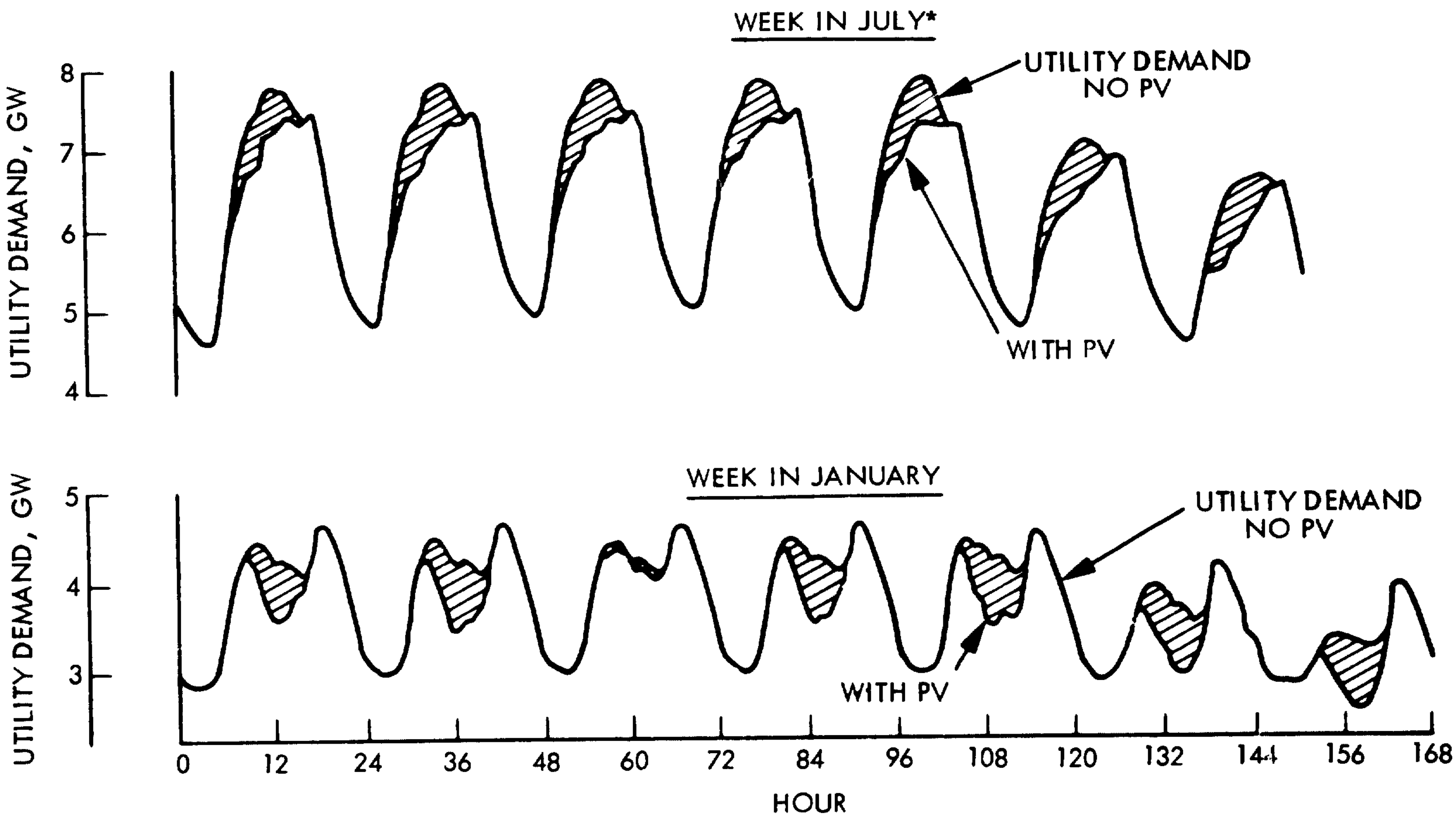
*Dispatch refers to the order and timing with which electrical generation sources are brought on line to meet the time-variant loads of electric grids.

**This can be thought of in additional ways: (1) at low (less than 10%) penetrations, PV systems and utility system storage compete to serve the peak (the penetration of a technology into a grid system refers to the percentage of total grid electrical energy produced by that technology); (2) PV and system storage are substitutes until there is so much PV that it becomes optimal to charge some of the storage with some of the PV; or, most precisely, (3) at low penetrations the derivative of the marginal product of PV with respect to storage is negative, as is the derivative of the marginal product of storage with respect to PV.



*Shaded area shows photovoltaic output

Figure 4. Simulation of Southwestern United States Utility Load Profile, With and Without Photovoltaics.
Source: Aerospace Corp. Presentation at Photovoltaics Program Annual Review Meeting, April 1980.

correlation of system peaks and PV output in the summer. On the other hand, the dual winter demand peaks are exacerbated by photovoltaics. (The third day of this week in January was apparently quite cloudy.) As shown below, the economic value of PV is estimated by valuing the types of changes in the net load curve shown in this figure extended to the expected life of the PV system. These changes consist primarily of the conventional fuel and capacity savings which result from the PV output.

In addition to these obvious problems (high cost and variability of output), photovoltaics suffers from a number of other potential impediments to rapid introduction. Opinions on the significances of these impediments differ. Included are land-use implications, potential environmental dangers, reliability and lifetime uncertainties, and technical difficulties with grid interconnection or utility-system operation, maintenance, and control. In building applications there are concerns about solar access and construction- industry inertia. The current lack of industrial product standards, standard component and system warranties, and adequate system design integration are of concern to many. Since electricity is traded in regulated markets, institutional and non-optimal pricing impediments are likely. There may be other regulatory, legal, aesthetic, social or institutional impediments to PV system deployment. Discussion of these potential impediments is deferred to a later volume.

Many of these concerns are exacerbated by the urgency contained in the present Photovoltaics Program strategy. In essence, the PV Program as administered by the Carter Administration promises to do whatever is required, within appropriate limitations including budgets, to establish a general availability (or capability of rapid supply) of privately produced and marketed photovoltaic systems by the end of 1986.* The primary techniques available to the Program to obtain its objective are research and direct technology development (R&D). According to the strategy, attainment of the technical goals and economic (system price) goals of the Program will allow profitable sales without long-term reliance upon government solar subsidies. The rapidity with which this complicated objective is to be met has stimulated many of the concerns listed above.

Many observers have interpreted the present world energy crisis as one primarily of liquid-fuel supply, particularly of crude oil and its close substitutes. In this view, the energy threat is near-term and continuously present--a catastrophic reduction in the flow of crude oil from OPEC, especially from the Middle East, being the present danger. Photovoltaics offers only a modest hope of reducing oil imports and then only beginning in the late 1980s, the earliest time at which nationally significant deployments of PV systems are anticipated by the PV program. New sources of electricity are imperfect substitutes for oil, especially in a time frame suitable for PV deployment.

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*There has been substantial dispute over the extent to which the PV Program is or should be directly responsible for obtaining prespecified levels of actual PV deployment as opposed to simply creating a potential for rapid, competitive supply. In the latter view, private industry has a more active and prominent role in actual PV investment and sale decisions.

Approximately 10% of U.S. oil consumption is devoted to fueling electric utility boilers. Recent oil-price increases have created a strong incentive for utilities to reduce this oil consumption. Combined with a federal mandates (References 3 and 4) and other inducements to reduce utility consumption of oil, this incentive should result in a dramatic reduction in oil-fired utility generation over the next 10 years. Thus, although photovoltaics is suited for use as a utility fuel saver, it may not become generally available until after utility consumption of oil is itself greatly reduced.

Another 25% of U.S. oil consumption generates industrial process heat, and heating for homes and buildings. While there will be some opportunities for substitution of PV for these uses of oil, other fuels (e.g., solar heating, natural gas, and coal) and conservation will often prove to be more attractive. Much of the most attractive substitution will occur before development of competitive photovoltaic systems is completed.

The remainder of our oil consumption is not easily affected by electricity production. Transportation consumes more than 50% of our oil supplies, but the routes by which PV may affect transportation consumption of oil--for example, electric vehicles, electric hybrid vehicles, electric mass transit, or electrically supplemented production of liquid fuels--are themselves fraught with uncertainties and obstacles.

On the other hand, there are several regions in which utility oil consumption may remain significant for a sufficient length of time to allow some local displacement of oil by photovoltaics. For example, a significant deployment of photovoltaic systems, if accomplished over the next three to eight years and interconnected with California or Hawaii utilities,* would reduce oil consumption significantly there over the next decade. The importance of PV as a displacer of oil hinges on the probability, cost and value attached to such possibilities.

Critical as the problem of oil consumption may be for the near term, present U.S. government funding of electrical energy research is (or should be) prompted by a different concern--the long-run adequacy and social cost of future electricity supply. Several federal electrical energy R&D programs other than PV have at least as equally long-term consequences (e.g., fusion, solar thermal-electric, magnetohydrodynamics and ocean thermal). The most

*The combination of very high oil consumption by existing electricity plants, restrictions on all types of conventional generation sources, high insolation levels, and growing incomes and population make Southern California very attractive for PV. No new nuclear facilities are planned. Coal in California is extremely controversial, with most options relying upon construction of coal generators in bordering states shipping the power to California by transmission line. Reduced gas consumption is also a high priority of California utilites due to rapidly increasing gas prices and NOx dispatch algorithms. Finally, access to Northwest hydroelectric power through the Pacific Intertie is expected to fall substantially. Thus it is not clear that California utilities will be able to reduce oil consumption substantially in the near term. Similar arguments can be made for Hawaii.

attractive future sources of bulk electricity supply for the nation and the world are in much doubt. Furthermore, governments have good reasons, such as the important market failures present in electricity supply (e.g., pollution, monopoly), to be concerned about future electricity supply.

For the past 10 or 15 years, long-term planning for electricity supply has relied primarily on large projected expansions of nuclear power generation. Not long ago, predictions of 200 quads of primary fuel consumption in A.D. 2000 in the United States* were coupled to large growth plans for nuclear output. A detailed evolution of nuclear plant generation, including the introduction of breeder reactors as uranium resources are depleted, has been articulated and remains the basis upon which much of DOE's nuclear funding is determined (e.g., DOE's National Uranium Resource Evaluation Program). Clearly, the future of nuclear power is now highly uncertain. The probability that large deployments of nuclear power will continue has been greatly reduced.

If nuclear power generation cannot be relied upon as a future source of electricity, two questions arise: do we really need more electricity, and where else can we get it?

With respect to the latter, the prospects are bleak. Oil and natural gas suffer from well-known problems. Coal is the only remaining conventional source and has become the dominant choice of many analysts (e.g., Ford Foundation Study Group) and of national policy. There is no doubt that the use of coal for electricity production will increase substantially. Nevertheless, coal suffers from many problems, only some of which can be ameliorated through technological means. These "solutions" often result in new problems (e.g., scrubber sludge) or higher costs of unknown magnitude. Finally, there is the poorly understood problem of increased atmospheric CO_2 concentrations that may result from massive coal combustion. Significant environmental and cost uncertainties cloud the future of coal in electricity production.

Viewed in this context, photovoltaics is one of a number of potential long-term alternative sources of electrical energy. Each of these potential new sources (e.g., fusion, wind, ocean thermal, fuel cells) should be pursued, with vigor in proportion to the expected net social benefits from supplying electricity to the nation with that source. The Photovoltaics Program is based on the assumption that PV offers genuine possibilities for a relatively inexpensive, reliable, pollution-free electrical energy supply in the long run.

The urgency and priority attached to electricity R&D may depend on projections of electricity load growth. Estimates of future U.S. electricity load growth vary widely. Actual electricity demand has, for the last five to ten years, grown more slowly than was generally expected and most projections have been substantially lowered. As a result, many U.S. utilities have excess capacity and have cancelled or deferred new plant additions. Furthermore, real prices of electrical energy may continue rising for a number of reasons, including real escalation in fuel and capital costs and movements toward

*More recent projections are 80 to 120 quads.

marginal cost pricing. Combined with conservation subsidies and programs by governments, these price rises are likely to further reduce electricity load-growth in the near term in many parts of the country.

This has little bearing upon the long-term need for new electricity sources, however. Load growth may increase in the future if current energy tensions ease, or if we have shifts in consumption patterns that emphasize electricity consumption (e.g., electric vehicles). Old plants will have to be replaced and usage of oil-fueled generators will be reduced. High regional growth rates may require new electrical production facilities. A new, inexpensive, non-polluting source of electrical power could ease these transitions. Furthermore, given the large uncertainties concerning future fuel costs for conventional generation, society would appear to benefit from diversification of its electricity sources.

Finally, much of the world is without electrical power and will be adding capacity as real incomes grow. In many less developed countries (LDCs) the costs of conventional power (nuclear and coal) substantially exceed such costs in developed countries (although many LDCs have abundant and relatively inexpensive hydro resources). Use of conventional sources by LDCs may result in unwanted political consequences (e.g., nuclear proliferation, vulnerability to fuel embargo). Thus, new sources of electrical power could benefit foreign nations, reduce world oil consumption, and moderate harmful local and global environmental consequences of electricity production substantially. For these reasons, there appear to be ample potential benefits resulting from new environmentally benign sources of electrical power. If the two primary difficulties of cost and variability of output can be overcome, photovoltaics could become an attractive source of electrical power for both the developed and developing worlds. (Applications of PV systems in LDCs are discussed in the next section.)

PV systems have many attractive features. They are highly modular--a basic PV unit (flat-plate module) typically generates 10 to 100 peak watts. These can be ganged together to reach the voltage and current levels desired, with no particular upper-bound constraints other than those imposed by the site and the associated electrical equipment. Thus, while present commercial systems are usually no larger than a few hundred watts, photovoltaic-powered individual residences, commercial buildings, industrial parks, and large central stations (on the order of hundreds of megawatts) are under serious development or experimental construction.

This high degree of modularity adds flexibility to the siting of PV systems and allows land-use impacts to be minimized. In addition, large systems can be manufactured and installed employing mass production techniques--thousands of identical components can be produced and installed in an identical fashion. New photovoltaic capacity can be financed and brought on line in small increments, resulting in shorter lead times. Exploiting these characteristics forms a portion of the PV Program cost-reduction strategy.

The modularity of photovoltaic systems does not imply, however, that systems of different sizes can be expected to have the same costs per unit. System size is inextricably linked to type of application. For example, residential systems are assumed to be 2 to 10 kW_p, commercial 10 to 500 kW_p, industrial 500 to 2000 kW_p, central 2 to 200 MW_p. Because of unique or peculiar aspects of each application, such as residential and commercial rooftop availability, ownership, subsidy and tax differences, building regulations, and regulated electricity pricing, it is not known which type of application (and, thus, which system size range), if any, will prove to be least costly. Nor can we tell which applications will prove to be commercially dominant. This is a particularly important consideration in PV Program strategy development.

PV systems offer many other apparent advantages. They can be silent, and they can have no moving parts, depending on the specific PV system technology employed. They emit no effluents and their production need not cause significant or harmful emissions. The dominant photovoltaic material (silicon) is abundant (beach sand), and chemically inert. Thus PV systems offer potential advantages compared to conventional sources, if the cost, output variability, and other problems or potential problems can be overcome.

The nature of the potential benefits to be derived from PV development have important implications for its proper conduct and funding. Decisions on the type and degree of federal involvement are based on perceptions of: (1) the social benefits to be derived from PV, (2) the effectiveness of various potential forms of government involvement, and (3) the costs. From the nature of the nation's potential electricity supply problem, we can deduce that immediate emphasis on PV deployment is unlikely to alleviate the present energy crisis noticeably, and would apparently yield few other benefits (with California and Hawaii being potentially important exceptions). Thus, it is JPL's conclusion that immediate emphasis on government-financed deployment of grid-connected PV systems is not warranted. This is made especially important because large expenditures on system deployment are likely to reduce emphasis and funding of the crucial technological developments that are currently unfolding. JPL advocates vigorous government pursuit and support of emerging photovoltaic technology, both in PV collection devices and in related PV system components, design and engineering. We believe that a thoughtfully guided R&D program can lead to a healthy, competitive and significant PV industry, supplying bulk electricity markets. Of course the type and degree of federal involvement in R&D projects is itself a controversial subject in which JPL is, for obvious reasons, very interested.

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SECTION II

PHOTOVOLTAIC TECHNOLOGY

A photovoltaic system is composed of several subsystems--array, power processor, and possibly energy storage.* The energy storage subsystem, as described earlier, is not necessary for near-term grid-connected applications. This leaves two subsystems--array and power processor--that compose a grid-interconnected PV system. The array subsystem consists of the PV collector (which converts sunlight into direct current), support structure, foundation, tracking mechanism, land, and wiring. The power processor subsystem converts the dc energy into ac energy suitable for loads, or for being fed into the utility grid. The power processor subsystem consists of the power conditioners, switch gear, utility interconnection equipment, and associated wiring. The total price of a PV system is the hardware price, including marketing and distribution, and the indirect (non-hardware) costs, namely land, architect-engineer, design and project management fees, interest during construction, sales fee, etc., as applicable. Historically, attention has been focused on the photovoltaic collector, as it is this portion of the system that contains the true "photovoltaic" elements. Nevertheless, the remainder of the system hardware and the indirect (non-hardware) items currently constitute approximately half of the total cost of a PV system and therefore are receiving increasing attention.

A. PHOTOVOLTAIC COLLECTORS

PV collectors may themselves be sorted into two groups: flat-plate collectors, which intercept sunlight directly with the semiconductor PV cells (units of active material), and concentrating collectors, which use reflective or refractive devices to concentrate sunlight onto smaller areas of photovoltaic material, thereby conserving the semiconductor material.

Potential concentration ratios range from two or three suns to as high as 2000 suns; that is, the intensity of light striking the PV cell may be as high as 2000 times the intensity of the sunlight striking the earth's surface. The efficiency of photovoltaic conversion is, by and large, an increasing function of the concentration ratio at a constant temperature.** Photovoltaic cells respond to light regardless of its angle of incidence; flat-plate collectors are able to convert both direct and diffuse radiation. Most concentrators, however, are able to concentrate direct radiation only. Thus, as the concentration ratio increases, collectors become more dependent on the direct component of the radiation. For example, most concentrators will not operate on cloudy days, while flat-plate systems may (although with substantially reduced output).

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*Historically, PV system costs have been divided between the collector and the balance of system (BOS), or "everything else." This breakdown has been superseded by the subsystem divisions discussed below.

**For example, the efficiency of a typical concentrator silicon cell rises from 13% at 1 sun to 22% at 300 suns, dropping off thereafter.

A wide variety of semiconducting materials may be employed in PV collectors, including polycrystalline, amorphous and single-crystalline silicon, cadmium sulfide/copper sulfide, gallium arsenide, germanium, titanium oxide, and a broad range of other uncommon materials. In addition, a wide variety of concentrating approaches are available, including Fresnel lenses, parabolic troughs, split-beam concentrators (which refract light of different wavelengths onto PV cells that are optimal for the wavelength each receives), luminescent dye concentrators, and thermophotovoltaics. Opportunities abound for experimental and theoretical investigation of various PV collector concepts. A great many promising concepts have not yet been thoroughly investigated, nor is it clear what today's research activity will find. Funding of basic investigations into new materials and device concepts presently absorbs approximately 25% to 30% of the resources of the National Photovoltaics Program.

Photovoltaic collectors may be fixed in place or they may track the sun. Tracking collectors range from those with seasonally adjustable tilt angles to two-axis continuous trackers. In general, concentration ratios above 8 require at least one-axis tracking. High concentration ratios (above 50) require accurate two-axis tracking to maximize the direct component of incident radiation. In addition, the shape of the output profile of a PV system (through the course of a day or year) depends primarily on the tracking mechanism, ignoring variations due to weather. For example, fixed-tilt systems (typically flat-plate) have sharply peaked daily output profiles, as they cannot collect the morning and afternoon sunlight as well as systems that track the sun from east to west can.*

The National PV Program has chosen to concentrate on collector concepts that offer some promise of electricity production at a cost competitive with power supplied by modern electric utilities. This is, of course, necessary for widespread private application in the developed world. While a wide range of novel concepts offer encouraging possibilities of low-cost production, none has yet fulfilled that promise and only a few are sufficiently understood to have been designated Technically Feasible. This designation is a formal milestone of the PV Program that all government-sponsored collector technologies must reach. Achieving this milestone implies that a well-defined set of technical conditions has been met (Reference 5); these include stability and reproducibility of the conversion material, environmental acceptability and amenability to development of production technology whose projected costs meet the competitive with conventional sources criterion. Once a collector concept has achieved Technical Feasibility, emphasis moves from research aimed at materials properties,

*Output profile shape can be an important consideration, especially for photovoltaic systems supplying electricity to electric grids where a shift in the hour of generation can affect the conventional cost of producing a kilowatt hour (and thus the value of a PV kilowatt hour) by a factor of 10 or more (Reference 6). Fixed-tilt collectors maximize their annual output if oriented due south. However, by pointing the array more to the east or west, the daily peak in the PV output can be shifted as far as early morning or late afternoon, although total energy output is sacrificed thereby.

cell design, and device physics to technical and engineering development of collector production technology.

Several flat-plate and concentrator collector concepts are presently considered Technically Feasible. All of these use silicon as a conversion material, either single-crystalline or in some polycrystalline form. The dominant concentrating concepts for which production technology is under investigation are point-focusing Fresnel lenses and linear-focusing reflective troughs and Fresnel lenses. Both one- and two-axis tracking designs are being pursued. Approximately 35% of PV Program resources are expended on development of production technology for Technically Feasible collector concepts.

The next formal milestone through which a collector concept must pass is Technical Readiness.* In essence, achievement of this milestone implies: (1) prototype production equipment and machines for competitively priced production have been designed, built, and demonstrated in small pilot facilities, (2) prototype collectors have been produced and field tested, and (3) analysis indicates that a full-scale integrated facility would produce the collector at competitive costs. Thus Technical Readiness implies that construction of a full-scale facility is the only remaining step to demonstrate fully the achievement of total production costs that allow profitable sale of PV collectors at a price meeting the Program goals, given a competitive market. No collector concept is presently considered Technically Ready for grid-competitive applications, and none is expected to become Technically Ready before the end of FY82.

B. PHOTOVOLTAIC SYSTEMS

As discussed in the introduction to this section, a photovoltaic system requires additional components besides the collector, and must be designed, marketed, shipped, installed, and connected to loads. The system configuration is highly dependent on the application.

For many applications the direct-current output of PV collectors must be converted to alternating current. Harmonics are generated, as a result of this inversion, that may require filtering before the power can be fed back to the utility line. Various other power-processing features may be required for operation in parallel with the grid (e.g., power factor correction).** The basic building block of the power processor subsystem (which also includes safety, switching, and grid interface equipment) is the power conditioner. Power conditioners are commercially available from uninterruptible power supply

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*A detailed formal definition of this concept has been formulated (Reference 7).

**PV power conditioners can be designed to provide whatever power factor the utility finds most desirable, although definite cost trade-offs are involved.

(UPS) manufacturers who supply UPS devices for special applications such as computers and hospitals, although modifications are required before they can be used in PV applications. Power conditioning is receiving increasing attention in the PV Program, with the objective of designing and testing inexpensive, reliable, effective PV power conditioners for all important applications. Cost reduction is a prime objective. For some applications (large industrial, commercial and central stations) power conditioners (when modified) apparently can be ordered at prices that meet the power-conditioning price goals of the Program (if the order size is large enough). This is not true for residential-size power conditioners because existing UPS designs require further technical development and cost reduction for residential applications.

Most photovoltaic applications require some form of backup power. (Water pumping and corrosion protection are examples of applications that do not require backup.) In applications remote from electric grids this backup often takes the form of electrical storage, although backup from diesel generators is becoming attractive in large, remote, attended applications. When electrical storage is employed, batteries (especially lead-calcium) are presently preferred. Of course, the PV system must be large enough to handle the daytime load and charge the batteries too.

Near a utility grid, the grid is an obvious back-up source. There appear to be no insurmountable technical problems in fully interconnecting PV systems with electric grids (see below), even at the end of distribution feeders (e.g., residential PV systems). Interconnecting PV systems in parallel with the grid allows two-way power flow--excess PV electricity is fed into the grid, and the grid supplies power to any loads associated with the system whenever the PV power output is insufficient.

Besides supplying an inexpensive source of backup, interconnection of PV systems allows PV power to be dispatched efficiently to meet the system load. Pooling of stochastic loads is an obvious advantage of all electric grids, as is the enhanced reliability resulting from multiple generation sources, each of which is small compared with the system load. Finally, grid interconnection allows excess PV power to be utilized efficiently, by sale to the grid, compared with the efficiency losses and wasted excess power obtained in stand-alone systems with electrical storage. For these reasons, fully interactive grid-connected PV systems without storage are the dominant configuration under investigation by the PV Program for grid-competitive markets.*

Figure 5 shows two weeks of simulated homeowner load and PV output profiles for a large home in Phoenix. The consumption of electricity is quite high during the July week (approximately 725 kWh), absorbing most of the PV output. In addition, the summer PV output is positively correlated with the apparent air-conditioning load of this household. The homeowner load appears more sensitive to seasons than the PV output in this example. Comparatively

*In essence, the grid acts as a storage device in that the coal or oil that was not consumed due to the presence of excess PV power fed into the grid is "stored" for use when the PV systems are not producing.

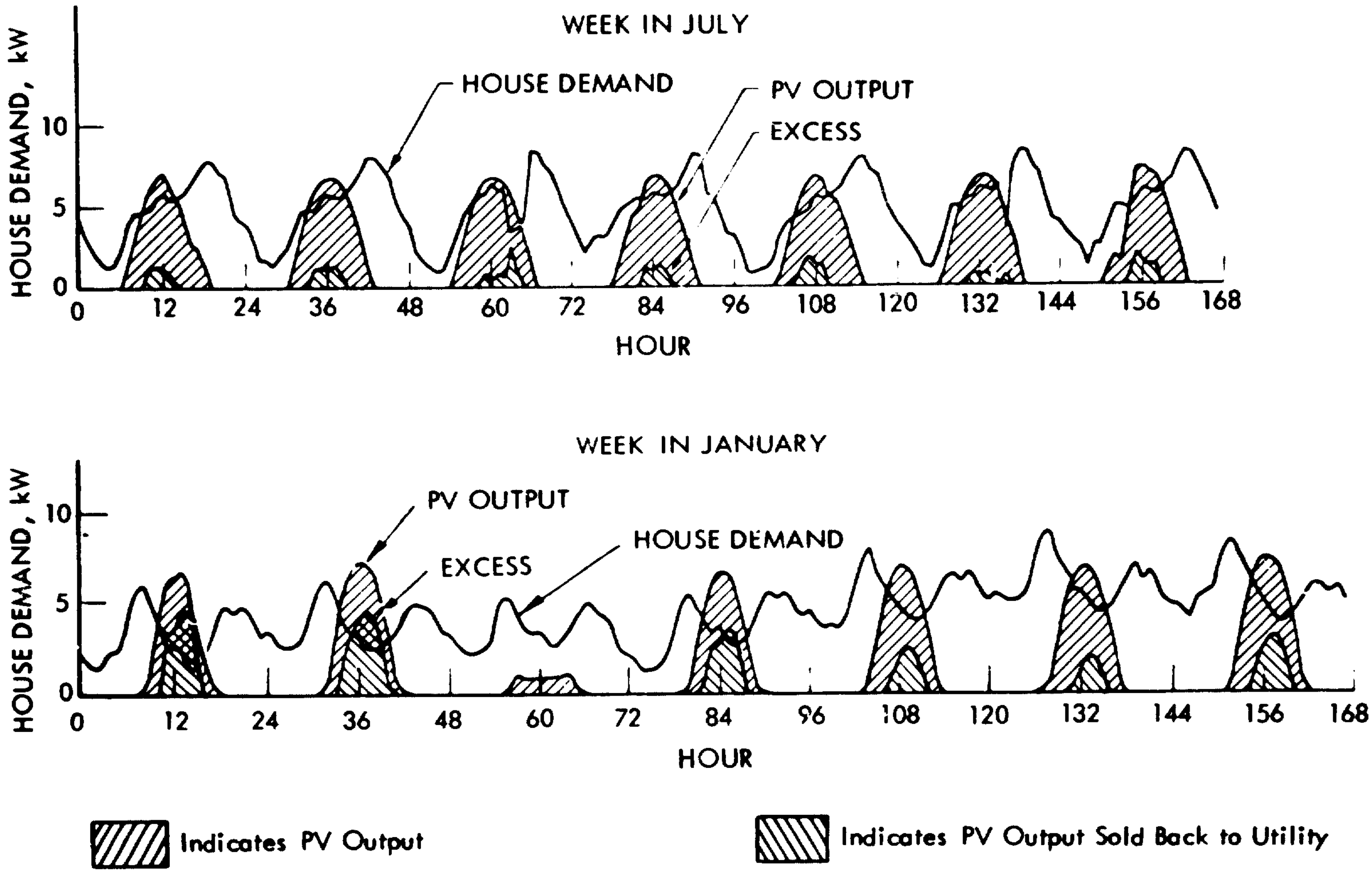

Figure 5. Simulation of Load and PV Output Profiles for PV Home Located in Phoenix With an 8 kWp PV System. Source: Aerospace Corp. Presentation at PV-Program Annual Review Meeting, April 1980

little PV excess is generated in the winter week either. Most residential PV systems this large would generate considerably more excess than this example does, due primarily to smaller average loads and to poorer correlation between output and consumption.

PV systems produce waste heat, although this is a minor consideration for most flat-plate systems since they have free air flow across the back surface (but not for integral roof-mounted systems, since the back surface is insulated by the roof) and the sunlight is unconcentrated. For concentrating collectors, the problem is more acute in that during the concentration process the infrared (heat-bearing) portion of the solar spectrum is also intensified, raising the temperature of the cell. Since the PV conversion efficiency is an inverse function of temperature, overall efficiency drops from what would be expected if the cell temperature could be held constant. Concentrator collector design is consequently a trade-off between concentration ratio (and its subsequent temperature rise) and overall cell efficiency. Some concentrating collectors (up through a concentration ratio of about 50) use passive cooling, which results in a higher cell temperature than with flat-plate collectors. For high-concentration systems, waste heat can be a serious problem requiring active cooling subsystems. The conversion efficiency of some PV materials (e.g., amorphous silicon) is not as sensitive to high temperatures as others. The waste heat produced by PV systems can be considered a by-product that may be usefully employed, although the heat produced is of low quality (temperature). Advantageous use of this heat is most likely to occur in the commercial and industrial sectors using concentrating PV systems and is being developed. In addition, the PV Program has undertaken investigations of combined photovoltaic/thermal (PV/T) collectors for residential applications. Whether these collectors will prove technically or economically feasible is not yet known.

Other system components may also be required, such as metering and display equipment, tracking mechanisms, foundation and support structures, wiring and cabling. Many components are available off the shelf. Selection and development of inexpensive, reliable foundations and support structures is important and is being pursued. Utilities have begun a long process of meter replacement to introduce new technology, thereby reducing costs and adding flexibility to rate-structure and load-management options. An important objective of this transformation is reduction in visual meter reading through automatic communications and control. Other metering changes are also decided largely without consideration of PV introduction. Metering and display equipment for PV systems that anticipate and take advantage of these trends must be developed.

In addition to hardware components, various services (marketing, shipping, etc.) make large contributions to the total cost of a PV system. Much of the strategy with respect to such intangibles is to attempt to avoid them as much as possible. For example, these costs may differ in magnitude among various applications: large central stations may minimize the costs of many of the non-hardware components on a per-unit basis. This could influence the choice between central vs distributed grid-connected applications.* In addition, proper foresight and planning can reduce many costs related to system design, legal, esthetic, institutional, regulatory, and other considerations.

*Distributed PV systems are all grid-connected systems other than central stations (e.g., residential, commercial, industrial and agricultural small power producers).

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SECTION III

PHOTOVOLTAIC APPLICATIONS

As discussed above, today's commercial photovoltaic systems serve small, unattended loads, where the competitive power sources are also quite expensive. However, PV system prices are widely expected to drop in the next five years, thereby opening up significant new PV markets.

Probably the most important factor in defining the competitive environment for photovoltaic systems at any particular site (load) is the presence or absence of utility-supplied power. Even though the prices of electricity from electric utilities vary by a factor of five within the U.S. (from 2¢/kWh to 10¢/kWh),* utility power is still quite cheap compared with other electricity sources throughout the developed world.** Thus, if considerable distance separates the load from the nearest utility feeder, a competitive environment exists that is fundamentally different from that where the grid is nearby. (Of course, the distance over which the grid can be efficiently extended is very sensitive to the size of the electric load to be served.)

A. REMOTE APPLICATIONS

Table 1 presents a list of current PV applications. Common characteristics are small power demands and either remoteness or inappropriateness for grid interconnection (e.g., the requirement of portability). While the worldwide demand for such small, self-sufficient power generators is a potential source of significant growth for the PV industry, its satisfaction through photovoltaics is incidental to the primary objectives of the Photovoltaic Program. Compared with the loads of modern electric utilities, the power demands of these markets will always remain small. Of course, the Program objective of promoting a healthy, competitive PV industry is substantially aided by the sales revenues generated in these markets.

In the LDCs, a potentially much more significant remote market exists for the obvious reason that grid networks are much less extensive in these countries. However, electrification is a primary goal of almost all LDCs, and this has most often meant vigorous pursuit, within budget constraints, of grid extensions.

For almost all applications requiring more than 1 to 5 kilowatts, the best alternative to grid power has been diesel generators. For smaller power requirements, batteries, thermionic generators and gasoline engines are competitors with PV. In any case, all significant remote markets can be and are now supplied primarily by diesel. Even some small grids are supplied exclusively by diesel power (e.g., Catalina Island). At current diesel fuel

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*Considerably higher in small or isolated systems (e.g., the Hawaiian Islands, Catalina Island).

**Some LDCs apparently have grid power costs as high as 50¢/kWh.

Table 1. Current Photovoltaic Applications

Marking & Warning Devices	Monitoring & Sensing Devices	Consumer Products
Remote airfield lighting	Pipeline controls	Watches
Destruction hazard lights	Intrusion alarms	Calculators
Navigation buoys	Pollution monitors	Boating applications
Onshore navigation systems	Gas detectors	Flashlights
Offshore platforms	Weather monitors	Pocket paging systems
Railroad crossings	Flood monitors	
Highway signs	Oceanographic data platforms	
	Earthquake monitors	
Corrosion Protection	**Communication Equipment**	**Miscellaneous PV Applications**
Pipelines	Portable radios (DOD)	Water pumping stations
Wellheads & casings	Repeater stations	Space satellite applications
Marine structures	Telephone call boxes	Military test sites
Highway bridges	Air navigation systems	Instrumentation
	Remote TV	Railroad switching
		Remote housing and villages

SOURCE: Photovoltaic Power Systems Market Identification and Analysis, Volume 1, BDM Corp., August 1978, p. II-9, with JPL modifications prices, photovoltaic systems start to become competitive with smaller, isolated diesels at module prices of about $\$5.00/W_p$. If module prices approach $\$2.00/W_p$, as they could do in the next two to four years, PV remote power systems could become a viable competitor with intermediate-size (5 to 500 kW) diesels. However, if electrical storage prices (especially for batteries) do not fall, a system configuration could dominate in which diesels are used as PV backup (or equivalently, PV systems are used as diesel-fuel displacers, since diesel fuel transportation and storage can be very expensive).

While the potential for significant PV sales in remote international markets has encouraged many observers, the actual size and significance of this market is extremely uncertain. Current sales of diesel generators for such applications in international markets are unknown. The large international diesel manufacturers do not make their sales figures public. LDC statistical information is difficult to collect and interpret. In many LDCs the majority of the population lives at an income level below that at which expenditures on products that require electricity are common. Funding must be provided from governmental or charitable sources, and PV must compete with many urgent needs of these poor people. In some higher-income countries photovoltaic system sales are hampered by either subsidized oil prices (e.g., Mexico, Saudi Arabia) or marketing restrictions (e.g., South Korea, Brazil, Taiwan).

Several attempts have been made to estimate the size of potential international remote PV markets. Two of the most recent and well-known attempts are found in a 1978 Solar Energy Research Institute (SERI) report, Photovoltaic Venture Analysis (Reference 8) and in a report prepared for DOE by Battelle's Northwest Laboratories, Export Potential for Photovoltaic Systems (Reference 9). If these projections are accurate, large markets may be available in water pumping and village power: the upper-bound Battelle estimate of the PV remote system installation rate for A.D. 2000 is equivalent in energy production to the installation of a 350 to 400 MW base-load coal facility every year. Several important U.S. photovoltaic manufacturers are convinced that this market is very large and have begun major international marketing efforts. Foreign PV manufacturers are also actively pursuing these markets.

International markets are expected to play a more important role in PV development than is reflected solely in their size. Even if the remote markets develop only modestly (compared with electric utilities) as system prices fall, PV sales growth will nevertheless be very rapid compared with the present photovoltaic market. This market growth will support sizable private investment in new manufacturing facilities required to attain PV system prices competitive with conventional generators. Thus, these markets are sometimes referred to as transition markets.

B. GRID-CONNECTED APPLICATIONS

In the developed world all significant applications of photovoltaic systems will necessarily be near grid power supplies. For reasons introduced above, the dominant system configuration in such cases is expected to include grid interconnection with the capability of two-way energy flow. While this eliminates the requirement of storage,* significantly reducing system cost and solving the variability-of-output problem simultaneously, it introduces a number of problems and complications of its own.

Not the least of these problems are the technical considerations arising from grid interconnection. Electricity may enter or leave the electrical circuit at any location. However, the amount of electrical energy available to serve a load is dependent upon where that load is in relation to the generating source. As the energy travels farther down a transmission line, it incurs losses (resistance heating); a power plant located at the end of a 300-mile transmission line suffers significantly greater line losses than would a residential interconnected PV system that occasionally supplied excess power to neighboring houses. But entry at the end of distribution feeders introduces complications of uncertain importance. Residential transformers may serve fewer PV homes per transformer than is common in existing non-PV neighborhoods. Utility substation protection systems and distribution system sizing may be affected by the presence of distributed PV. Distributed PV may interact with other distributed sources or with utility communication and control functions. Also, utilities are concerned that the characteristics (e.g., harmonics, power factor) of the PV power fed back into the grid and safety devices included in the PV system meet their quality standards. The PV system must be stable under normal and abnormal utility system conditions and must meet code and safety requirements. Technically, these and other possible interconnection problems or difficulties are relatively minor. However, whether they can be handled adequately within cost-effectiveness constraints is an open question. (Needless to say, interconnection problems are primarily associated with distributed PV concepts because PV central-facility hookups can be practically identical with conventional bus bars.)

Stability and control of the grid may pose more difficult technical problems, however. With large quantities of photovoltaic systems supplying electricity not damped by electrical storage devices, severe system-wide transients could be introduced by rapidly shifting cloud covers. These transients may be inherently more rapid than those normally experienced with conventional utility rotating machinery. Many conventional generators can be loaded at 10% or more above rated capacity for short periods (less than 30 minutes, depending on temperature), a characteristic not shared by PV systems. In addition, cloud patterns as well as the normal seasonal and daily sun patterns will introduce new complications into utility dispatch strategies, spinning-reserve requirements, maintenance scheduling and maintenance procedures, especially with distributed PV systems. Most of these difficulties will only arise, however, if PV systems become a significant fraction of a grid's generation mix (approximately 5% to 10% of energy produced), a configuration that should be far enough in the future to allow gradual adaptation. Many of these problems may disappear or be overcome for reasons unrelated to photovoltaics, such as the appearance of significant cogeneration or wind sources. None appears at this time likely to prevent significant quantities of photovoltaic energy from usefully forming a part of the nation's generation mix.

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*Storage may still be desirable, however, for a variety of possible reasons.

However, even if the grid interface questions are satisfactorily resolved, the objective of cost competitiveness places stringent requirements on PV cost-reduction strategies. Tables 2 and 3 present the primary cost (or price) goals of the National Photovoltaics Program for grid-connected markets.* Note that the markets are divided into three segments--residential, intermediate-load center (ILC), and central (or utility) markets. The ILC market includes all distributed systems other than low-density residential housing (e.g., commercial and industrial buildings, schools, apartments). Not only do system sizes differ among these three application sectors, but also the financial and tax environments and electricity rate structures differ substantially among the various classes of potential PV system owners associated with each sector. Thus, break-even prices and the relative attractiveness of the various market sectors may also differ widely.

To derive price goals for PV systems that reflect the criterion that those prices be competitive with conventional sources, it is necessary to translate the criterion into a measurable concept. The concept adopted is referred to as break-even price. This price is the PV system purchase price at which the total cost of supplying electricity with photovoltaics is equal to the total cost of supplying the same amount of electricity from the best alternative source, whatever that source may be (e.g., grid purchases, conservation, diesel generators, batteries), to the same market. Total costs over the entire lifetime of both the PV and alternative systems must be considered. (The details of the break-even price calculation are addressed in Volume II of this series.) The requirement that photovoltaic system prices fall to a point at or below break-even will, if achieved, ensure that PV electricity is as cheap as electricity from any other source.

Considerable controversy has arisen over the effects that significant penetrations of grid-connected photovoltaic systems are likely to have on the evolution of grid-generation mix. In particular, do additions of photovoltaic systems defer or displace conventional capacity: that is, does PV earn a capacity credit? Or are PV systems fuel displacers only? If grid-connected PV systems without storage do not displace conventional capacity, the obvious implication is that all planned conventional capacity additions will be needed regardless of the PV additions.** Put differently, all of the value of PV would be contained in the reduced consumption of conventional fuel, if no capacity is displaced. Through the use of sophisticated utility modelling procedures (discussed in the next paper) it can be shown that under favorable circumstances conventional capacity is displaced by PV additions (with or without storage). This displacement ranges from 0 to 40% of the nameplate rating of the PV system.

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*The price goals shown in the tables and the backup analytical activities were produced by JPL for DOE in conjunction with its cooperation with the Department in the development of Carter Administration PV Program strategy and writing of the National Photovoltaics Program Multi-Year Program Plan (MYPP) (Reference 1).

**Although the optimal mix of conventional capacities is still likely to be altered, and could easily be altered to favor system storage.

Table 2. Photovoltaic System Price Goals: Residential and Intermediate Load Centers (1980$)

Application and Year	Location	Observed Range of Energy Prices (¢/kWh)	System Prices Required to Compete ($/$W_p$)	System Readiness Price Goal ($/$W_p$)	Photovoltaic Energy Prices Assuming Price Goal is Met (¢/kWh)	
					50% Sellback	100% Sellback
Residential 1986	Phoenix	4.5 - 5.7	1.35 - 1.80		5.2	3.9
	Miami	4.3 - 5.5	0.85 - 1.20	1.60	6.9	5.2
	Boston	7.4 - 9.4	1.30 - 1.75		8.7	6.6
Selected Intermediate Load Centers 1986	Phoenix	5.1 - 6.4	1.45 - 1.90		NA	5.5
	Miami	5.5 - 7.0	1.15 - 1.55	1.60	NA	7.3
	Boston	6.3 - 8.0	1.00 - 1.35		NA	9.2

SOURCE: National Photovoltaics Program Multi-Year Program Plan, U.S. Department of Energy, June 6, 1979, p. 2-3.

Table 3. Photovoltaic System Price Goals: Central Station (1980$)

Application and Year	Location	Break-Even System Prices ($\$/W_p$)	System Readiness Price Goal ($\$/W_p$)	Resultant Energy Prices Assuming System Price Goal is Met (¢/kWh)
Central Station 1990	Phoenix	0.85 - 1.35		4.2 - 4.8
	Miami	0.65 - 1.25	1.10 - 1.30[a]	5.5 - 6.4
	Boston	0.75 - 1.30		7.0 - 8.1

(a)The range reflects uncertainty about the best goal.

SOURCE: Multi-Year Program Plan, National Photovoltaics Program, P. 2-4, U. S. Department of Energy, June 6, 1979.

Intuitively, this result can be understood for the following reason: most utilities determine their needs for new capacity on the basis of consideration of either of two measures of the generation reliability of the grid--the reserve margin (percentage by which rated system capacity is expected to exceed annual utility peak demand), or the loss-of-load probability (LOLP). LOLP is the expected number of days per year during which the daily peak demand is expected to exceed utility system capacity.* Whenever LOLP rises above a preselected point or reserve margin falls below a certain point, utilities initiate capacity additions to maintain the reliability of the system. Typical values are one day in 10 years for LOLP and 20% to 30% for reserve margin. Volume II of this document will show that additions of PV systems decrease (improve) the LOLP of many utilities because the most likely times at which peak demand is likely to exceed conventional capacity (the daily and seasonal peaks) occur relatively infrequently and often during times when PV systems are producing significant quantities of electricity (e.g., hot summer afternoons). The particular characteristics of each utility with respect to load shape, climate, and conventional generation mix have large effects on this result-- some utilities may not realize any capacity credit with PV additions. Finally, the displacement of conventional fuel and capacity by PV systems occurs regardless of the point of interconnection (e.g., in central or distributed systems).

*Thus, LOLP can be interpreted as the mean of a probability distribution. Equivalently, it can be interpreted as the probability of generation insufficiency during the peak hour of a randomly selected day.

A crucial consideration arises in ownership of the PV systems. A utility that owns a PV system directly realizes the conventional fuel and capital-cost savings. For non-utility owners of PV systems, however, all of the savings occur through reductions in purchases from the utility and sellback of excess production to the utility. Electricity rate structures (prices) are interposed between the actual realized savings of the utility and the savings seen by a distributed PV system owner. Thus, rates are crucial to the economic attractiveness of distributed PV systems. In practice, rates for purchase and sale of power can only approximate the actual savings in fuel and capacity. In many cases, rate structures are constrained by metering capabilities.

Table 2, which partially illustrates this dependency on rates, shows the System Readiness price goal to be $1.60/$W_p$ for both distributed market applications. This is the calculated break-even price for these markets.*

Note that according to this table, PV systems are almost as competitive in Boston as they are in Phoenix, owing to the higher electricity prices in the Northeast. Thus, sensitivity to electricity prices overcomes the lower insolation levels of the Northeast.

Table 3 shows the central-station price goal of $1.10-$1.30/W_p. While several analyses have yielded preliminary results showing higher break-even prices for distributed systems than for central systems, as reflected in the goals, the actual causes of these analytical results are uncertain. Furthermore, the assertion that electricity entering a grid from one generation source is inherently more or less valuable than electricity entering from a different location in the grid contradicts the previous argument that the point of interconnection is relatively unimportant. And, in fact, the calculated differences between distributed and central break-even prices are most often attributed to differences in the tax and financial environments of the prospective owners or to effective grid electricity prices that do not adequately reflect costs of service.

Nevertheless, the higher calculated break-even price for distributed systems combined with additional social and political arguments has had a large impact on Photovoltaics Program strategy. Even though all application sectors are being pursued, the Program has been aimed primarily at the

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*The final column of Table 2 shows the total cost of photovoltaic electricity per kilowatt hour under the assumption that the price goal is achieved and that the sellback rate for excess PV electricity is either 50% or 100% of the retail purchase rate. These are directly comparable to the actual range of electricity prices shown in the third column (predicted for the date of commercial readiness: 1986). Comparison of these columns shows that at a purchase price of $1.60/$W_p$ the PV system produces electricity at a cost approximately equivalent to the electricity prices expected to be prevailing in 1986. Thus, at $1.60/$W_p$, distributed PV systems break even. (All prices are quoted in constant 1980 dollars.)

distributed sector.* A high percentage of government PV system development activity has been directed at distributed grid-connected systems.

This primary emphasis on building usages may prove inappropriate if significant cost differences arise between the two classes of applications. While land area can be conserved through the use of available roof space in distributed applications and structure costs may be reduced, almost all other cost factors work against distributed systems. System installation, maintenance, sales, distribution, power conditioning, safety features, controls and displays, and insurance are all likely to cost more per unit in distributed applications. Building codes, product standards and liability, solar access, zoning restrictions, aesthetics, utility system maintenance, operation, emergency procedures, utility interconnection, PV installer training, and other complications are introduced or exacerbated in distributed applications. Thus, it is not at all clear that distributed PV systems are more attractive on a cost/benefit basis than central systems. On the other hand, strong legitimate arguments have been made in support of a distributed emphasis. These arguments often invoke strongly-felt concerns over the evolution of our social and economic structure and may be more or less directly related to electricity generation. Many would prefer distributed photovoltaics because it could reduce the monopoly power utilities hold over electric generation sources; others would like to reduce the remoteness and impersonality of electricity supply or decrease the economic and political power of utilities and "big business" in general.

Within the distributed sector, newly constructed single-family homes are one of the most attractive applications. Businesses can deduct conventional fuel costs from their taxable income; homeowners cannot. The available roof area on most commercial and industrial establishments is often adequate to serve only small fractions of their load. Residential electricity rates often are high. (Small commercial rates are usually highest, industrial lowest.) New construction can employ roof-integral PV modules, which actually replace and act as the roof of the house, with the PV cells buried in the roofing materials. (Prototypes of such modules exist.) Adequate appropriate roof area exists in most new residential subdivisions such that they could easily become net exporters of electricity, given proper initial design, without serious disruption to the aesthetic attractiveness of the neighborhood. Homeowners have historically been able to obtain attractive financing for new-home purchases, thereby financing the integral PV system as well. Retrofit of existing buildings with photovoltaics is hampered by inadequate roof supports, inappropriate building orientation and roof-tilt angles, zoning and building code restrictions, financing and solar access difficulties. For these reasons the newly constructed single-family home seems to be the most attractive distributed market. This does not imply, however, that the residential retrofit, commercial, or industrial markets show no promise.

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*Within the Department of Energy, the Photovoltaics Division along with the Active Solar Heating and Cooling Division and the Passive Solar Division constitute the Office of Buildings within the Conservation and Solar Energy Assistant Secretariat. Thus, the distributed emphasis is reflected in Department organization.

An important complication is introduced by the sale of excess electricity (sellback) from the distributed PV system to the grid. At what price (rate) should this transaction take place? As part of the National Energy Acts of 1978, Congress passed the Public Utility Regulatory Policies Act (PURPA) (Reference 11). Part of this Act is concerned with the setting of sellback rates for small power producers and cogenerators. Further discussion of electricity rates, their implications for distributed PV systems, and the methods used to arrive analytically at these implications is deferred to the next paper.

SECTION IV

THE NATIONAL PHOTOVOLTAICS PROGRAM

Much present research activity in photovoltaics is funded by the federal government. Table 4 shows the history of government PV Program funding and terrestrial PV industry sales revenue. As the table shows, federal expenditures have grown rapidly in the last half decade.

The federal Program began in FY 72 as a fairly small NSF research effort devoted primarily to collector development. JPL was an early participant in the national Program; the Low-Cost Solar Array (LSA) Project was funded in January 1975, and still constitutes JPL's primary involvement, along with the more recently established Photovoltaics Lead Center. During this early period a collector price goal of $70¢/W_p$ (1980 $) was set, a goal that was retained by today's Program and that appears to be within reach.

The major legislative mandate for the Photovoltaics Program is found in the Solar Photovoltaic Energy Research, Development and Demonstration Act of 1978 (Reference 12). This Act, signed in November 1978, established a 10-year, $1.5 billion Photovoltaics Program. Several goals for the Program were included in the Act:

(1) To establish "...an aggressive research, development and demonstration program..." for PV systems to produce electricity "...cost competitive with utility-generated electricity...."

(2) To double the annual production of PV systems every year beginning in FY79 and culminating with 2000 peak megawatts (MW_p) annually in FY88.

(3) To reduce the average cost of installed PV systems to $\$1/W_p$ by FY88.

(4) To ensure that at least 90% of all PV systems produced in FY88 are purchased by private buyers.

In addition, the Act authorized an international photovoltaics demonstration program, cost-shared domestic demonstrations and a wide variety of other government activities such as PV standards development, information dissemination, interagency and intergovernment actions, as well as ongoing research and development activities. A few months before passing this legislation, Congress enacted the Federal Photovoltaic Utilization Program (FPUP), authorizing the expenditures of $98 million over three years (FY79-81) for the purchase of photovoltaic systems for federal buildings and other federal applications. Approximately $25 million has been appropriated by Congress for FPUP. Thus, with these acts Congress made clear its intention to promote photovoltaics as rapidly as possible.

Concurrent with this emerging congressional mandate, however, the DOE PV Program of the Carter Administration was evolving a PV development philosophy of its own. This philosophy had its major articulation in two documents: the

Table 4. PV Program Funding and Terrestrial PV Industry Sales (current dollars)

	Federal Photovoltaic Appropriations (in thousands)	Photovoltaic Module Production (kW_p)	Total Industry Sales Revenue (in millions)
1973	$ 3,475[a]	NA	NA
1974	6,334[a]	NA	NA
1975	11,448[a]	NA	NA
1976	47,575[b]	417[f]	$12.5[f]
1977	65,666[b]	500[g]	15.0[g]
1978	88,200[c]	800[g]	16.0[g]
1979	118,500[d]	2000[h]	18.7[h]
1980	157,000[d]	4000[h]	40.7[h]
1981	160,200[e]	7000[h]	83.3[h]
1982	NA	14000[h]	158.7[h]

(a) Survey by Oak Ridge National Laboratory, Inventory of Energy Research and Development: 1973-1975, for the Subcommittee on Energy Research, Development and Demonstration of the Committee on Science and Technology, Volume I, Washington, D.C., 1976.

(b) Survey by (Oak Ridge National Laboratory, Inventory of Advanced Energy Technologies and Energy Conservation Research and Development: 1976-1978, for the Committee on Science and Technology, Volume I, Washington, D. C., 1979.

(c) FY79 Congressional Budget Request, Volume 1, Energy--Operating Expenses and Capital Acquisition.

(d) Appropriations for FY79 (PL 95-482) and FY80 (PL 86-690).

(e) Carter Administration request.

(f) Photovoltaic Procurement Strategies: An Assessment, Solar Energy Research Institute, June 1979.

(g) Assessment of Solar Photovoltaic Industry, Markets and Technologies, Draft Report, P. IV-3, Booz, Allen, and Hamilton, Inc., Betheада, Maryland, September 1978.

(h) Solar Energy Industry Association estimates and projections, September 1980.

Multi-Year Photovoltaics Program Plan, June 1979 (Reference 1), and Federal Policies to Promote the Widespread Utilization of Photovoltaic Systems, Volumes I & II, April 1980 (Reference 13). Both documents were DOE publications prepared by JPL with major DOE interaction.

In many aspects the congressional and Carter Administration PV strategies are similar. Both view cost reduction as a prime objective, adopting very similar cost- reduction goals. Both appear to favor a distributed, grid-connected emphasis without ruling out other options. They suggest similar funding levels (MYPP: $1.3 billion FY80-86; Congress PV RD&D Act $1.5 billion FY80-88).

Nevertheless, substantial disagreements exist. Congress has mandated very aggressive (large and early) photovoltaic system demonstrations funded by the government. While generally agreeing that the Congressional PV production goals are much too ambitious, Carter Administration policy with respect to commercialization, or market development, activities (as the demonstration program has come to be known) has been the subject of intense debate among several DOE and PV Program groups. Opinions differ widely on the purpose and effect of, and proper implementation procedures for, these market development activities.

To some extent this difference in Congressional and Administration PV policy views is a recurrence of an earlier debate surrounding the so-called "market pull" hypothesis. According to this hypothesis, photovoltaic prices are best reduced through increases in the total cumulative production of photovoltaic systems. An obvious way to accomplish this is by government purchases. Most often, the rationale to support this relationship invokes a concept known as the learning curve. The learning curve is a much-discussed and occasionally observed negative linear relationship between the log of a product's real price and the log of the total cumulative production of that product.* Many private PV and other industry spokesmen have supported a causal interpretation of this phenomenon in which all possible causes of cost reduction are subsumed within the correlation between cumulative output and product price decline.

DOE and the PV Program do not support this causal interpretation of the learning curve, nor does the PV Program strategy invoke a cumulative output-price decline relationship. JPL and the Program argue that directed research and production technology development can yield significant cost reductions. Thus, cost reduction may be directly sought and funded without relying primarily upon the incentives resulting from growing output. Congress, on the other hand, with strong encouragement and support from the PV industry, has relied much

*Learning curves have purportedly been identified for computers, hand-held calculators, airplanes, steel, and automobiles during periods of declining real prices.

relied much more heavily on cumulative output and, thus, government PV system (or module) purchases to effect photovoltaic price reductions.*

Nevertheless, this does not imply that the Carter Administration does not support significant government purchases of PV systems. Experimentation, demonstration, and achieving economies of scale (through minimum rates of output) are all invoked by various groups within DOE as appropriate objectives of government PV system purchases. Furthermore, there is substantial sentiment favoring support of the growth of the fledgling PV industry. Substantial disagreements exist among these groups over the primary objectives and optimal timing and sizes of these purchases.

Figure 6 shows that PV Program activities may be divided into three broad categories or elements. The first element--Research--includes all work directed at collector materials, processes and device concepts that have not yet become technically feasible. Once a material or concept becomes technically feasible it advances to the second element, Technology Development (TD). Here, production technology is developed for all components and for complete photovoltaic systems capable of producing these systems at the price goals. In addition, a limited quantity of fielded PV systems are required for tests within the TD element. The existing PV Multi-Year Program Plan (Reference 1) deals with these first two elements in detail. The third element--Market Development--is less well defined. The DOE report (Reference 13) presents a wide range of options for this Program element, but does not make any recommendations. Congress, on the other hand, has expressed a desire to make massive PV system purchases. No clear government policy has emerged from the Carter Administration with respect to Market Development or "commercialization."

A lively debate has arisen over the definition, and need, of a "breakthrough" in PV technology in order for photovoltaics to become competitive.**

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*A widely quoted three-volume Solar Energy Research Institute (SERI) study, the Photovoltaic Venture Analysis, June 1978 (Reference 8), attempted to investigate the value of cost reduction through system purchases under the assumption that the learning curve is, in fact, a causal phenomenon. Even under this assumption, SERI reached the conclusion that the discounted benefits resulting from massive government PV purchases were less than the discounted government expenditures necessary to effect significant cost reduction. Thus, DOE and the PV Program do not rely upon cumulative output to achieve the price goals of the Program. Interpreted this way, the dispute between Congress and DOE is, in essence, a dispute over the best PV cost-reduction technique.

**At least four prominent reviews of photovoltaics have emphasized the importance of a "breakthrough": Photovoltaic Venture Analysis, SERI, June 1978 (Reference 8); Principal Conclusions of the American Physical Society Study Group on Solar Photovoltaic Energy Conversion, January 1979 (Reference 14); Assessment of Solar Photovoltaic Industry, Markets and Technology, Booz Allen, July 1978 (Reference 15); Incentive Options for the Photovoltaic Industry, The Mitre Corporation, May 1979 (Reference 16).

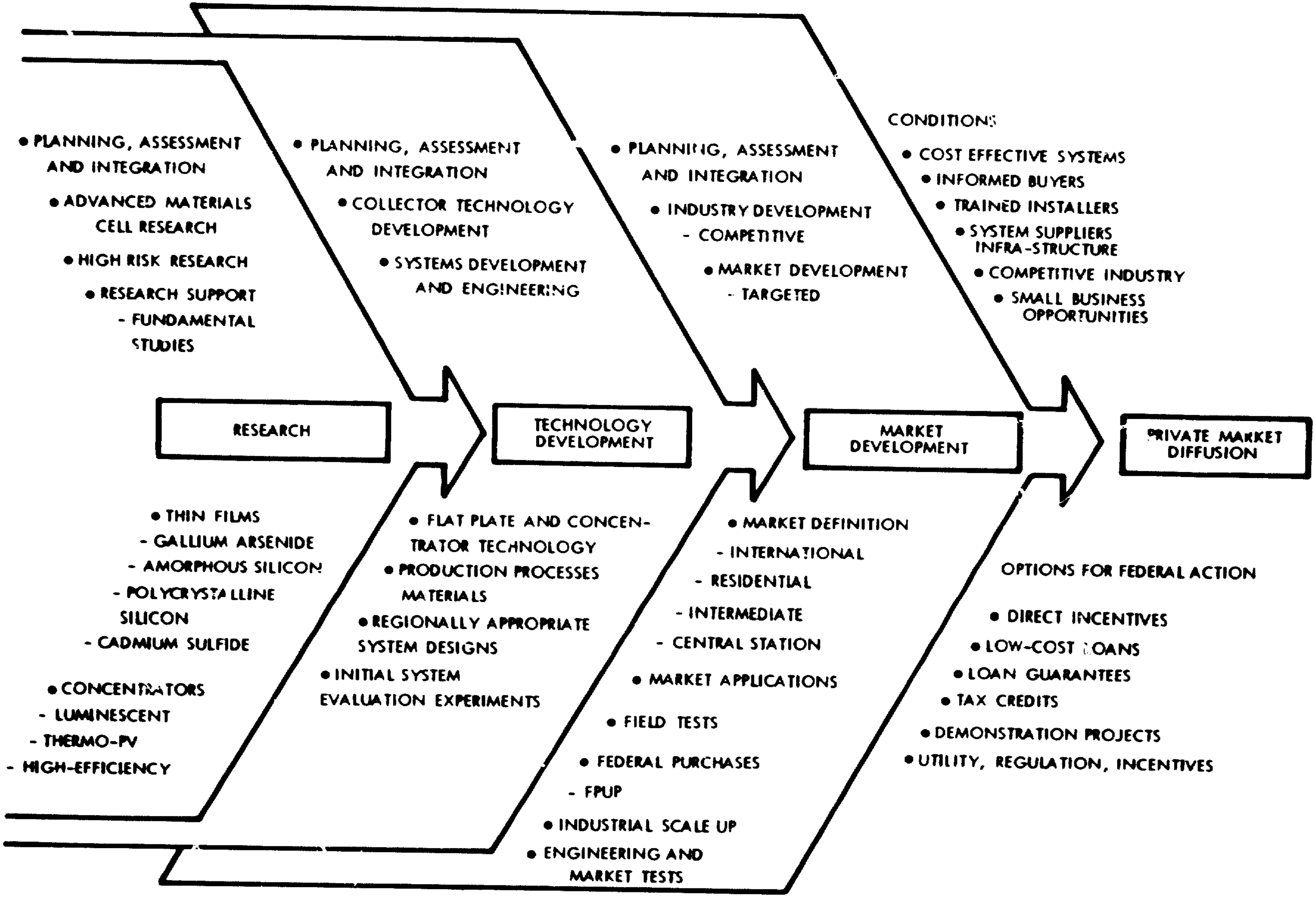

Figure 6. Photovoltaics Program Strategy

The term "breakthrough" carries an unfortunate connotation, however, that success in accomplishment of Program goals requires a major and unforeseen discovery of some heretofore unexpected phenomenon. This interpretation imparts a high level of uncertainty to the eventual outcome of PV R&D. While the possibility of such a breakthrough is not discounted, JPL does not believe that such a breakthrough is required to achieve the Program goals of Technology Readiness. These goals are achieved by technology and engineering development proceeding in small, incremental steps. Parallel approaches and techniques are pursued for each major step in the production process, all of which show promise of achieving the goals. Thus, accomplishment of PV Program goals does not require a breakthrough (in the sense it has been used), provided that the TD activities of the Program are successful.

This confusion may have arisen due to inadequate differentiation between Research and Technology Development. For each of the not-yet Technically Feasible collector concepts (those in the Research element), a major obstacle is perceived to prevent that collector concept from attaining Technical Readiness (e.g., inherently low efficiency, inability to achieve competitive costs, environmental unacceptability, unreliability, instability). Removal of these obstacles requires basic research into device physics, materials properties, etc., of a kind generically different from the R&D conducted on Technically Feasible collectors (those that have achieved Technical Feasibility and are, therefore, undergoing production Technology Development). It is this fundamental research that is more likely to result in breakthroughs. But achievement of the price goals of the Program (excepting 1990 central-station goals) does not depend on any non-Technically Feasible concepts--they can be achieved with single-crystal silicon and its close cousins through aggressive TD, according to JPL and the PV Program.

Figure 7 shows the existing DOE Program organization and participants, including their major roles. DOE has adopted a policy of decentralized management, reflected in the two co-equal Lead Centers. The Solar Energy Research Institute is the Lead Center for all non-Technically Feasible collector materials and device Research.* JPL is the Lead Center for Technology Development and Applications, which constitutes the balance of the PV Program. Several major projects report to the JPL Lead Center, including JPL's LSA Project, Sandia Laboratories, MIT Energy Laboratory, MIT Lincoln Laboratory, and NASA Lewis Research Center.

*The formal designation for the Research activities of the PV Program is Advanced Research and Development.

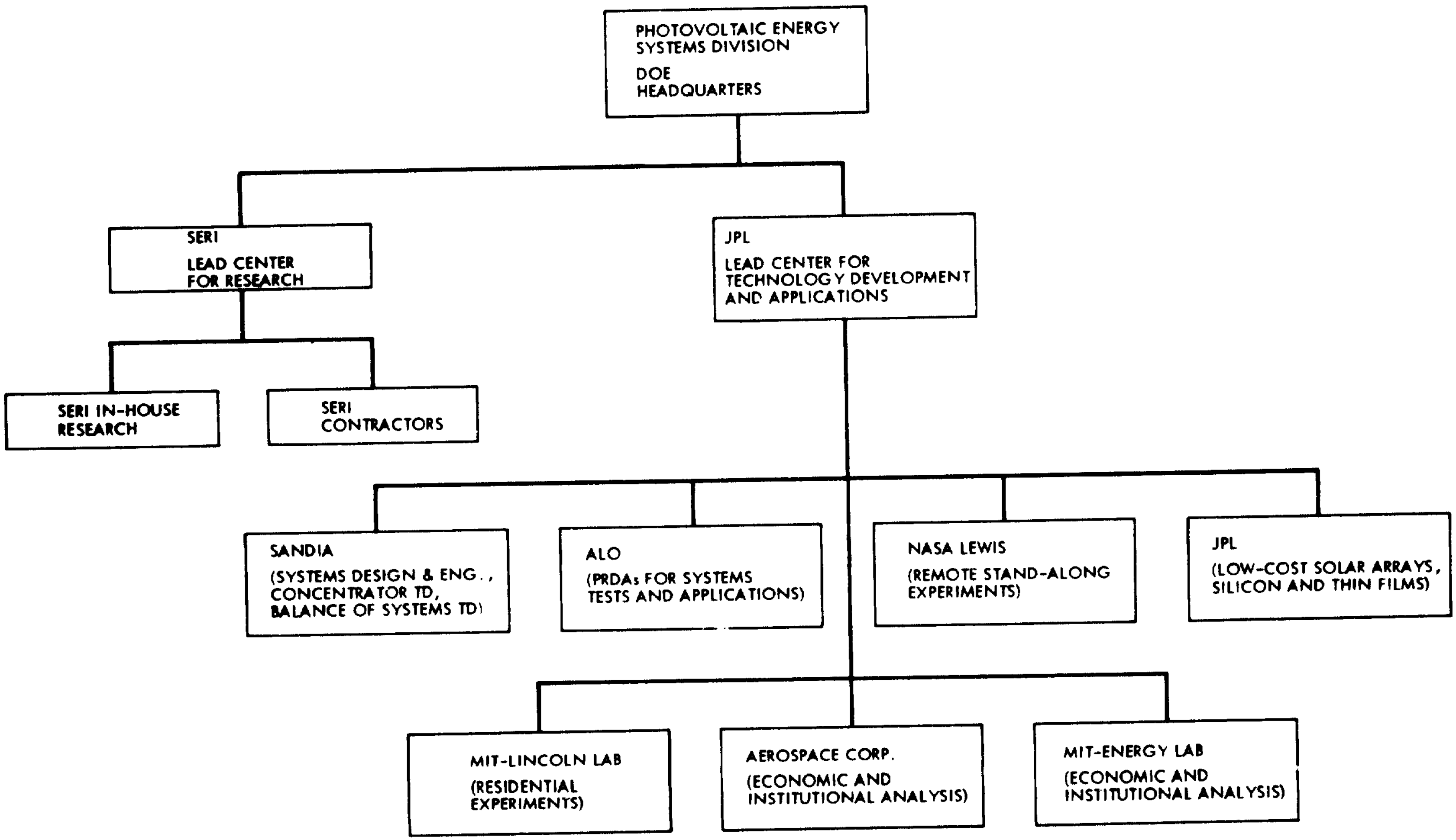

Figure 7. DOE Program Organization

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