

# Photovoltaics—Is the big price breakthrough just around the corner, or the next corner, or...

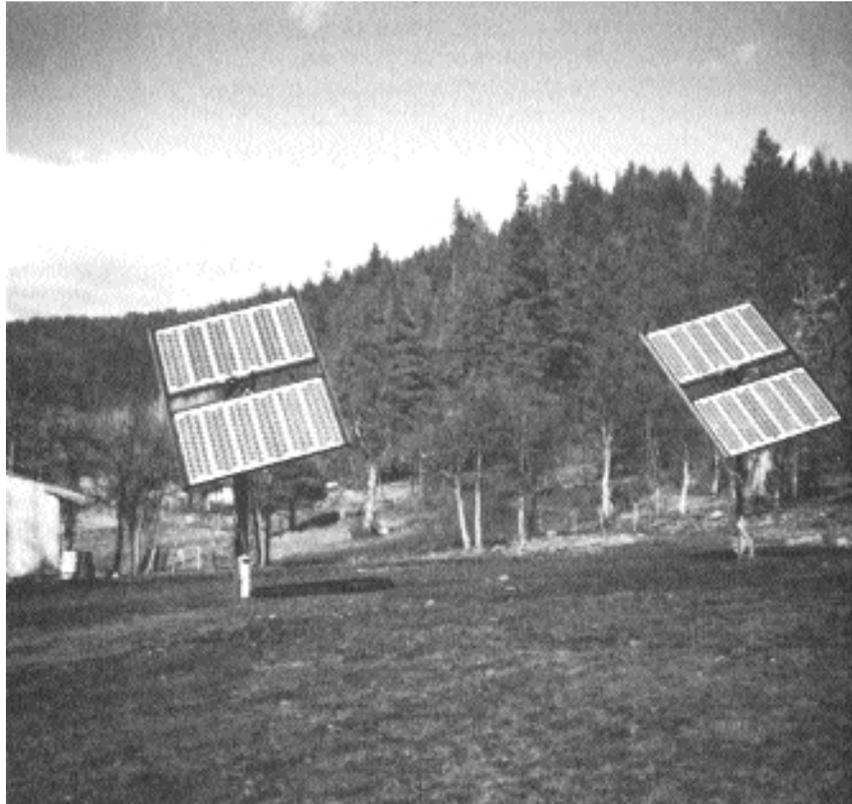
(The Photovoltaics field seems to have a cost “breakthrough” or “near breakthrough” about every other month, if you believe the Industry and public media. With the widely publicized announcement recently by Southern California Edison and Texas Instruments that after years of secret research they were on the verge of a major photovoltaic (PV) breakthrough that would soon make PV competitively priced with fossil fuel-produced electricity, we thought it time to explore the current and anticipated state of the PV Industry, including all the known avenues of research that may indeed provide major price breakthroughs.—Editor.)

By Paul Maycock

**T**he conversion of solar energy to electricity using the solar cell “photovoltaics” is an incredibly exciting path to abundant electricity which causes no pollution and allows each of us to control our own energy destiny by generating our own electricity for our cars, boats, motor homes, and our houses. The article will attempt to answer some basic questions:

- **What is photovoltaics and what does it do?**
- **What is the status of photovoltaics in 1991?**
- **What can photovoltaics do for a typical U.S. consumer, now?**
- **What does the future of photovoltaics offer?**

Before I attempt to answer the questions, let me digress for a moment to give you a brief summary of the impact of photovoltaics on myself. It will be clear that I am a “PV advocate.” However, long experience makes me cautiously optimistic that PV will power our houses and cars, hopefully before the year 2000. (It seems like I have been saying “Economic PV for residences is 10 years away” for 20 years!)



*Two Zomeworks' track racks holding 24 Arco photovoltaic modules produce electricity from the sun for a ranch in the Siskiyou Mountains of Oregon.*

I first interacted with PV in September of 1957 when I worked with Dr. Paul Rappaport, one of the founders of modern PV. I was a summer employee of RCA and was given an opportunity to act as a technician for Dr. Rappaport as he and Dr. Joe Loferski, Brown University, did their important research on the sensitivity to solar cells to space radiation.

RCA was doing the early work that would answer the important question: “Could the silicon solar cell survive the harsh environment of space as a power source for our satellites?” The answer was “yes,” and nearly all U.S.

satellites have been powered by solar cells!

I next met PV in 1958-1961 while I was working in the Office of Naval Research where we funded advanced energy conversion devices. Again, the PV topic was of much interest and several contracts were awarded which set the scene for today’s industry.

Next, while working for Texas Instruments (1962-1975) we addressed reducing the cost of silicon for solar cells, and I had the pleasure of working on the early phases of the recently announced and much publicized PV “breakthrough” by Texas Instruments that involved silicon sphere PV gener-

ators. (More on that in the "What does the future offer?" section).

I started working on PV full time in 1975 when I joined the Energy Research and Development Administration (predecessor to the Department of Energy). In 1977 I was named Division Director for the U.S. Photovoltaics Program, under President Carter's leadership, PV flourished, and the DOE budget grew to \$153 million in 1981. We had a 10-year plan (1978-1988) that called for \$2 billion to be invested in PV in a comprehensive Research, Development, Demonstration, and Commercialization program that would stimulate the photovoltaics community to develop fully economic PV electricity generation by 1990.

We enacted the PURPA law, which permits a U.S. homeowner to generate electricity and sell excess electricity to the utility. It required the utility to provide its normal service when the customer required it. Solar residential and commercial tax credits were also implemented and PV was on its way!

But in 1981, the Reagan Administration ordered DOE to cut all solar research and reduce the PV budget to less than \$40 million—in one year! Having worked in the industry all my life, I was really mad! I could not see myself part of the destruction of photovoltaics, so I resigned in May of 1981.

In order to lobby the Congress and try to get the budget restored, I became the first director of the Renewable Energy Institute. Also, I formed my own PV company, Photovoltaic Energy Systems, which is a consulting and information products firm dedicated to the success of photovoltaics.

### What is photovoltaics?

Photovoltaics is the direct conversion of sunlight into electricity. The effect was discovered 150 years ago by French scientist Becquerel, but it took the American space program to launch modern photovoltaics. Bell Labs succeeded in making PV cells

from silicon, and they were used to power satellites.

The solar cell is a two-layer device which has one region with an excess of electrons and another with a deficiency of electrons. When the sun shines on this solid layer of semiconductor material (normally silicon), the electrons pick up the energy from the light and have the ability to do work. The two layers develop a voltage (.5 Volts in silicon) that can drive the activated electrons through a load—a light, a motor, etc.

The solar cell converts about 15% of the energy of the sun into direct current (DC) electricity. The DC electricity can be stored in a battery or used directly to power an electrical load. On a sunny day in June the solar energy on a square meter of solar cells is about 1000 Watts. If a square meter of solar cells, is aimed at the sun and it converts 15% of the solar energy to electricity, the output of the photovoltaic module is 150 Watts—enough to power 10, 15-watt fluorescent lights. We can connect the solar cell in all kinds of series and parallel patterns to get most any voltage and current that we desire provided the area is large enough. A set of cells wired together is called a "module" and a set of modules wired together is called an "array".

The bottom line is that photovoltaics can serve electrical loads from fractions of a Watt (calculators, battery chargers, watches) to large central power stations that generate megawatts of electricity.

### What is the status of photovoltaics in 1991?

The world photovoltaics industry will ship about 50 million peak Watts of PV modules in 1991. (A "peak Watt" is the electrical power produced by a solar cell when it is exposed to a sun that is delivering 1000 Watts of solar power per square meter to the PV module. A noon day sun on a clear day in June delivers about 1000 Watts per square meter). The average factory price for PV modules is \$5 per peak Watt.

The world PV module market is only \$250 million per year. The typical PV customer buys, in addition to the module, some racks to mount the module on the roof or ground, some wiring, a battery to store the electricity, and some electronics to charge and control the load. This installed system can cost the typical customer from \$12-20 per peak Watt. The total photovoltaic installed systems market is from \$600 to \$1 billion per year. Figure 1 shows the PV module shipments for the past few years in megawatts (MW).

It is interesting that world module shipments were only 100 kilowatts in 1971 so that the PV industry has grown 500 times in 10 years! Despite this growth, photovoltaics is still a very small industry world wide.

Figure 2 shows the module shipments by the U.S. PV industry. Two players, Siemens Solar Industries (formerly ARCO-Solar) and Solarex account for nearly all U.S. shipments. There are several companies preparing

COUNTRY	1985	1986	1987	1988	1989	1990
UNITED STATES	7.7	7.1	8.7	11.3	14.1	14.8
JAPAN	10.3	12.6	13.2	12.8	14.2	15.8
EUROPE	3.4	4.0	4.5	6.7	7.9	10.2
REST OF WORLD	1.4	2.3	2.8	3.0	4.0	4.7
TOTAL	22.8	26.0	29.2	33.8	40.2	45.5

Figure 2

### U.S. MODULE SHIPMENTS BY COMPANY (MW)

COMPANY	1985	1986	1987	1988	1989	1990
SIEMENS SOLAR	4.7	4.0	4.2	5.5	5.5	7.0
SOLAREX	2.1	1.9	2.9	3.2	5.0	5.4
CHRONAR	0.2	0.3	0.7	1.0	0.5	0.3
SOLEC INTN'L	0.3	0.3	0.3	0.8	0.9	0.9
SOVONICS	0.05	0.1	0.3	0.4	0.5	0.6
ENTECH	--	--	--	0.2	0.3	0.03
MOBIL SOLAR	0.2	0.2	0.05	0.1	0.05	0.05
ASTROPOWER	--	--	--	0.1	0.2	0.4
OTHER	0.15	0.3	0.2	0.2	0.15	0.12
<b>TOTAL</b>	<b>7.7</b>	<b>7.1</b>	<b>8.65</b>	<b>11.3</b>	<b>14.1</b>	<b>14.8</b>

Figure 2

to enter the U.S. PV industry. The cost of entry and the technical requirements for competitive production of PV modules is so great that few are able to raise the capital to make the entry into production.

More than \$2 billion dollars have been invested in the U.S. (\$600 million from DOE and over \$1.5 billion from the industry) to improve the efficiency and reduce the cost of photovoltaics. PV prices have been reduced from the \$100 per Watt in 1976 to the \$5 per Watt range, but another factor of two in cost reductions will be required before PV is competitively priced with the cost of electricity for our homes. Depending on the climate and the cost of money, electricity from PV costs 30 to 60 cents per kilowatt hour. This compares to electricity costs from our local utility of 8 to 20 cents per kilowatt hour.

#### What can PV do for a typical U.S. consumer, NOW?

If the PV industry ships 50 megawatts this year, PV will serve millions of customers with reliable electricity in over 60 countries for thousands of applications. Less than five of the megawatts will be subsidized experiments or gifts to the

developing world. The remaining 45 megawatts will be for customers who want PV, believe it is "economic," and expect PV to deliver electricity reliably for a long time. The thousands of Americans who are interested in PV to power remote homes that are beyond the reach of commercial power lines are in this category.

Figure 3 shows PV module shipments by major market sector. Each sector and its products will be discussed from the point of view of the 1991 customer. It is interesting to note that the 1991 market is dominated by

small, portable, consumer applications, and at the same time, PV is the preferred source of electricity for commercial remote, stand alone, ultra high reliability communications, signals, and sensors.

The reason for this diverse market is based on the fact that the need for electricity where the utility is not immediately available is great and that the conventional alternative - batteries, diesel generators, extension of the grid, etc., are very expensive, and in many cases, unreliable.

#### Consumer PV products

The consumer purchases nearly 30% of the PV sold in the world today. This sector includes PV's largest single market-the calculator. About 130 million calculators are served by PV cells, most by Japanese producers of the thin film solar cell, amorphous silicon.

Other consumer "electronic" PV applications include: watches, trickle chargers for batteries, portable radios and TVs, electronic scales, toys, games, and remote controls, with new applications being introduced every day. Most of these applications use less than one Watt and are incorporated into the product so that the customer does not make a "PV decision." The product just happens to have PV in it.

### U.S. MODULE SHIPMENTS BY SECTOR (MEGAWATTS)

APPLICATION	1985	1986	1987	1988	1989	1990
GRID-CONNECTED	0.5	0.5	0.2	0.8	0.4	0.4
CENTRAL STATION 1MW+	0.3	--	--	--	--	--
EXPORTS	2.8	3.8	4.7	5.5	5.9	6.4
OFF-GRID RESIDENTIAL	1.5	0.6	1.5	2.2	2.5	2.8
GOVERNMENT PROJECTS	1.4	0.3	0.05	0.2	0.5	0.5
OFF-GRID INDUSTRIAL AND COMMERCIAL	1.1	1.4	1.5	2.0	2.3	2.5
CONSUMER PRODUCTS (LESS THAN 10W)	0.1	0.5	0.5	0.8	2.5	2.2
<b>TOTAL</b>	<b>7.7</b>	<b>7.1</b>	<b>8.65</b>	<b>11.3</b>	<b>14.1</b>	<b>14.8</b>

Figure 3

Table 1 Photovoltaic applications for consumers (1 to 10 Watts – \$30-\$300)	
Application	Comment
● small, portable lights	— used for marking paths, decoration, landscaping, etc.; early product had less than enough light and had some reliability problems; new product has more power, more reliability
● battery trickle chargers	— millions sold; keeps batteries on boats, cars, lawn mowers, cycles, etc. charged; extends battery life, increases reliability
● security lights	— IR sensors activate; high cost and low light level limit sales
● ventilators	— for boats, closed spaces, homes, motor homes; prevents mildew, odors, "airs out" closed spaces
● electric fence charger	— dramatically increases reliability and pays for itself in 2-3 years due to battery life

Photovoltaic applications for consumer (10 Watts and larger – \$200-\$500)	
Application	Comment
● vacation cabins, houseboats, motor homes, boats and other spaces where use is 1-2 days/week	— tens of thousands sold; usually 40 watt panel with controller and battery
● outdoor lights	— 20-30 watt fluorescent metal halide, LP, HP sodium coming
● battery charging stations	— 10 watts will keep several batteries topped up

As we move up in size and cost, the PV decision is made where there are alternatives. Again the consumer has purchased millions of small PV systems that, hopefully, were going to fill a need. The list of products in this market sector is growing every day. Table 1 lists some of the more important products in 1991.

Other applications include: PV security systems, monitors, electric gate openers, PV golf cart roofs, PV powered fans, PV powered "swamp coolers," PV powered water pumping, etc.

We could go on for several pages listing the clever ways that the American consumer is using photovoltaics. The consumer PV market is the backbone of the PV industry. The following key conclusions can be made at this point:

Whenever a small amount of electricity is needed and the utility power is a few hundred feet or dollars away from the load, then photovoltaics should be seriously considered. PV is fully economic against the use of batteries in powering remote loads, and it is nearly economic against small (1-5 KW) diesel or gasoline electrical generators.

### What is the future of PV?

The only barrier to massive use of photovoltaics, is its cost. The performance and reliability are excellent and the fist of new applications is growing daily.

My personal objective is to see PV fully economic for residential use, either grid connected or stand alone.

Presently a quality PV system for a home costs about \$12 per peak Watt installed and the cost of electricity from today's system is 40 to 50 cents per kilowatt hour. If the customer is in an excellent climate (2600 peak hours per year), has a cost of money of 10%, and a present cost of electricity of 14 cents per kilowatt hour, and a PURPA buy back rate of 14 cents, then the PV system must cost about \$4 per Watt installed.

All components of the cost of an installed PV system must be reduced. Module prices must be reduced from today's \$6 per Watt to \$2 per Watt. Power conditioners must be reduced from \$2 per Watt to less than 50 cents per Watt. Packaging and design will reduce installation costs.

The most difficult cost reduction appears to be in reducing the module cost. The PV industry and the U.S. Department of Energy have been

aggressively pursuing this elusive \$2 per Watt module price.

The industry has spent well over a billion dollars on PV R&D, and the DOE has spent nearly a billion dollars.

Most of the funds being spent on the single crystal and polycrystal sliced silicon were diverted to more risky research on thin films.

### Thin film

Most of the industry and DOE funds have been spent on the development of amorphous silicon thin film solar cells, but after over \$2 billion worldwide, the amorphous silicon is still a power source for calculators, watches, and small battery chargers.

The key problems in developing amorphous silicon for power products have been low efficiency in production, instability of modules when used outdoors, and higher manufacturing costs than anticipated. The industry has been unable to get production efficiencies (presently 5%) up to the levels obtained in the research labs (12-14%). Amorphous silicon modules have degraded up to 50% in the field and thousands of modules have totally failed. Intense packaging development and new manufacturing approaches are making progress on the stability issue, but all tend to increase the cost well above the anticipated "too cheap to meter" claims of the 1970's.

Despite the slow progress in thin film product development, there have been significant strides made in reduction of manufacturing costs of PV modules. There are several major efforts to move amorphous silicon power modules into production.

Solarex, of New Town, PA has a new pilot plant in operation. Energy Conversion Devices and Canon, in their joint venture called United Solar Systems, Troy, MI, are completing a three megawatt-per-year update and modification of the Sovonics amorphous silicon plant. And Advanced Photovoltaic Systems, Princeton, NJ, is completing a 10-megawatt plant to manufacture 2.5-foot by 5-foot modules.

## PV DC MODULE EFFICIENCIES (%) PRODUCTION MODULES IN MARKET

CELL TECHNOLOGY	1990	1995	2000	2010
SINGLE CRYSTAL	15	17	18	24
POLYCRYSTAL INGOT	14	16	17	22
RIBBON (SHEET)	12	15	17	22
CONCENTRATORS	17	20	25	30
AMORPHOUS SI (INCLUDES STACKED CELL)	5-7	8-10	10	12
COPPER INDIUM DISELENIDE		8-10	12	14
CADMIUM TELLURIDE		10	11	12

2010 FORECAST IS LIMIT OF TECHNOLOGY

Figure 4

There is also extensive research on other materials including Copper Indium Diselenide, Gallium Arsenide, Cadmium Telluride, polycrystal silicon thin films, and cells made from

tiny spheres of silicon. All appear to have some real value for reducing cost while maintaining quality. At the moment, I cannot pick a clear winner.

MANUFACTURING COST OF TERRESTRIAL MODULES				
OPTION	1990 COST/PRICE	1995 COST/PRICE	2000 COST/PRICE	2010 COST/PRICE
SINGLE XTAL	3.25/5.40	2.40/4.00	2.00/3.33	1.50/2.50
POLYCRYSTAL	3.00/5.00	2.00/3.33	1.50/2.50	1.30/2.20
RIBBON	3.60/6.00	3.00/5.00	2.40/4.00	1.50/2.50
CONCENTRATOR	3.00/5.00	2.00/3.33	1.20/2.00	1.00/1.67
AMORPHOUS SI (INCLUDING STACKED CELL)	3.00/5.00	2.00/3.33	1.20/2.00	0.90/1.50
LOW PRICE (BAU)	5.00	3.75	2.50	2.00
LOW PRICE (ACCEL)	5.00	3.25	2.00	1.50
NOTE: TOO EARLY TO FORECAST CIS, CdTe, etc				
1990\$ - 2010 FORECAST IS LIMIT OF TECHNOLOGY				

Figure 5

We seem to have “breakthrough of the month” but no real change in the cost or performance of the PV module. There are three areas that appeal to me.

### Polycrystal film

The first is the polycrystal film on low cost substrate being developed by Astropower, Newark, Delaware. Dr. Allen Barnett, Astropower president, has patented the deposition of a multicrystalline film about three thousandths of an inch thick on a very low cost substrate. Research efficiencies in the 12-14% range have been obtained. Pre-pilot cells having efficiency over 10% are now being made. It appears that this approach can have the performance, stability and reduced cost that forms the basis for fully economic residential PV.

### Spherical silicon cells —TI/Edison breakthrough

Another exciting event is the Texas Instruments/Southern California Edison announcement of a new cell process which uses thousands of small, three thousandths of an inch thick, spherical silicon solar cells connected together to form a solar cell. The material consumption of the TI process is 1/50th of the sliced silicon option which is our standard. TI also claims to make the silicon spheres from less pure metallurgical grade silicon thereby reducing the material cost another factor of 10. Pilot production indicates cell efficiencies of 10% with all the stability of ‘crystalline silicon.

Full production by TI is probably 3-4 years away, but this development has a the features of low cost, reliable, efficient PV electricity generation.

### Optical concentration

My third favorite is the use of optical concentration to focus the sunlight on a small solar cell. This concentration permits the use of much less cell material and cells which cost more than those used for flat plate modules.

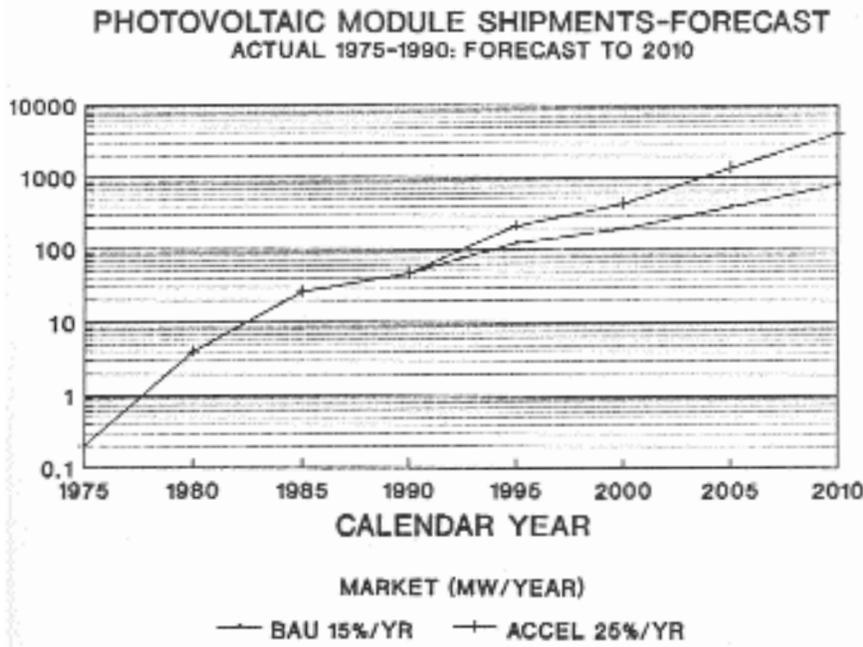


Figure 6

I forecast that the concentrator will be 25% efficient and have the lowest manufacturing cost of all the PV options, including the advanced thin films.

**Forecast**

For the past 15 years, I have been trying to forecast the future of Photo-voltaics. Figures 4 and 5 show my latest

**PV WORLD MARKET FORECAST  
ACCELERATED SCENARIO**

MARKET SECTOR	1990	1995	2000	2010
CONSUMER PRODUCTS	16	70	80	500
US OFF GRID RES	3	20	40	100
WORLD OFF GRID RURAL	6	15	40	600
COMMUNICATION,SIGNAL	14	40	60	200
PV/DIESEL COMMCL	7	50	100	1000
GRID CONN RES/COMMCL	1	5	20	600
CENTRAL STATION	1	10	100	1000
<b>TOTAL MEGAWATT/YR</b>	<b>48</b>	<b>210</b>	<b>440</b>	<b>4000</b>

2010 FORECAST 25%/YEAR-2000 TO 2010

Figure 7

attempt to forecast the performance and manufacturing cost of PV modules for the principal cell options.

I also have added the value of the "profitable price". Often claims are made for PV cost reduction break-throughs. However, prices without a reasonable profit will preclude real growth of PV. To the best of my knowledge there is only one U.S. PV company that is and has been profitable. This is Solec International in Hawthorne, California. All other U.S. PV companies have invested over \$1 billion in PV development and none are profitable.

Finally, I will try to go out on another limb and put it all together. Figures 6 and 7 show my attempt to forecast the market to 2010. I've outlived my 1975 forecasts; they were too optimistic!

I've hedged my bet by breaking the forecast into two scenarios- "Business as Usual" and "accelerated".

The BAU scenario assumes flat oil and gas prices, no major pro-renewable policy actions from the DOE, no real concern for Earth Warming, no major nuclear "accident," and continued energy malaise. Under the Bush Energy Plan we are clearly in the BAU mode.

The Accelerated mode assumes major R & D on renewables, 2% escalation in oil and gas prices, internalization of the social costs of oil, coal and nuclear generation of electricity, and accelerated commercialization of the laboratory results. Δ

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*If you would not be forgotten,  
As soon as you are dead and  
rotten,  
Either write things worthy  
reading,  
Or do things worth the writing.*

Benjamin Franklin  
1706-1790