WORKING PAPERS

The Dawning of Solar Cells

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The **Institute for Local Self-Reliance** is a non-profit, tax exempt research and educational organization based in Washington, DC. It explores the possibilities of urban communities becoming productive, increasingly self-reliant systems — raising their own food, generating their own energy, utilizing their "wastes," and directing their own affairs. The Institute investigates the technological, economic, and legal tools needed to make those possibilities real.

Abstract

Solar cells are devices which convert sunlight to electricity. Often overlooked as a possible source of electricity in the near future, solar cells can, according to those presently manufacturing them, and various government reports, supply almost 100% of our electrical requirements by the year 2000 and can be producing significant amounts of electricity within the next five to ten years. The technology is currently available to bring the cost of electricity from solar cells close to that of electricity generated by conventional power plants.

Solar cells are already being manufactured and sold. Their use, however, is limited to remote applications. They are presently too expensive for widespread utilization. What is needed is for an artificial market to be created for a short period of time while the cells are expensive in order to permit automation of plant facilities and the initiation of a learning curve which could reduce the cost of the cells rapidly. This can be accomplished within the next five to ten years.

Solar cells have relatively few economies of scale. A household can generate its own power just as, or more, efficiently as can a central power plant. As a result of solar cell technology we will have to re-evaluate our present system of increasingly centralized metropolitan and even regional generating plants.

In addition, there is a pressing need to educate the public to the immediacy of the potential of this overlooked energy resource, and to initiate training programs for personnel who can install and service solar cell systems, as well as for professionals who can supervise production.

Given the amounts of funding which are required for this undertaking, and the kinds of public education programs and training which are involved, federal intervention will probably not be the major factor in determining whether solar cells have widespread acceptance and use in the near future. Smaller units of government, such as single cities, or counties, or states, could develop low cost solar cell technology by utilizing their own capital mechanisms, with the federal government assisting by giving tax breaks to businesses and homeowners involved in solar cell production or installation. Investment and production tables developed by those currently manufacturing solar cells indicate that through contractual arrangements a city or county could well subsidize solar cell development through its initial high cost period with relatively minor funding, and could gain this back within a decade through reduced fuel costs or increased "export" sales.

What are Solar Cells?

Solar cells, or photovoltaic cells, are semi-conductor devices which convert sunlight directly into electricity. Most solar cells are made from silicon, the second most abundant element in the earth. Silicon is usually reduced from sand, which is mostly silicon dioxide. Impurities of another material are added to the silicon (a process called "doping") in order to produce the photovoltaic effect. When the cell is connected to an electrical circuit, a light photon striking the doped silicon causes electrons to move and a current to flow.

Solar cells are very thin, wafer-like devices. Each solar cell produces a small amount of voltage and current. The cells are connected in series or parallel, in order to gain the required voltage and current. **Cells** are interconnected into what are called **modules** and several modules connected together comprise a solar **panel**. These panels are covered with a protective coating, at present a transparent silicone rubber coating.

These panels are installed at slopes of 45 degrees facing the sun. The entire package is called a solar **array**. The arrays, in turn, are part of a **system**, which includes devices for power conditioning, inverting the current, and storage.

The current leaving the solar panels is direct current. However, most of our appliances, especially those with motors in them, require alternating current. A device called an inverter is currently available at relatively low cost which changes direct current into alternating current at about 90% efficiency.

Energy is produced from solar cells only when the sun is shining. Therefore a system for storing the electricity for those times when the sun is not shining is necessary. At present this means using lead acid batteries, heavy duty batteries slightly larger than those we now have in our automobiles. One expert has determined that in a residence with 2000 square feet of rooftop solar panels it would require 25 cubic feet of batteries for 3-5 days storage needs (1). The total cost would be around $600.

Solar cells currently manufactured have efficiencies between 12 and 18%. This means that between 12 and 18% of the sunlight striking the cell's surface is converted into electricity. At noon on a clear day at sea level, the amount of sunlight striking the earth has a power of about 1 kilowatt per square yard. Thus, if a square yard were covered by solar cells having a sunlight to electricity conversion efficiency of 12% it would produce about 120 watts of power.

Researchers in the 1950's discover-
d that to make efficient cells the
ımbled polycrystalline structure of
ıetallurgical, or regular, silicon,
ıust first be converted into the
rderly, all-in-a-line structure of
ingle crystal silicon. In other words,
he molecules in the silicon must be
ıade orderly for the cell to attain any
ind of efficiency. The technique of
rystal growing used then, and now,
called the Czochralski process. The
ıllowing description gives a good
lea of both the process of solar cell
ıanufacturing, and the inefficiencies
ıvolved in it.

One batch of silicon must be melted for each ingot. A pinch of boron, phosphorous, or another impurity, converts the purified silicon (a poor electrical conductor) into a semi-conductor. Then a silicon seed crystal is lowered into the 2588° F. liquid and an ingot is "grown" [ed. note— A better word might be "pulled". There is never more material coming out than is going in. One puts in, for example, two pounds of poly-crystalline silicon and gets out two pounds of single crystal silicon.] by twirling and pulling the seed upwards at a few inches per hour.

But, once an ingot has been painstakingly grown, up to three-quarters of it must be destroyed to produce solar ells. . . . A circular diamond saw, which looks much like its cousin at your meat counter, zips slices from icicle-like silicon ingots as easily as it would cut through bologna. The silicon slices are only 10 to 12 thou-sandths of an inch thick. But since the saw blade is also this thick much of the ingot becomes sawdust. Rectangular cells, used for compactness in space, waste still more silicon.

Grinding and polishing these silicon wafers pushes labor costs higher. Wafers are then baked in a chemical atmosphere that diffuses another semi-conducting layer into one surface. (2)

Each solar cell has etched into it
hreads of aluminum, much like the
ıetwork of veins in a leaf. These pick
ıp the electricity from the cell. Elec-
rical terminals are attached to these
hreads and the wafers are wired into
olar panels.

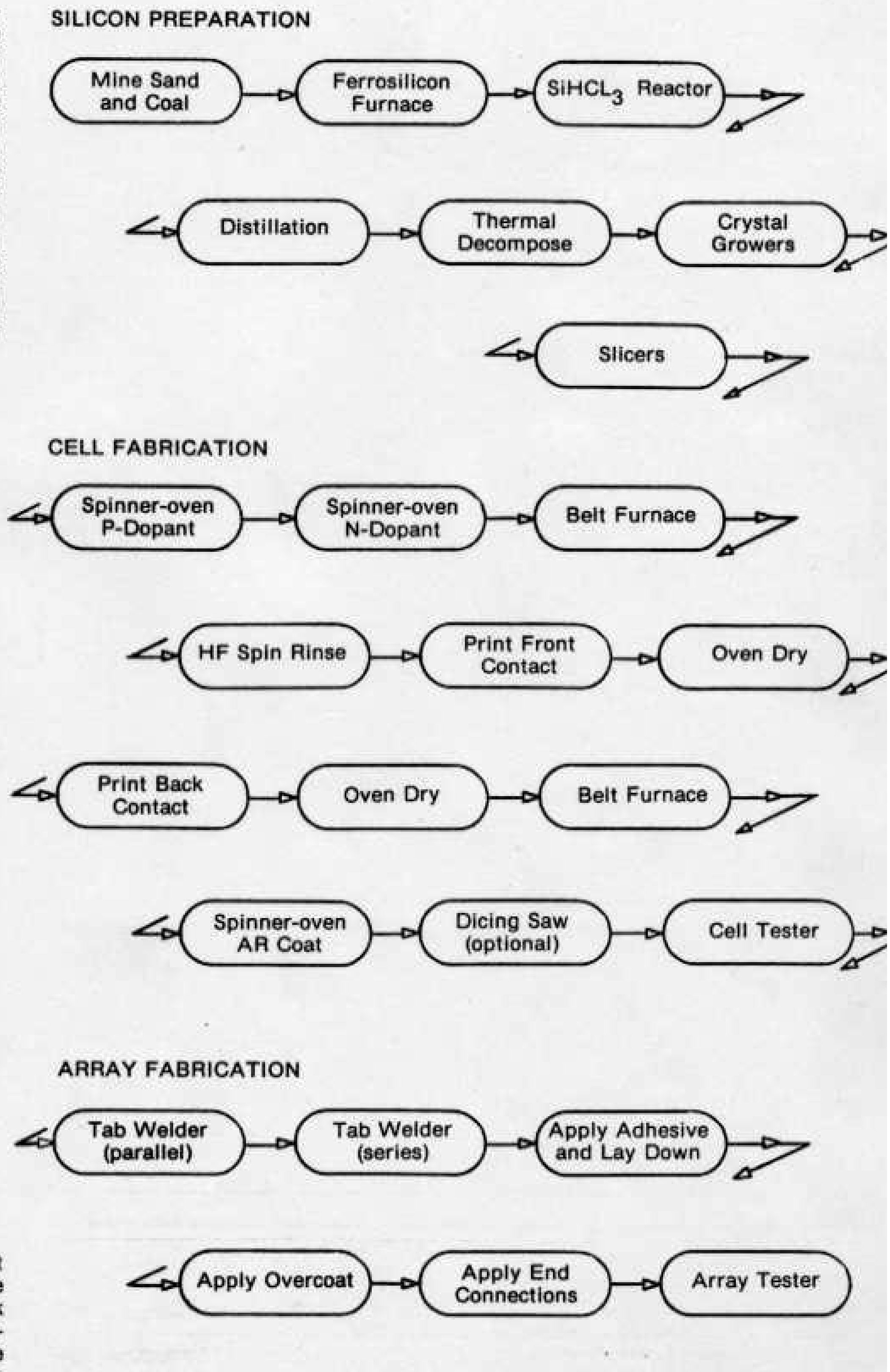


Figure 1. SOLAR CELL MANUFACTURING FLOW DIAGRAM

There are other processes which are currently being developed to permit single crystal silicon to be "pulled" at much faster rates than the present 4 inches per hour and to reduce the loss of over ¾ of a silicon cylinder when wafers are cut from it. The major difficulty is how to grow the single crystal silicon rapidly while retaining the high degree of crystallinity within it which is required for the cell to have even moderate levels of efficiency.

The most highly developed, and publicized, technique, is called the Edge Defined Film Fed Growth process whch produces ribbons of silicon which can be cut into blank solar cells. In this process a powder of raw silicon is placed in a heat-resistant metallic crucible. A coil surrounding the crucible induces a magnetic field in the metal, heating the container and fusing the powder into a white hot molten base. This liquid rises within metal capillary tubes inside the crucible. Then a seed crystal is fused to the top of the capillary liquid and is pulled slowly upward. The liquid flows only to the edge of the capillary form, whose shape determines the pattern of the growing crystal.

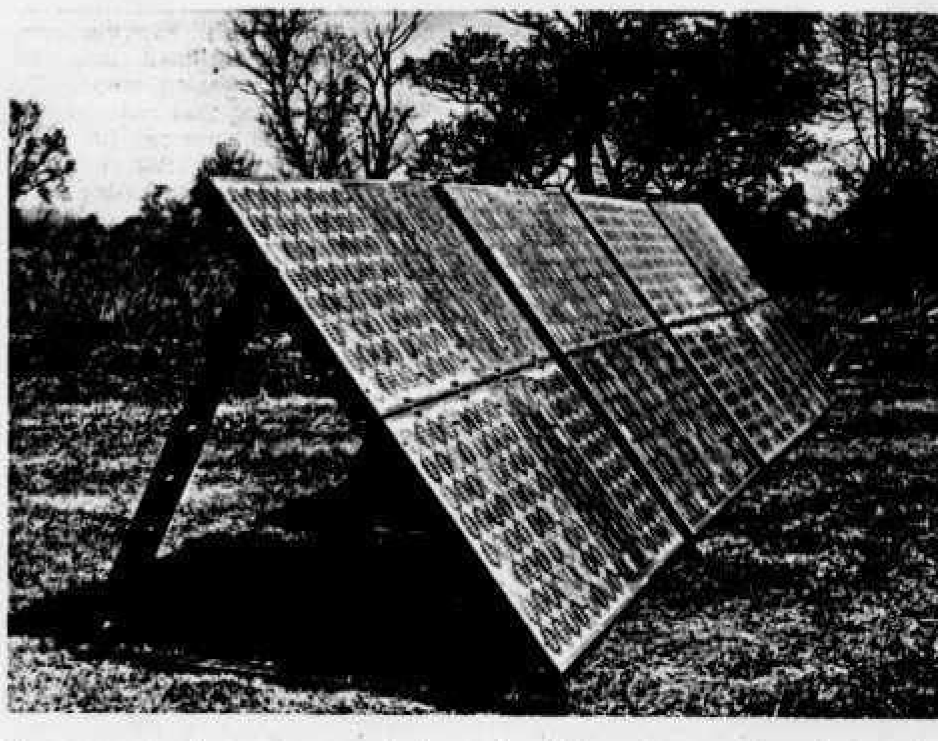
The Cost of Solar Cells

Solar cells have been manufactured for almost twenty years. However, most solar cells were used in space satellites, where cost was not a vital criterion since there was no comparable fuel source for satellite batteries. It was only in 1972 and 1973 that solar cell technology was first applied to the production of inexpensive solar cells for terrestrial use. In 1972 the cost of solar electric generating capacity was over $100 per watt compared to about $1 per watt or less for fossil fuel generated electricity. Within a year, mostly through the efforts of the Solarex Corporation, and with an investment of less than half a million dollars, this cost was reduced from 100 times to 20 times the cost of conventional electrical generating facilities.

Solar cells currently cost $20 per peak watt for a complete panel (however, in 1975, Solarex Corporation of Rockville, Maryland lowered the price to $17 per peak watt for orders of a few kilowatts, and in 1976 the low bid for ERDA procurement contracts was $13 per peak watt). In solar terminology a peak power rating is defined as the amount of power that would be generated in direct sunlight in the middle of a bright day at 77° F. Since we must take into account cloudy and rainy days, as well as times when the sun is not shining, another term, called average power, is used. Average power is about one-fifth of peak power. If I have a solar array on the roof which generates 1 kilowatt of peak power, it actually generates an average of around 200 watts assuming that I have an adequate storage system that can store the energy produced when the sun is shining to use it when the sun is not. In other words, I can count on a 1 kilowatt peak power system delivering 200 watts of power whenever I want it.

The ratio of 5-1 average to peak power is widely accepted. In areas where there is a great deal of sunlight, like the American Southwest, the ratio drops to 4-1. The rule of thumb is that we need five times the average power requirements on the roof. The average household in the United States requires 1 kilowatt of average power for its electrical needs, assuming that it is not heating with electricity. The average household uses 500-600 kilowatt hours of electricity per month. This requires solar arrays which have a peak power of five kilowatts, and this, in turn, for a solar system of 10% efficiency, requires rooftop space of 420 square feet.

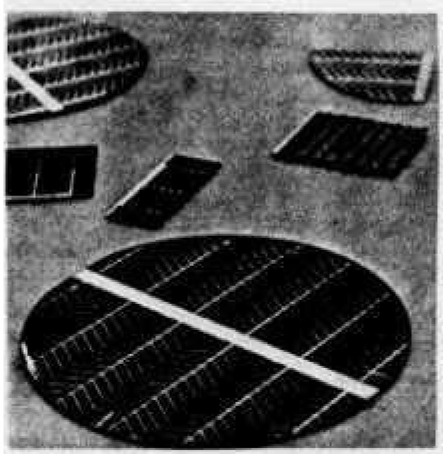
At present, manufacturing techniques for solar cell production are comparable to those at the start of the industrial revolution in England in the 18th century. A visit to a solar cell factory shows everything done by hand, inefficiently and slowly. The wafers are cut by simple machines; individual cells are tested by hand, and etched by hand, and the coatings are applied by hand. Nothing is automated, although most of the processes lend themselves readily to automation. Fig. 1 is a schematic representation of the solar cell manufacturing process.



An array of solar cells manufactured by Solarex Corporation of Rockville, Maryland.

There are many areas where the cost of manufacturing could be rapidly reduced. One such area concerns the cost of single crystal silicon blanks (upon which the solar cell is made, by adding impurities and etching the silvery threads which conduct the electricity). Silicon now used in solar cells must be bought from the semi-conductor industry, and meets the very rigorous standards of that industry. Silicon used for semi-conductors has an impurity of one-fifth part per billion, or is about 99.99999998% pure. Metallurgical silicon, that is, silicon gained directly from sand, has a purity of 98%. Pure silicon is about 100 times the cost of metallurgical silicon, $10-20 per pound, or $2 per watt, versus 10 to 20 cents per pound (about the cost of steel). One of the major reasons for this difference in cost is the complicated process and huge amounts of energy inputs necessary to remove the last few percent of impurities in the regular silicon. It is believed that silicon of one part per million purity is sufficient for solar cell production. Dr. Paul Rappaport, Director of Process and Applied Materials Research Laboratory of RCA has noted:

the starting material called polysilicon could be reduced in cost by a factor of 3 if one grade of material is required which does not have some of the special specifications as needed for present day applications. (3)



Standardized panels, manufactured by Solarex may be used individually, in parellel or in series to provide the required power.

In fact, part of the reason that the price of silicon is so high to the infant solar cell industry is that it buys in such small quantities. The price would drop below the $2 per watt level immediately if the industry could begin to buy in sufficient quantity.

The factor of automation itself could dramatically decrease the price of the cells. Dr. Charles E. Backus, Associate Professor of Engineering at Arizona State University, has explained:

The nature of the solar cell combined with the high technology history of the electronic industry indicates that large cost reductions are possible as compared with highly material intensive solar thermal systems. The solar cell is an electronic product and lends itself to mass production techniques and complete system packaging in a manufacturing plant. (4)

Currently almost 70 to 80% of the total cost is labor. Dr. Rappaport predicts that automatic fabrication of cells could produce a cost saving factor of over 20. In fact, he adds:

A solar cell is a much more simple device to make than an integrated circuit. For the integrated circuit we have about 500 individual processing steps. We have something that sells for $10 per chip. The solar cell probably requires less than 100 steps for fabrication. Fabricationwise it is relatively simple. (5)

In the federal government's Project Independence Task Force Report on Solar Energy, published in November 1974 (hereafter called the Task Force Report), Spectrolab, at the time a division of Textron, Inc., did a cost analysis study of solar cell development using current technology and off-the-shelf equipment, assuming no major breakthroughs and only sufficient volume purchases to justify automation (6). They predicted that the cost of producing and manufacturing solar cells could be brought down from $20 to $2.15 per peak watt by 1977. If some moderate assumptions were made, such as assuming a cost reduction of silicon (not by new processes such as the Edge Defined Film Fed process but merely as a result of a new process development aimed at producing material especially purified for solar cell use), an increase in the growth rate of the crystals from 4 inches to 8 inches per hour, and a reduction in slice thickness and kerf (losses due to the saw blade cutting through) and etching losses, the figure could be reduced to $1.14 per peak watt, or, in the opinion of several observers, very close to that of fossil fuel generated electricity in the late 1970's.

If one further assumption is made, that volume orders increase enough to justify new fabrication equipment that increases output to 3600 units per hour rather than the 900 units assumed under the scenario laid out above, the results would reduce array costs to only 68 cents per peak watt. And, most important of all, this could happen in just a few years, due to the introduction of mass production techniques rather than technological breakthroughs.

What will all this mean for the average household? How much will the solar cell system of the near future cost the individual homeowner? The Task Force Report addressed itself directly to that point. The table in Fig. 2 summarizes the costs of a residential electric generating system in 1985 with sufficient power to meet the average residence's electrical needs (7). At that time it estimates a cost of 50 cents per peak watt, or $500 per peak kilowatt; in 1995 the cost is seen to drop to $100 per peak kilowatt.

As we see from the table, the total costs include storage facilities for 18 hours plus installation costs and a contingency fund of 10%. Included also is an assumed cost of capital of 8% per year for 30 years. The variation in the total cost depends on whether a 5:1 or 4:1 ratio is used of average to peak power. Given the relatively short storage period, back-up might be required in some areas of the country which have multiple cloudy days, although the storage facilities could be increased without dramatically increasing the cost of the system.

What we see is that for around $4000 in 1985 and around $2000 in 1995 a household might produce all the electricity it needs for air conditioning, cooking, refrigeration, appliances, and lighting. If we examine the cost of such a system in terms of the cost per kilowatt hour of electricity generated over the life of the system we discover that the 1985 system costs between 6.9 and 8.1 cents per kilowatt hour. In 1995 the cost of operating would drop to around 3.9 to 4.7 cents per kilowatt hour. Current costs of electricity vary widely in the United States, with an average of 3.5 to 4 cents per kilowatt hour; the highest rate occurs in New York City with a rate of 9 cents per kilowatt hours.

A Long Aside on Costs

Even these estimates may well prove to be conservative. As Dr. Martin Wolf, research associate professor of the University of Pennsylvania points out:

Since fuel costs are not incurred in solar energy utilization and other operating costs are expected to be held to a negligible level, the annual capital costs form the major cost item. These in turn are determined primarily by the original costs of the system, its life, and the interest costs. (8)

In almost all of the cost estimates we have seen the interest costs have been spread out over the life of the system, with the life given as 25 to 30 years. As a result, using an interest rate of 8% per year we find that a $4000 system will actually cost around $10,500 over the 30 year period. As a result approximately $6500 or 60% of the total cost is in interest. Yet it is not at all clear why the average homeowner would want to pay out interest over this long period. Instead of using home mortgage financing as our basis for comparison (incidentally home mortgages are now financed over 20, not 30 years) it might be more apt to use automobile financing figures. A $4000 car is usually financed over 3 to 4 years. Total payments come to around $4500 - 4700 with payments of $100 per month. It is true that a person would need to pay higher sums in the beginning of this period to pay off the system cost, but would not be saddled by high interest payments over long periods of time. Using the example of a 4 year payback we find that payments of around $100 per month are required for a car in the $4000 bracket. In New York City, which has the highest cost for electricity, but which many observers see as a good indication of where many electrical systems will be in a very few years, we find that the average family pays around $50-60 per month for electricity. Thus people will have to pay out between two and three times what they are currently paying for electricity for four years, and will then have decades of free electricity ahead of them.

And, of course, this does not take into account the fact that the government might well move to decrease interest rates used in buying solar cells since in buying them people will be decreasing pollution, and helping the balance of payments crisis in this country.

If this kind of cost accounting system is used, rather than the 30 years at 8% commonly accepted, we find that solar cells will become competitive with conventional generating facilities at the $2-3 per peak watt level, instead of the 50 cents to $1 per peak watt figure currently used.

In addition, the operating life of the solar cell system may well be much longer than the 25-30 year period the Task Force Report uses. Most people with whom we have spoken in the solar cell industry point out that the solar cells themselves should have an indefinite life. Modern solar cells were invented in

Residence	**1985**	**1995**
Array Cost	$500/kWe (pk)	$100/kWe (pk)
Support Structure/Install ($15/m^2)	126	126
Electrical	16	16
Power Conditioning	30	30
Storage Cost (18 hours)	136	136
Misc. Plant/Install	40	40
	$842/kWe (pk)	$448/kWe (av)
Contingency/Spares (10%)	85	45
	$933/kWe (pk)	$493/kWe (pl)
Ins (av)/Ins (pk)	.25 - .20	.25 - .20
Total Systems Cost	$3732-4465/kWe (av)	$1972-2465/kWe (av)
O & M Cost	5 mills/kWh	5 mills/kWh
Power Cost (25-30 year life)	69-81 mills/kWh	39-47 mills/kWh

*Assumption: Cost of capital = 8% (per year)

Figure 2. COST OF A RESIDENTIAL ELECTRIC GENERATING SYSYTEM IN 1985.

1954; cells manufactured around that time continue to generate electricity with unchanged efficiency. As Dr. Joseph J. Loferski, Professor of Engineering at Brown University has said, "Indeed, the operating life of solar cells in terrestrial systems is essentially infinite; to stop them from generating the cells would have to be subjected to deliberate physical destruction." (9)

The solar panel, however, is not so invulnerable. The electrodes and electrical connections, and the coating, usually a silicon transparent coating, might break down over time. But this means only that every fifteen or twenty years or so the panels might need maintenance and recoating, much as one's house needs to be repainted. But the house need not be rebuilt, and the solar cells need not be totally replaced.

It is, however, difficult in the real business world to take this indefinite life into account. Banks will not permit loans to cover 100 years; it is difficult to amortize systems over that period because there is the feeling that the house itself may no longer be standing, or its owner might be dead, etc. Of course, it is also true that the cells could be removed and used on other sites fairly easily. They are transportable. If we were to give solar cells a life of 75 years in our calculations we find that they become close to competitive near the $5-8 per peak watt level, a level which could be reached within two to three years.

One final comment about maintenance. Solar panels will collect a fine film of dust immediately, which in no way reduces their efficiency. It will not collect more dust than that, however. Ice doesn't affect its performance (solar cells operate efficiently at the south pole) and even a heavy snowfall is only a temporary bother, although even with some snow on them the cells will continue to operate at reduced efficiency. As a result maintenance costs are kept at an absolute minimum.

Technological Breakthroughs

Price reductions are not dependent on technological breakthroughs. As the Solar Energy Task Force Report of Project Independence noted, "by just extending conventional silicon crystal growing and slicing techniques and not counting on any major new technology advancements we are able to project solar cell array costs to about 75 cents per peak watt."

However, technological breakthroughs can reduce the price still further, and may permit decreases in the price more rapidly. There is work now going on to research the viability of using other materials than silicon for solar cells. Work is progressing on the development of gallium arsenide as well as organic solar cells. The cadmium sulfide cell is apparently out of the experimental stage after a year of testing. Solar Energy Systems, a subsidiary of Shell Oil, is now selling such cells, and plans on having a 600 kw production capability in 1977.

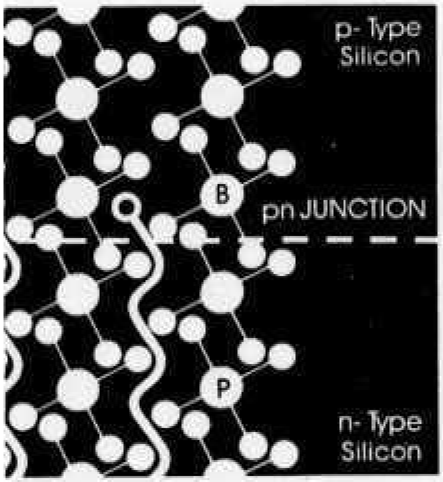
Cadmium sulfide has always been potentially cheaper to manufacture than silicon solar cells, partially because cadmium can be laid down in thicknesses which are 1-2 microns thick, instead of the 100 micron thickness needed for silicon solar cells. Cadmium sulfide cells have in the past been plagued by a rapid breakdown in the cells and low efficiencies. But testing by the French space agency indicates that hermetically sealed cells work very well over several years of exposure to the elements. Although cadmium sulfide cells have much lower efficiencies than silicon solar cells (7% versus 16%) some experts believe that for equally large productions levels cadmium sulfide cells can be manufactured at a much lower cost than silicon solar cells.

The federal government is still emphasizing silicon solar cells. ERDA is hoping to use concentrators to lower the cost per power output while the cost of the cell is still high. A concentrator of 40 has been demonstrated at Sandia Labs, in New Mexico. The concentration phase of development is a short term venture, because as the price of the cell drops to 50 cents per peak watt the concentrator itself will become the major cost component of the system, and will be eliminated. It is hoped that concentration can open up the intermediate market soon.

There is much work going on to reduce the cost of the raw material, silicon. With respect to manufacturing procedures, it has been noted that solar cells are easier to produce than integrated circuits, the latter requiring 500 fabrication steps, and the former only 100. But the solar cell uses vastly more silicon than the integrated circuit, and the cost of high purity single crystal silicon is now about $2-3 per peak watt. It is hoped that the Czochralski process can be bypassed completely by depositing good quality single-crystal silicon directly from silane (SiH_4). This would reduce the consumption of electrical power, reducing the payback period to a matter of months (see section on net energy), and would eliminate the crystal growing stage and reduce the loss of silicon incurred in shaping cells to produce high packing factors. In addition, silane is more suitable to production of thin films because deposition occurs at much lower temperatures.

Two methods of ribbon growth of the silicon crystals are being investigated. One, called the Edge Defined Film Fed Process, developed by Tyco Laboratories, a subsidiary of Mobil Oil, is a process of pulling the silicon through a die. Cells produced by this process have reached 10% efficiency, and ribbons several feet long have been pulled, but unfortunately there is a high proportion of "dirty" silicon, meaning silicon with poor crystallinity, and this process appears to be several years from commercialization.

The second process is called the web dendrite process, whereby the silicon crystal is pulled directly from the molten silicon. Westinghouse is currently experimenting with this under a grant from NASA, and it appears that commercialization is further in the future than the Edge Defined Film Fed Process.



Solar Cells: Impact on the Nation's electrical Needs

How quickly can solar cells have a significant impact on our nation's electricity supply? The Task Force Report relates two scenarios for future use of solar cells. The first is called the "business-as-usual" scenario, that is, assuming current levels of government funding (which at the time was $1.2 million per year, although the proposed current budget calls for $10 million to photovoltaic cell development), no tax breaks for those who produce or install a solar cell system, and no policy to encourage solar cell use. Basically this scenario calls for private capital to bear the burden of solar cell development almost entirely.

The other scenario is called the "accelerated orderly" schedule (there is, interestingly, no schedule for a crash program). This assumes that the government will provide tax incentives for industry and homeowners, and that there will be a heavier government subsidy to the program (although in no case do they propose subsidies more than 5 to 10% of the subsidies planned for nuclear fusion research). Also it assumes that the government will encourage solar cell development by creating an artificial market for high priced solar cells to permit automation and cost reduction. Basically this scenario calls for the federal government to take certain steps to insure that the large initial investment in solar cells by the homeowner or industry can be spread out over a number of years through accelerated depreciation allowances, tax credits, or outright tax grants.

With a rather minimal level of government intervention, the following schedule is predicted:

Fiscal Year 1979 — Demonstration of technological feasibility of 50 cents per peak watt solar array
Fiscal Year 1979 — Designing plant for automated production of solar cells and arrays
Fiscal Year 1983 — Installation of plant for large scale production of arrays at less than 50 cents per peak watt

When we examine the estimates for how quickly solar cells can have a major impact on our nation's electricity needs we run up against probably the major understanding in this entire area. There are, to be sure, some government officials, like Dr. H. Richard Blieden, deputy director of the National Science Foundation division of Advanced Energy Research and Technology who predict that solar energy's share of the nation's electric power needs could be as high as 30% by the year 2000 (10). But most public statements by government officials suggest that we can hope for only a 1% contribution to total electricity by the year 2000. These kinds of projections overlook three important factors: the current decline in electricity usage in this country; the exponential aspect of solar cell production; and, the effect that solar cell generated electricity will have on fossil fuel reserves.

One of the major difficulties is that the federal government is still projecting electricity demand growth based on the late 1960's, when the growth rate was 7% per year and total electrical demand was doubling roughly every ten years. Thus many government reports project that we will need three to four times the electricity we now consume, in the year 2000.

However, due to skyrocketing rates and conservation efforts by customers the power industry's summer peak increased by only 1.04% in 1974, according to **Electric World** (11). Almost half of the 77 utilities surveyed had summer peaks which actually declined from the previous year. The Federal Power Commission's own Bureau of Power has compiled electric generation data for the first nine months of 1974 showing that the amount of electricity generated that year was 1.63% **less** than for the same period in 1973. After a $4 million two year study the Ford Foundation's Energy Policy Project found that a long-term average growth of about 2% annually is both technically feasible and economical. This would mean that the demand would grow by around 80% by the year 2000, instead of the 300% projected by federal government estimates.

This becomes especially important if we examine the table in Fig. 3, reproduced from the Task Force Report (12). The figures are given in BTU's which may not be readily understandable to the average reader. But the figure for the year 2000 for photovoltaic cells is equal to the total electric power capacity in the year 1972. If we assume that the electric demand growth will rise by less than two times in the intervening years we find that we might attain almost 50% of our electricity needs from solar cells by the year 2000 under an accelerated orderly schedule.*

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* There are some who see more than ignorance in this underestimating of the potential for solar cells by the year 2000. The Task Force Report we are citing is focussed only on solar energy. The Project Independence Final Report, which contains a summary of all the Task Force reports, is the much more widely publicized. Yet, according to John Furber, a researcher in this field, a draft of this report, the **Project Independence Draft Blueprint**, had the entire table on the next page reproduced. This draft was circulated for comment among several federal agencies during October, 1974. Yet, in the **Final Report**, the table was truncated, cut off at the year 1985, so that the figures for all the solar technologies, especially solar cells, looked meager. The **Solar Energy Task Force Report**, however, was published with the complete table.

However, there is another equally mportant aspect of solar cell produc-:ion which is overlooked by most observers, and that is the exponential nature of the manufacturing process. Everyone in the industry agrees that growth rates of two to three times per year will be not only reasonable, but required to permit the kind of experi-ence or learning curve necessary for rapid cost reductions. Yet such exponential rates have crucial dy-namics. The Task Force Report itself contains a table in the appendix which, under a business-as-usual scenario using a doubling of produc-tion every year, projects that by the middle of the 1980's solar cell production will be around 200 Mega-watts of electricity (MWe) per year (13). Extrapolating from the table, by the mid 1990's we would be pro-ducing almost 410,000 MWe per year, or around 82,000 MWe aver-age. The total electrical power gen-erating capacity in the United States in the year 1970, for comparison, was 350,000 MWe. Thus, under the business-as-usual schedule we would by the year 2010, have an enormous surplus of electrical capacity in this country.

Admittedly, one cannot extrapolate an exponential growth curve forever. Industry production will level off at some time. But when the government publically states that only 1% of the nation's electricity can be produced from solar cells by the year 2000 the average person, not realizing the exponential growth rate of the production curve, assumes that if it takes 25 years to get to 1% it might well take equally long to get to any-thing substantially over 1%. How-ever, if we assume a doubling of production per year, even if we were to only attain 1% by the year 2000, we would attain 100% by the year 2006!

There is one further aspect of solar cell electric generation that is often overlooked and that is the enormous waste of our fossil fuels which are now burned to produce electricity. When we burn coal, or oil, or uranium to make electricity almost 2/3 of it is given off as waste heat, going into the air, or the water, or the earth. In 1970, 28% of our total energy was used to produce elec-tricity, even though electricity ac-counted for only 8% of total energy use (14). The Task Force Report projects that given current growth rates (which are quite generous, as pointed out above) in the year 2000 about 40% of total energy will be used in producing electricity. This 40% could be eliminated by using solar cells. That means drastically reducing pollution, strip mining, oil spills, and our huge dependence on foreign supplies. Fossil fuels should be used for chemistry, not for burn-ing wherever possible. Using con-servative estimates the National Science Foundation found that by the year 2000 we could save the equiva-lent of over $4 billion worth of fuel oil **per year**, a savings many times the amount that such a system of solar cells would cost to develop (15). In fact, there is the strong likelihood that by the year 2000 the United States could have a multi-billion dollar export industry in solar cells, adding to our balance of payments rather than, with our reliance on foreign oil, subtracting from it.

Solar Cells: Economies of Scale

It is unfortunate that among many governmental policymakers there is the belief that solar cells can only become widespread when they can be proven effective in central power stations. The trend, recently aggra-vated by nuclear technology, of having more and more centralized facilities, has supported this conven-tional wisdom. These people envision a system similar to that of today. Customers will still pay their monthly electric bill but their local utility will be using sunlight, rather than fossil fuels or uranium, as its energy source.

However, one of the most in-triguing aspects of solar cells, and a factor which could have enormous political and economic implications,

Figure 3.
SUMMARY OF POTENTIAL IMPACTS OF SOLAR ENERGY TECHNOLOGIES
[Units of 10^{15} Btu/Yr of Output Energy Provided by Solar Energy Systems]

	1980	1985	1990	1995	2000
Heating and Cooling	0.3 (0.01)	0.6 (0.3)	1.5 (0.6)	2.4 (1.3)	3.5 (2.3)
Solar Thermal	.0 (.0)	0.002 (0.002)	0.02 (0.02)	0.2 (0.1)	1.3 (0.6)
Wind Conversion	0.01 (0.008)	0.5 (0.4)	2.0 (1.6)	3.4 (2.7)	5 (4.0)
Bioconversion	0.06 (0.06)	0.3 (0.1)	0.9 (0.2)	3.3 (0.4)	15 (0.7)
Ocean Thermal	0 (0)	0.03 (0.03)	0.2 (0.1)	1.0 (0.4)	7 (1.7)
Photovoltaic Conversion	Neg. (Neg.)	0.01 (0.003)	0.3 (0.07)	2.4 (0.3)	7 (1.5)
Total U.S. Demand*	93	120	144	165	180

- Assumptions include (1) the successful completion of the recommended R&D program plan for solar energy technologies; and, (2) conventional fuel prices equivalent to $11 per barrel of oil.
- Numbers shown without parentheses are for the Accelerated implementation plan; those shown in parentheses are for the Business-as-Usual implementation plan.

*Estimates based on pre-embargo analyses. See "The Nation's Energy Future," AEC, 1 December 1973.

Figure 4. ECONOMICS OF IMPLEMENTATION — PHOTOVOLTAIC CONVERSION

Type/Time	Average [1] Power, KW	Area sq. ft.	Array Costs $/KW [peak]	System Costs [4] $/KW [average]	Operating Costs Mills/KWH	Lifetime [years]	Power Cost Mills/KWH
Residence/1985	1	420	500	4000	1 to 5	25-30	40 to 80
Residence/1995	1	420	100	2000	1 to 5	25-30	20 to 46
Central Station/1995	10,000	4.2×10^6	100	1400 (4)	1 to 2	25-30	22 to 43

Footnotes:

(1) Average output power — (Integrated Peak Insolation) x (Duty Factor) x (System Efficiency) (2)
— (Constant over 6 hours) x (1/5) x (12% to 15%)

(2) System Efficiency (Eff.) — (Basic Cell Conversion Eff.) x (Array Eff.)
x (Power Cond. Eff.) x (Overall Loss Eff.)
— (16% to 20%) x (92%) x (90%) x (90%) — 12% to 15%

(3) Equivalent to $700/KW (rated) for intermediate load application with capacity factor of 0.4 (4)

(4) See Appendix B

is that there are few economies of scale in use and relatively few even in production. According to a market analysis done by Spectrolab, "smaller plants, located close to an end user, may compete with power worth up to three times the central power station costs due to the savings in distribution cost and the higher fuel costs of conventional 'intermediate load' plants" (16). In the 1972 report by the Atomic Energy Commission on Solar Energy as a National Energy Resource the task force investigating energy transportation, distribution, and storage noted that single dwelling units, even with expensive battery storage systems, would be economical because transmission and distribution costs are eliminated (17).

According to the Task Force Report, there is almost no difference between central power stations and individual residences in terms of the cost of electricity. As we can see from the table in Fig. 4, in 1995, with a cost of solar cells of $100 per peak watt, the power costs of the residential power unit and those of the central power station are approximately equal.

Everyone in the industry agrees that individual residential arrays will come on line first. However, to many the critical test will come later, when large central power facilities are constructed. It is, however, possible that we need never get to the stage where we need large generating facilities.

In general, the cost per watt of photovoltaic arrays will not vary with the system size. The limiting factor is usually rooftop space and the amount of sunlight the roof area gets. Doctor Joseph Loferski has estimated that in Rhode Island and, indeed, in most of the country, 20% of the rooftop space could generate enough electricity for all Rhode Island's electricity needs (18). In the October 15, 1974, **Forbes Magazine**, Jerold Noel, a solid state physicist working with Tyco Laboratories is quoted as saying, "We have made a calculation that the roof of an average house around Philadelphia could produce enough energy to supply the needs of the home, with enough left over to, say, charge an electric car." According to Doctor Martin Wolf, about three times the present average household consumption of electric power can be collected from an average sized family house, even in the northeastern part of the United States which doesn't get as much sunlight as other sections of the country (19).

Still, there will be limitations. High rise buildings, for example, probably do not have enough rooftop space for their energy needs. Certain industrial processes, like aluminum manufacturing, require enormous amounts of energy. And, even in high density areas of the city, with townhouses, or apartment houses, or even in areas where single family dwellings are surrounded by towering shade trees, one might find it not feasible to have rooftops generating electricity.

It is also possible that there are certain storage technologies which would make it more economical for individual residences to share storage facilities on the block or neighborhood level.

However, even where existing rooftop space is inadequate we find that the next step is not metropolitan or regional generating facilities, but on-site, nearby electric generation from relatively small plants. According to the Spectrolab report in the Task Force Report photovoltaic power system cost characteristics do not change significantly with size over approximately 4 MWe peak output (20). That is enough to power about 800 homes. According to this report, the optimum size plant, in terms of dollar per output in watts probably falls in the 4-10 MWe range (around 800-2,000 homes, about the size of a small neighborhood in the city, or a subdivision in the suburbs).

Storage Systems

Solar energy technologies, based on the use of an intermittent fuel source, require storage systems. The cost and extent of such a system depends on a wide variety of factors. The goal of any storage/generating system is to provide similar reliability to traditional generating companies, or one day out every ten years.

One study performed by a group associated with the University of Delaware, in conjunction with the local utility, found that solar cells (in this case cadmium sulfide cells) generated electricity at precisely the time that peak loading was most in evidence. If no storage system were used, the use of solar cells would not be economical because the utility company would require the same amount of peak generating capacity to cover those times the sun is not shining. But with minimal storage systems the peak load could be shaved, saving utilities a great deal of money. The criterion in this system is whether the use of solar cells provides capacity displacement, in addition to energy displacement.

Perhaps more attractive, from a social and political standpoint, is the possibility of independent power systems. These can be either totally independent, or can be dependent on backup systems which themselves are decentralized. Such backup systems should have relatively low capital costs and relatively high operating costs. Nuclear power plants, on the other hand, can never be used economically as backup systems, for their very high capital costs and relatively low operating costs make them economical only if run at very high load factors. (Already the cost of nuclear exceeds that of coal, partially because the load factor of nuclear plants is about 55% instead of the 85% originally used to estimate costs.) The Office of Technology Assessment, in its critique of the ERDA national plan in October, 1975, noted that solar energy systems could rely on self-contained auxiliary sources like fuel oil, and asked directly of ERDA the question, "What methods appear attractive for self-contained, on-site, supplementary energy storage?"

Although the scale of generating facilities can be on the household level, as noted before, the scale of storage systems is by no means as clear. Community storage systems might spread out the peak load and the cost of the extra storage capability among many residents. Backup plants might be better in communities rather than on-site. These questions remain unanswered.

Presently lead acid batteries meet the storage requirements. Battery banks in hospitals have been operating for a very long time, switching on in a fraction of a second if the regular power system should fail. Lead acid batteries presently cost about $40 per kwh of storage capacity, and have a life expectancy of 5-7 years.

There is a significant amount of research in the area of battery and other storage systems, primarily as a result of utility company interest. The cost of constructing new power generation facilities is now so high, and the projections of future demand levels are so ambivalent, that utility companies are examining the possibility of shaving their peak capacity by using a bank of batteries that can be charged during off-peak hours for on-peak usage. Currently utility companies consider the cost of such batteries to be almost twice what they deem desirable, but this could change rapidly.

Storage costs at present represent only a small part of the total cost of the solar cell system. However, as solar cell prices decline the storage system becomes a significant cost item. At $40 per kwh, if 36 hours of storage are required it would cost $1440. If the system lasts 7 years it will cost about $200 per year. An average house uses 8720 kwh per year, so the cost per kwh is 2.3 cents.

It is expected that these prices will decrease in the near future. Even at present such cost estimates are crude and vague, because the life expectancy of the batteries depends in great part on the depth of discharge of the battery during each cycle, that is, whether all the energy stored in the battery is drained each time it is used. It may well be that by having a slight excess capacity in the storage system the life of each battery can be extended significantly by draining the battery less each time the storage system is tapped.

There will eventually be a resource limitation with respect to lead when solar cells (or, indeed, other forms of electrical generation using solar energy) become widespread, but for the near future there is no problem. One half pound of lead now stores 12 wh. Assuming 36 hours of storage, and using world reserves of 93.3 million short tons, we have enough lead to store the energy for 130 million average U.S. homes. There are currently a little over 90 million living units in this country, with most using far less electricity than the average home uses.

These figures are very rough, of course. Not all lead can go into storage batteries. Half of the world's lead is now used for leaded gasoline. But environmental legislation is forcing its removal from gasoline and paints, and other household products. Lead is one of our most highly and easily recycled resources; the plates in a typical storage battery are already using recovered lead.

New batteries, including the lithium sulfide battery and a zinc chloride battery, are being developed, to be on-line by 1980. Also there are investigations into flywheel storage systems, and in those areas with the capability, pumped storage is feasible.

The federal government is not supporting research into storage systems. In fiscal year 1975 the federal government spent only $680,000 on electrical storage R&D other than for the Gould and Pitcher batteries, which are primarily targeted for automobiles. In fiscal year 1977 this figure is expected to increase only to $1.5 million. This is especially unfortunate because the cost, and configuration, of storage systems is a critical item in any solar electric future.

Energy in Processing		
Slicing (10 kWh/500 slices)		0.02 kWh/slice
Diffusion (5 kWh/100 slices)		0.05 kWh/slice
Alloy (similar to diffusion)		0.05 kWh/slice
Evaporations (10 kWh/100 slices)		0.10 kWh/slice
Other Steps		0.03 kWh/slice
	Total	0.25 kWh/slice
Energy used from sand to solar cell		
Reduction		0.20 kWh/slice
Ingot		0.20 kWh/slice
Process (see above)		0.25 kWh/slice
	Total	0.65 kWh/slice
Energy Produced [at average U.S. location]		
3'' cell, 10% efficiency	0.456 W (peak)	0.082 W (cont)
1 year		0.718 kWh
2 years		1.44 kWh
20 years		14.37 kWh
30 years		21.55 kWh
Energy Produced [at average U.S. location]		
3'' cell, 15% efficiency	0.684 W (peak)	0.123 (cont)
1 year		1.08 kWh
2 years		2.16 kWh
20 years		21.57 kWh
30 years		32.26 kWh

Figure 5. NET ENERGY OF SOLAR CELLS.

Net Energy and Solar Cells

Any analysis of a new energy technology must take into account the amount of energy required to produce the technology in the first place. Solar cells perform very well by this criterion. There have been several studies of the net energy of solar cells done. Dr. Lindmayer, the president of Solarex Corporation, developed the breakdown of energy inputs and outputs shown in Fig. 5.

Dr. Lindmayer estimates that the energy used even in the energy-intensive semi-conductor grade silicon is no more than 1 kWh/slice, and that examining the slice to panel production, 50 kW (peak) power was generated by using 42,000 kWh in the form of direct electrical energy.

Thus we can see that the payback time for the slice to panel cycle is around 0.5 years, and for the total process the payback period is less than 2.5 years, using present production techniques.

In addition it should be noted that less than 1% of present panel costs come from energy costs. This may become significant in the future, when energy related inflation pushes prices of many goods up but should have relatively little impact on production costs of solar cells. Indeed, Solarex Corporation has proposed the construction of a solar breeder, a facility which would test the net energy aspects of solar cells by using solar cell electricity to produce further solar cells.

Politics and Solar Cells

One may wonder why, with all this recommending it, sdlar cells are not more widely publicized, nor supported. Part of the answer is that the industry is relatively new. But most of the answer has to dwell on the federal government and its relationship to large corporations.

One significant reason is that the Energy Research and Development Administration was only a year ago the Atomic Energy Commission, and has, as a result, a strong built-in bias in favor of nuclear energy. Until a few short months ago the head of the photovoltaic section was a nuclear physicist.

Second, the federal government believes that only big business can significantly affect future energy supplies, and solar cells are now made almost only by small manufacturers.

The Federal Government and Solar Cells

The federal government agrees that it is not a question of whether solar cells will become a significant contributor to the nation's energy picture, but when. However, their funding program is designed to forestall any rapid progress in this area. Although ERDA's national energy R&D plan states, "The technologies for producing essentially inexhaustible supplies of electric power from solar energy will be given priority comparable to fusion and the breeder reactor" the Administration requests, in its fiscal year 1977 budget proposal, almost 12 times as much funding for fusion and the breeder as for solar-electric applications, $880 million compared to $73 million. If we add to the R&D expenditures related funding for nuclear, such as net expenditures for uranium enrichment facilities, funding for high energy physics research, naval reactor development, and so forth, we find that the total proposed nuclear outlays for fiscal year 1977 reach about $3 billion.

In comparison the total solar budget for that year is just $110.5 million, or only 3% of the nuclear request. It is ironic that the federal government is proposing to spend twice as much to protect Americans from nuclear reactor wastes and possible malfunctions as on the entire solar budget.

For the first time the photovoltaic division has directly purchased solar cells. But even this modest step is weakened by the fact that contracts were let six months late, and the amount of such purchases is very modest. In the Project Independence Solar Energy Task Force Report, a business-as-usual scenario, with no government intervention in the marketplace, would have the government buy $5 million worth of solar cells in the second year, and $25 million in the eighth year, at which time solar cells would become competitive. Yet ERDA's photovoltaic division proposes to spend only $1 million in fiscal year 1976 on direct purchases, about $8 million in 1980, and progressively less in succeeding years.

Rather than a direct commitment on the part of the energy wing of the government, ERDA, and FEA, are trying to attract the attention of other federal agencies and in this manner spur development. Thus, ERDA purchases solar cells only after the Department of the Army indicates the kinds of units it may need. With ERDA acting like the middle person in this arrangement costs are probably higher than they would be if the Army directly purchased such cells.

More money is going into feasibility studies and research papers than on direct purchasing of solar cells. And, in the latest series of grants provided in September, 1975, 99% went to large companies, none of which had any experience in the production of silicon solar cells. Once again, the goal of the government was to attract big business into the field, a step which it feels is essential to have rapid introduction of solar cells.

Small business, however, which has been until recently the pioneers in the field, is hurt by these procedures. (Recently large conventional energy companies have bought up subsidiaries in the solar cell area. Shell Oil, Exxon, Mobil, Hughes Tool Company, Varian Associates, are all very large firms currently owning solar cell companies.) To a large company like General Electric, a $200,000 research grant does little to whet the corporate appetite. One attorney for a very large aerospace firm called me after an article I had written was published and expressed his interest in solar cells. When I inquired why that company with its enormous technical and financial resources, was not entering the market, he responded, "They are waiting for the price to drop." As has been traditionally the case in history, these companies are waiting for the small entrepreneurs to innovate and develop the market, at which point they will enter the market. **Electronics Magazine** itself, in a sharp editorial in November, 1975, admonished the electronic giants for their timidity and sharply criticized the tendency to wait until they had a government-guaranteed market before entering.

This indifference to solar cells is tragic, particularly because there is general agreement that costs will not drop rapidly unless the government creates an artificial market which can permit facilities to be automated and unit costs to decrease. This is unlike the case with solar heating and cooling where tax incentives for both consumer and producer are sufficient to develop the market.

No one is sure when the natural market will develop. One professional in the field estimates that at $10 per peak watt the cost will be very close to competitive (21). Others talk about $2 per peak watt (22). Most agree that $1 per peak watt is a minimum figure for other than central power station applications.

Basically, what is required is the creation of sufficient orders in advance so that production can be geared up to mass production techniques. (In addition, since production machinery will become obsolete very quickly as a result of this development, either the government should supply such equipment, as the Defense Department has done on several occasions, or manufacturers should be permitted very rapid depreciation.) Such increased production initiates a learning curve; that is, or e learns more about how to produce an item the more that item is produced. Consequently one produces at a lower unit cost. This experience curve turns out to be remarkably similar for many industries, from washing machines to transistors. The Boston Consulting Group, in a book called **Perspectives on Experience**, traced the experience curve for many industries. The learning curve predicts that for every doubling in volume one can expect a 20-30% reduction in cost. This was the case with the transistor, and most solar experts see that industry as a good indicator of future solar cell cost projections.

The problem, again, is one of market creation. The Coast Guard is now using solar cells on its light buoy systems off the coast of Florida, and the National Park Service is beginning to use them in remote park stations. Yet there is not a commitment to develop such cells. This is especially surprising in the case of the Department of Defense. In the early 1950's there was a need by the Army for a very lightweight electronic replacement for vacuum tubes. At the time transistors cost $20 apiece. Within ten years they were down to 25-30 cents apiece through the support of the Defense Department. In the 1960's the Defense Department spurred a dramatic decrease in the price of integrated circuits because it needed them for the development of the Minuteman missile.

Current surveys indicate that in remote military installations, where diesel generators are used for electricity, the cost is 20 cents per kwh, and solar cells are close to being competitive. Yet, according to a personal communication from Dr. John Teems, then head of the ERDA solar energy program, the Defense Department does not see a need for solar cells as a component of our defense program. This may change, in that the export of nuclear reactors and the use of reactor wastes to produce nuclear weapons might lead Defense officials to see the limitation of nuclear exports as a key to our national security, and might then move to develop low-cost solar cell facilities.

As with any embryonic industry, the experience curve is extremely important. Currently cost reductions are being made slowly, with a shallow sloped experience curve. At Solarex Corporation, for example, the solar cell size has been increased to 3 inches in diameter instead of the previous 2¼ inches, effectively doubling the area and therefore doubling the power output. As a result, they can now get about twice the power with approximately the same labor, and can reduce the costs by about 12% on large orders. The lowest bid on the latest ERDA procurement contracts was about $13 per peak watt, and this may go down slightly by the end of 1976.

But these kinds of cost reductions cannot continue without increasing sales. To be increasingly efficient now means corporate suicide. The best example comes from the space satellite solar cell industry in the late 1960's. At that time there were 5 companies manufacturing solar cells, each one grossing about $2.5 million per year. If they were to become efficient enough to reduce the price by a factor of ten they would have been earning only $250,000 per year, effectively undermining their busi-

Figure 6. SOLAR CELL PRODUCTION AND SALES [based on assumptions 2 and 3 below]

Year	Dollars per Watt peak	Annual Cost to purchase power generating capacity	Additional homes served	Cumulative homes served	Cost per house without storage or interest costs
1(1975)	17	1.7 million	20	20	85,000 dollars
2(1976)	10.60	3.18 million	60	80	53,000 dollars
3(1977)	6.60	6.6 million	200	280	33,000 dollars
4(1978)	4.10	13.94 million	680	960	20,500 dollars
5(1979)	2.60	27.3 million	2,100	3,060	13,000 dollars
6(1980)	1.60	54.4 million	6,800	9,860	8,000 dollars
7(1981)	1.00	107 million	21,200	31,060	5,000 dollars
8(1982)	62 cents	198 million	64,000	95,060	3,100 dollars
9(1983)	39 cents	390 million	200,000	295,060	1,950 dollars
10(1984)	30 cents	1.05 billion	750,000	1,045,060	1,400 dollars

Year	Weighted Average/$ per peak watt	Cumulative Cost for power generating capacity	Cumulative Generating Capacity [in Megawatts[e]]**
1(1976)	$17.00	$1.7 million	.1
2(1977)	12.20	4.88	.4
3(1978)	8.20	11.48	1.4
4(1979)	5.30	25.42	4.7
5(1980)	3.44	52.72	15.22
6(1981)	2.17	107.12	48.7
7(1982)	1.38	214.12	156.1
8(1983)	.87	412.12	499.7
9(1984)	.54	802.12	1,599.2
10(1985)	.35	1,852.12	5,117.6

*Assumptions:

1. a twofold increase in sales of solar cells per year, measured in dollars
2. a 37.5% reduction in cell cost per year
3. a 3.2 fold increase in kilowatts produced per year

**Projected electrical generating capacity in U.S. in 1980, in MW — 665,000 MW(e)

nesses because the reduced price would not have led to increased sales volume. Terrestrial solar cell manufacturers currently face a similar situation. This is especially true for small manufacturers, who do not have large sums of capital to invest in new production machinery unless they are guaranteed a rapidly expanding market.

However, it is not only an increased market which is necessary since the price reduction in solar cells is not the only factor involved if solar cells are to have a major impact on our nation's electricity picture. An enormous amount of educational and training work will be required. Skilled and unskilled workers must be trained both to work in the solar cell factories and to install and service the systems. For the latter job electricians are the best trained, but need to learn more about direct current, inverters, and electronics. Training programs in our colleges and universities are required so that a new generation of physicists and engineers will know about the sun's electric potential and the materials technology required to produce efficient solar cells. And, perhaps of greatest importance, there must be an educational program to teach the average citizen what the possibilities are of this sophisticated, yet simple technology.

Although the cost of the solar cell is the basic precondition for all the rest, it is not enough to have competitive solar cells if we have a population that doesn't understand their potential, if we have developed no corps of people who can manufacture the cells, or who can install and service them, or we have not developed the kinds of subsidiary industries involved in power conditioning, building heavy duty transformers to handle the power flows from the solar arrays, and the converters and storage aspects of the system.

Local Government and Solar Cells

The need for comprehensive planning and development makes local governments and states ideal locations for such efforts. The first question to be addressed is whether localities or states have sufficient funds to develop solar cells. One corporation, Solarex, has developed a production-investment table based on the experience curve mentioned above, and their own manufacturing experience. The table, revised and expanded, is shown in Fig. 6.

This table uncovers some vital facts. The major sales purchases are done in the later years, and relatively few purchases are needed during the first few years. Thus relatively small purchases of high cost cells are required, and increasingly larger purchases as the cost of the cells declines. After the seventh or eighth year, assuming no technological breakthroughs, solar cells are competitive with fossil fuel generating facilities.

The total cost, over and above the cost of traditional electricity, over eight years would be about $200 million. The Project Independence Report agrees with this figure in its accelerated orderly schedule of investment.

This means an investment of some $25 million per year for eight years. Yet this is an exaggerated figure in that such a subsidy might well not be required. Some of the production of the manufacturer could be sold elsewhere, in remote applications. And a state could find that within its own borders there are many places where solar cells are cost competitive immediately, that is, where it could actually save money by investing in solar cells (see the list of applications in Fig. 7).

States can finance such development through the issuance of revenue bonds, and municipalities also have the right to do this, possibly through the use of anti-pollution bonding authority (couldn't solar cells be designated as anti-pollution technology?). In municipalities educational programs could be carried out effectively and quickly. Demonstration models are easily seen and visited by homeowners thinking about alternative energy systems. City colleges and universities have large professional resources to train those needed by this rapdily expanding industry, and to do the backup research required. And, finally, public service money might be used to train the unemployed to work in solar cell factories or in the installation of these devices.

A state, or consortium of states, could approach a manufacturer and develop, through negotiations, a contract spanning several years. The state would agree to purchase an increasing amount of solar cell power each year, and the manufacturer would agree to lower his price accordingly. With this kind of contractual agreement it should not be difficult for any manufacturer to raise the $100 million in investment capital which would be needed over the eight years it would take to become competitive (indeed, most of this capital would need to be raised in the last few years, at a time that the price of solar cells is very close to competitive, and at that moment we can confidently expect a veritable flood of private capital into the solar cell sector).

Perhaps it is relevant to point out here that though the cost of solar cells will be falling rapidly, the technology itself will remain similar. A state need not worry about buying into a technology which is going to be made obsolete in a few years. The solar cell you buy in the year 2000 will be very similar to the one you buy today. The process of manufacturing will be much different. This, of course, is very different from the development of nuclear technology, which has been changing so rapidly over time, that it is unclear that what we are investing in today will be workable and economical tomorrow.

What is the payoff for states to invest this kind of money? Why not wait for the federal government to do this kind of development? One reason is that the federal government is moving ponderously slowly in this area, with a firm commitment to nuclear, not solar. The other is that, as noted above, the amount of money required is small enough that a state could easily handle it. Illinois, for comparison purposes, is investing $70 million in research into coal production and conversion, and $10 million into alternate energy sources. And, finally, if we look at the amount of money the federal government is putting into the direct purchase of solar cells, it is extraordinarily modest, capable of being matched even by medium-sized municipalities.

But perhaps the most important consideration is that states which enter into contract negotiations at this time can reap the benefits of being first. The state might buy into the company itself, getting repaid as the profits of the company increase. Or the state might arrange to purchase solar cells at cost after the price drops to $1 per peak watt. The difference between the retail and at-cost price will easily repay the City's initial investment very rapidly. Also the state can ask the manufacturer to establish his base of operations in its area. The manufacturer can lend his expertise and assistance in designing apprenticeship programs and in designing academic curriculum in state universities, thereby creating the technical base for this new industry and establishing a great potential for increased employment

Figure 7. TYPICAL SOLAR CELL APPLICATIONS

Application	Range of Power Required	
Mobile Radio Communications	5-10 watts	(6 or 12 volt)
Radio Repeater Stations	50-100 watts	(12 volt)
Microwave Repeaters	100-1000 watts	(12-24 volt)
Pipeline Monitors	10-20 watts	(12 volt)
Flood Control Sensors	5-10 watts	(12 volt)
Irrigation	500 watts +	(12-24 volt)
Remote Television Receivers	6-10 watts	(12 volt)
Railroad Crossing Flashers	50-100 watts	(12 volt)
Environmental Monitoring	3-6 watts	(6 volt)
Navigation Buoys	5-10 watts	(12 volt)

opportunities as this industry, which promises to be a multi-billion dollar one by the early 1980's, grows.

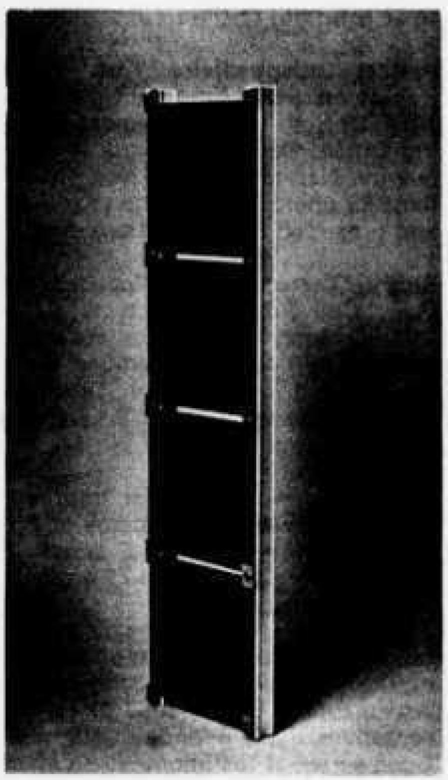
It is, of course, difficult to sketch out strict contract terms. That is not the purpose of this paper. It is the purpose to initiate the dialogue between local governments and manufacturers and to present the thesis that the barriers to such a contractual agreement do not seem to be insurmountable.

It may be good to end with a few words about the kinds of cities or states where such an arrangement would prove feasible. First, it might be good to have an area sufficiently large to gain by having at-cost cells by the tenth year, although this becomes unimportant if a consortium of states or cities are involved. Second, the city or state should be located in the southern portion of the country, especially in the southwest, where there is a great deal of sunlight, where there are few multiple days of clouds, and where air conditioning, which occurs very near peak sunshine hours, is the major energy requirement. This reduces the need for large arrays by about 25% and reduces the storage component possibly even more.

Third, we might choose an area which is far removed from fossil fuel reserves, or where there is already considerable controversy over nuclear reactor siting so that either future cost considerations or environmental concerns will permit public support of the project in its early years. Electricity rates have been increasing by 15-35% per year over the last two years, and two of the major reasons given for such rate hikes have been rapdily rising fuel costs and environmental control costs, factors which will be even more burdensome in the future.

Already states and cities are becoming involved in energy generation. Utility companies which have overextended themselves with the purchase of nuclear reactors at the same time as demand has slackened, have turned to government to bail them out. In New York, the State's Power Authority bailed Con Edison out of financial trouble in 1974 by buying two generators for $500 million. (Interestingly, according to one source, given the stock market price of Con Ed at the time, for $500 million New York State could have bought the entire company.) (24) Currently Con Ed is trying to sell New York a nuclear reactor. This kind of money could have been used to develop a solar cell industry. Instead New York State now has two huge fossil fueled generators which will probably be obsolete in ten or twenty years, if this is not already the case.

Thus public authority can no longer choose to remain neutral in the controversy over future energy generation facilities. It is being dragged into the controversy through rate hikes to its citizens, use of public bonding authority to bail out existing utility companies, and weakening of environmental legislation to permit high sulfur oil and coal to be burned. It is not unreasonable to suggest that public money should be directed, instead, to the development of an indigenous solar cell industry to service the state and its surroundings.



A four-module solar cell panel manufactured by **Solar Energy Systems**. Each module is eight inches square and provides 12 volt service.

Conclusion

We end as we began. Solar cells require only to move from the present labor-intensive, low production, high cost manufacturing methods to mass production techniques to reduce costs greatly. Even with current levels of federal funding for research and development the cost of solar cells is expected to fall significantly within the next ten years, possibly becoming competitive within the early part of the next decade. However, this is dependent upon the creation of an artificial market which can get the industry over the initial phase where cells are too expensive for widespread use. The artificial market required is quite modest, and the amount of investment is on a scale whereby a city, or state, or at most, a consortium of either, could easily, through contractual arrangements with existing manufacturers, move the nation dramatically toward self-sufficiency in energy generation.

States should begin to do their own economic analyses, to discover what the initial investment might be in their case, and what the payback period will be. The question now is not whether solar cells will be introduced on a wide scale, but when. Will it be within the next ten years, or the next fifty? It is within the means and powers of our states and cities to decide this question.

Footnotes

(1) Doctor Joseph J. Loferski, Division of Engineering, Brown University; **Solar Photovoltaic Energy Hearings** before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974, 93rd Congress, 2nd Session, p. 4 (hereafter called Photovoltaic Hearings)
(2) **Popular Science**, December 1974
(3) **Photovoltaic Hearings**, p. 38
(4) **Ibid.** pp. 87
(5) **Ibid.** pp. 46-7
(6) **Federal Energy Administration Project Independence Final Task Force Report on Solar Energy**, November 1974, p. VII C-51-55 (hereafter called Task Force Report)
(7) **Task Force Report**, p. VII B-3
(8; **Photovoltaic Hearings**, p. 147
(9) **Ibid.**, p. 3
(10) **Forbes Magazine**, October 15, 1974
(11) These figures on electric power growth are taken from Senator Lee Metcalf's insert in the **Congressional Record**, January 20, 1975, 94th Congress, 1st session.
(12) **Task Force Report**, Table I-1
(13) **Task Force Report**, VII C-67-8
(14) **Ibid.**, VII-4
(15) Statement of H. Guyford Stever, Director, National Science Foundation, **Photovoltaic Hearings**, p. 127
(16) **Task Force Report**, VII C-14
(17) NSF/NASA Solar Energy Panel, "An Assessment of Solar Energy as a National Resource", December 1972
(18) **Photovoltaic Hearings**, p. 3-4
(19) **Ibid.**, p. 141
(20) **Task Force Report**, VII C-14
(21) Dr. Eugene L. Ralph, vice president for research and development, Spectrolab, division of Textron, Inc., **Photovoltaic Hearings**, p. 26
(22) Dr. Paul Rappaport, **Ibid.**, p. 43
(23) The table presented in this paper was compiled from data from the Solarex Corporation and the adaptation of this data in an investment production schedule form in Senator Mike Gravel's **Energy Newsletter** of September 1974.
(24) **Dollars and Cents**, January 1975, p. 8

Books

Energy from the Sun, D.M. Chapin, Bell Telephone Laboratories, 1962 — oriented to the high school science student, this is the best layperson's discussion of the science of solar cells yet prepared. The booklet accompanies a kit with which the student can make solar cells, but the booklet stands on its own and hopefully can be purchased separately. It is available from Edmund Scientific Company in Barrington, New Jersey.

Executive Report of Workshop Conference on Photovoltaic Conversion of Solar Energy for Terrestrial Applications, held October 23-25, 1973 — from National Science Foundation. Only of minor value, but it gives the names and addresses of those who attended and the papers they prepared, a sort of who's who of the solar cell field at the time.

Project Independence Task Force Report on Solar Energy, November 1974. $6 from the Government Printing Office. Covers all forms of solar energy. Non-technical. Gives projections for photovoltaic to the year 2000 and projected cost reductions.

Study Terrestial Applications of Solar Cell Powered Systems (N74-2168S), Jerry W. Ravin, Heliotek, Sylman, California (September, 1973) (Distributed by National Technical Information Service, U.S. Department of Commerce)

Solar Cells — Outlook for Improved Efficiency, National Academy of Sciences, free — Technical series of papers given in the 1970-71 era.

Solar Photovoltaic Energy, Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives June 6 and 11, 1974 — Good series of testimony about short and long term potential of solar cells.

Sunlight to Electricity, Joseph A. Merrigan, MIT Press, 1975.

Solar Cells and Photocells, Rufus P. Turner, Howard W. Sams and Co., Inc., 1975.

Symposium on the Material Aspects of Thin Film Systems for Solar Energy Conversion, May 20-22, 1974, National Science Foundation—Highly technical, with some information on net energy of solar cell systems.

Wind/Solar Energy for Radiocommunications and Low-Power Electronic/Electric Applications, Edward M. Noll, Howard W. Sams and Co., Inc., 1975.

Manufacturers

Solarex Corporation
1335 Piccard Dr.
Rockville, MD 20850

SES, Inc. "Solar Energy Systems"
(Div. of Shell Oil)
One Tralee Industrial Park
Newark, DE 19711

Solar Power Corp.
(Subsidiary of Exxon Corp.)
Five Executive Park Dr.
North Billerica, MA 01862

Spectrolab Solar Power System
(Div. of Hughes)
12484 Gladstone Ave.
Sylmar, CA 91342

Sensor Technology, Inc.
21012 Lassen St.
Chatsworth, CA 91311

OCLI
(Optical Coating Laboratory, Inc.)
Photoelectronics Group
15251 E. Don Julian Rd.
City of Industry, CA 91746

Solar Technology International
9701 Lurline St.
Chatsworth, CA 91311