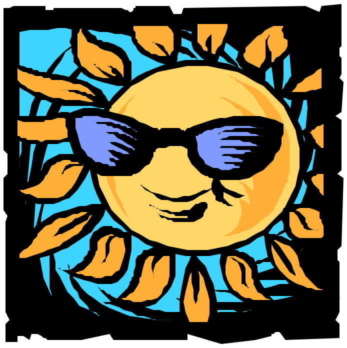

Can Photovoltaics Play a Significant Role in the U.S. Energy Sector?

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I. Introduction

The current US energy supply picture is heavily weighted toward fossil fuels. In 1997, 85% of the total energy supplied came from fossil fuels and a mere 8% from all renewable energy sources combined. [EIA, 1998] There are several reasons why the United States should move toward a more sustainable energy supply. Environmental pressures are escalating and significant reductions in CO2 emissions are going to become necessary as the global climate change problem intensifies. Photovoltaic (PV) energy is very well suited to meet environmental concerns. In the US, it is possible to get a 0.3 million ton reduction in CO^2 emissions by installing 1 gigawatt of photovoltaic energy. [EPRI and EERE, 1997]

Shifting from such reliance on fossil fuels will also help the United States budget. A large percentage of the fossil fuel used in the US is imported. Photovoltaics domesticate the energy supply thus reducing import costs. The domestication of energy sources also reducing national security expenditures as approximately 5% of our national defense budget goes toward protecting foreign energy supplies. This was the driver behind the Persian Gulf war. PV also contributes positively to our economy through exports. More than 70% of the photovoltaic systems produced in the US are sold abroad. [EPRI and EERE, 1997]

The United States is restructuring the electricity industry in part to address these issues. This deregulation is moving toward distributed energy sources and competitive markets for electricity. Photovoltaics can accelerate this transition to a cleaner, more secure distributed energy system by filling niche markets in the short term. [EPRI and EERE, 1997] The modularity and scalability of PV make it a seemly perfect candidate for a large role in the new energy economy.

If this is true, why are photovoltaics still such a tiny portion of the overall US energy picture? This paper will attempt to evaluate the technical, environmental, and economic aspects of photovoltaics to shed light on this question. Current and future policies will be examined to identify their impacts on renewable energy and photovoltaic systems. The role of the government today is to improve the operation of a competitive energy market and addressing the market's inherent limits, more than to regulate the entire energy sector16. This paper will consider the effectiveness of this approach by evaluating the benefits and limits to current federal and state policy initiatives. Through this analysis an assessment will be made of the future of photovoltaics.

II. Technology Review

Basics

Photovoltaic cells are solid-state semiconductor devices that convert sunlight directly into electricity. The electricity is generated when incident light (photons) knocks electrons in the cell free, promoting the generation of a current. The simplest cells consist of two types of semiconductor material that, when joined together, create a potential. The two types of material are generally referred to as 'n-type' (negative-type) and 'p-type' (positive-type) and the point at which the materials come in contact with one another is called the p-n junction. At this junction a voltage is created which directs the electrons to produce the useful current. A grid contact is placed on the topside of the cell and a sheet contact on the base to complete the circuit. The result is direct current which, in most cases, must be converted to an alternating current for it to be useful.

Generally, a photovoltaic system consists of two main parts, the module and the balance-of-system (BOS) components. The PV cells described above are joined together to create modules. They can be connected in parallel for greater current or series for greater voltage, depending on the needs to be met. Cells are generally coated with some type of anti-reflective layer to help increase their efficiency. Modules are encased in a frame or otherwise coated to protect the cells from the environment. Any equipment needed for mounting is also considered part of the module.

The BOS consists of everything else the system needs to operate. This includes inverters and other electronics to convert the DC output from the module to usable AC current, energy storage devices when necessary, and wiring. Some types of PV systems require mirrors or lenses to concentrate the incident sunlight or use mechanical tracking mechanisms that change the orientation of the system to follow the sun's movement across the sky.

PV systems are quite simple and very durable. The large majority of systems do not have tracking mechanisms and therefor have no moving parts. With no moving parts and no fuel storage requirements, the operation and maintenance efforts for most PV systems are minimal. The systems are also noiseless and odorless which adds to their promise. In addition, the photovoltaic industry has benefited tremendously from the advances in semiconductor technology made by the solid-state microelectronics industry5. Given the role of microelectronics in today's world, it is reasonable to predict that this advantage will continue for some time.

Efficiency

Efficiency measures how well photovoltaic cells convert sunlight into electricity. It is important to understand the basics of PV system efficiency because it plays a central role in determining how viable photovoltaics are as an alternative energy source. There are specific technological contributors to efficiency that will be addressed in future sections. There are other factors related to how photovoltaics work that impact how well they convert sunlight into electricity that need to be considered as well.

To generate the current, incident photons must be able to remove electrons from atoms. The minimum amount of energy that is required to free an electron from its atom is referred to as the bandgap. This energy is a material characteristic and therefore varies depending on the materials present in the cell. The photons therefore must transfer an amount of energy to the electron at least equal to the band gap of the cell. Not all photons have the same energy; some have more than enough energy to remove electrons, some have less than what is needed. Photons with energies lower than the bandgap will not be absorbed by the cell. Photons with energies higher than the bandgap use some of their energy to free electrons and transfer their remaining energy to the cell lattice to be lost as heat.

PV module efficiency is measured as the ratio of the electric power produced to the power of the incident light. [Benner and Kazmerski, 1999] As more of the incoming energy from the sun is used to remove electrons, more electricity is generated. As outlined above, not all the energy can be used. Therefore there is an inherent limit on the maximum achievable efficiency due to the physics of photovoltaics. This maximum is estimated to be between 25% and 35%, depending on the type of cell. [Benner and Kazmerski, 1999] Laboratory test cells have achieved efficiencies close to these values but commercial versions do not perform as well. A rough average efficiency for deployed PV modules is 15% to 20% but this varies dramatically depending on the type of cell. [Benner and Kazmerski, 1999]

In addition to the physics of semiconductors, there are other factors that affect the ability of PV modules to reach high theoretical limits. Some sunlight is reflected off the topside of the module and never has the opportunity to be absorbed. Some passes through the module without colliding with an atom. Modules themselves can get fouled by dust, ice, or snow, which prevents some portion of the light from entering the cells. Dislocations, defects, and grain boundaries in the crystal structure of the semiconductor material can cause freed electrons to recombine too quickly to contribute to the current. [Johansson and Kelly et. al. 1993] Obviously lower grade materials aggravate this problem. Also, the electrical characteristics of each cell are slightly different. [Benner and Kazmerski, 1999] Therefore when they are connected to form modules mismatches in voltage or current can occur. There is resistance in PV modules like any other electrical system that limits the relationship between current and voltage. The sheer fact that the cells are connected even contributes to the problem by reducing the amount of surface area available to receive incident light. [Benner and Kazmerski, 1999] These issues contribute approximately 10% to the 20% loss in efficiency seen in commercial versus laboratory modules. [Johansson and Kelly et. al., 1993]

Another important factor that impacts the efficiency of a PV module is temperature. Modules are designed to work best under standard conditions - i.e. 25°C. Most modules become less efficient as the temperature rises. Crystalline modules for example lose 0.5% of their efficiency per °C above their rated temperature. [Johansson and Kelly et. al., 1993] Modules generally function at temperatures on average 20°C higher than standard conditions and therefore the contribution to efficiency loss from thermal effects is: (20°C)x(0.5%) = 10%. This accounts for the remaining 10% loss in efficiency in commercial modules. [Johansson and Kelly et. al., 1993]

The lower the efficiency of a cell, the less electricity it will provide therefore the less it is worth to the owner. To make PV a more robust energy source, efficiencies must be as close to the theoretical maximum as possible. The catch is that generally, higher efficiency means higher cost and as will be pointed out later, cost is the biggest problem for photovoltaics today. There are other technical limitations to photovoltaic efficiency that result from design of the PV system. This of course varies with the type of system technology used.

Systems

There are two basic design strategies for photovoltaics; flat plate and concentrator systems. The material choices, module designs, and siting requirements are different for the two systems and therefore should be evaluated independently. The vast majority of PV installations to date have been flat plate systems. Concentrators are generally used for specialized or large-scale applications due to their complexity and cost.

Concentrator Systems

Concentrator systems use mirrors or lenses or a combination of both to direct solar radiation onto small PV cells. The three most common module designs are Fresnel lens, parabolic trough, and parabolic dish. [Johansson and Kelly et. al., 1993] Concentrating the solar energy increases the number of photons hitting the cells thus increasing the output from the module. This reduces the size of the PV cells required to produce a given output. Effective concentrators can reduce the required cell area by a factor of 1000. [EPRI and EERE, 1997]

A PV concentrator system consists of three main parts; the concentrator module, the support structures and the tracking equipment. The concentrator module contains both the PV cells and the optical concentration equipment. A single cell or a small set cells can be used. A single optical element is most often employed but a secondary element can be used in series to increase the level of concentration. Secondary elements also help correct for slight tracking errors and misalignment by catching light that might otherwise have missed the cells. [Johansson and Kelly et. al., 1993] The PV cells in concentrators are typically crystalline silicon but gallium arsenide and multi-junction cells are sometimes used in specialized applications (see descriptions below). It is anticipated that concentrator technologies will move from trough systems with silicon cells to point focus systems with gallium arsenide cells as development progresses. [EPRI and EERE, 1997] The cells themselves make up a very small portion of the area needed for these modules. Because the cell size is so small, higher efficiency cells can be used without added costs. Also, it is important that these modules have a built-in method for dissipating heat due to the intense conditions they are subject to. [Johansson and Kelly et. al., 1993] Passive cooling is normally used which involves radiating heat directly into the air through metal fins in the cell casing. Active cooling can also be used. This involves transferring the heat to a circulating fluid. If an active cooling system is used, the heat captured in the cooling media can be used locally as low temperature process water. [Johansson and Kelly et. al., 1993]

Concentrator systems can not use indirect (diffuse) sunlight. Only direct sunlight is reflected or focused onto the PV cells. To compensate for this, concentrators generally have sun-tracking systems that maximize the amount of direct insolation available over the course of the day. Concentrators can rotate about one or two axes and dual-axis tracking provides more slightly more concentration than single-axis tracking. The effectiveness of concentrator technologies can be measured by their concentration ratio - the ratio between the sun's intensity at the surface of the optical concentrating equipment and the intensity of the radiation hitting the cells. [Johansson and Kelly et. al., 1993] Single-axis tracking provides concentration ratios between 10 and 30 (10 times the amount of direct solar radiation that would hit the cells under normal conditions) while dual-axis systems can theoretically achieve concentration ratios between 1,000 and 5,000. [Johansson and Kelly et. al., 1993] The table below shows the theoretical and practical concentration ratios for some typical concentrator technologies.

Technology	**Maximum Theoretical Concentration**	**Maximum Practical Concentration**
Reflective parabolic dish	12,000	820
Reflective parabolic dish with secondary optical element	104,000	4,800
Square flat Fresnel lens	376	73
Square flat Fresnel lens with secondary optical element	Not available	1,700
Linear parabolic trough	108	29

Source: Johansson and Kelly et. al., 1993

Since concentrators can only use direct sunlight, cloud cover significantly reduces and in many cases eliminates the generation of electricity in concentrator systems. This makes these systems much less useful in areas where cloud cover is even moderately frequent. Concentration capability is also limited by other factors such as material and surface imperfections in the optical elements, chromatic aberration, resistance in the cells. [Johansson and Kelly et. al., 1993] There are technological fixes that can reduce the effects of some of these factors, all of which add complexity to the system. Clearly, systems with higher concentration ratios are more efficient, but as stated earlier, added efficiency equals added costs.

In addition to the factors affecting the concentration ratio, concentrators lose efficiency due to the concentrating optics. These elements are not perfectly transparent and therefore absorb some of the incident energy. For example, for a Fresnel lens system, only 75%-85% of the incident light actually makes it to the PV cells. [Johansson and Kelly et. al., 1993] Therefore, the overall module efficiency is 75%-85% of the efficiency of the cells themselves. [Johansson and Kelly et. al., 1993]

Concentrator systems do not work well for small-scale applications. They are difficult to install and require more maintenance than other types of PV systems. [EPRI and EERE, 1997] They are also unsightly and, because tracking is required, are considered somewhat less reliable. Utility-scale systems can be practical but only a few are in use today. One significant benefit of concentrator systems is their potential for rapid scale-up. [EPRI and EERE, 1997] The BOS parts needed for concentrators are for the most part readily available on the market today. The cells are the exception. Though they take time to construct, a few cells can make many concentrator systems. This increases concentrator system manufacturability and contributes to their future potential. [EPRI and EERE, 1997]

Flat Plate Systems

Unlike concentrator systems, flat plate systems rely on their surface area to collect sunlight. Since the output of a module is proportional to the amount of incident energy, these systems require larger modules. To their benefit, flat plate systems are able to use both direct and indirect sunlight to generate electricity. In addition, flat plate systems require less maintenance than concentrators and have a longer expected life. Flat plate systems are well suited for small-scale applications and can easily be mounted on the rooftops or facades of buildings. Overall, these benefits allow flat plate systems to be used for more applications in a broader range of locations than concentrator systems.

There are two types of flat plate module technologies: standard and thin film. Standard technologies include crystalline and polycrystalline silicon cells that are on average several hundred microns thick. [Johansson and Kelly et. al., 1993] Thin film technologies create cells that are an order of magnitude thinner and can be made from a wider variety of materials. [Johansson and Kelly et. al., 1993] Flat plate systems include PV modules, supporting (mounting) structures, wiring and inverters and other electronics. Some flat plate systems include energy storage devices such as batteries so that energy collected during the day can be used after the sun goes down. Also, some flat plate systems have tracking mechanisms similar to those used in concentrator systems. This is not common due to the small energy return received for the investment.

Crystalline and Polycrystalline Silicon

Crystalline silicon is the most common material used in PV cells today. Very pure silicon is needed for the production of PV cells but it does not need to be as pure as the silicon required for microelectronics. [Johansson and Kelly et. al., 1993] This means that the PV cell manufacturing industry can use the off-spec and waste material from the semiconductor industry as raw material. Currently, PV devices consume 10% of the total silicon that is processed into electronic devices. [Benner and Kazmerski, 1999]

The most common method used to manufacture crystalline or polycrystalline cells involves creating ingots that are subsequently sliced into wafers of the appropriate thickness. This is actually a very wasteful process. About half of the silicon material is lost during slicing. [EPRI and EERE, 1997] Instead of ingots, the silicon can be made into self-supported sheets that can then be used in part or as a whole. By creating the silicon material this way, less is wasted in the cell manufacturing process. Silicon can also be deposited directly onto supporting material to reduce the thickness of the silicon required or to enhance the rigidity of the cells. Because of the reactive nature of the silicon, it is difficult to find appropriate substrates so this process is not widely used. [Johansson and Kelly et. al., 1993]

The theoretical peak silicon-cell efficiency is in the 29%-30% range. [Johansson and Kelly et. al., 1993] Experimental silicon cells have been demonstrated efficiencies around 23%-24% and commercial cells are slightly higher than 15%. [Benner and Kazmerski, 1999] Bulk polycrystalline cells have been reported to have efficiencies between 18%-19%. [Benner and Kazmerski, 1999]

There are material and design-related characteristics that can affect these efficiencies. For crystalline and polycrystalline silicon cells, efficiency is related to thickness. The output of the module is directly proportional to the amount of light that is absorbed by the cells. Decreasing the thickness of the cells can increase the output voltage but at the same time, it reduces the amount of light absorbed by the cell, thus reducing efficiency. The optimum thickness that maximizes these parameters is 300-400 microns. [Johansson and Kelly et. al., 1993] By modifying the cells so that they trap more of the incident light, the cell efficiency can be increased. Changes to the surface texture of the cells, such as creating a grid of inverted pyramids, or choosing an anti-reflective material as the rear contact for the cell will improve the modules ability to capture photons. [Johansson and Kelly et. al., 1993] These changes cause light to be reflected within the cell, effectively increasing the optical path. This increases the likelihood that photons will be absorbed, hence improving the efficiency of the cell. Polycrystalline silicon cells have a higher rate of recombination than monocrystalline silicon cells due to grain boundaries and other chemical and structural characteristics. [Benner and Kazmerski, 1999] This effect lowers the efficiency of polycrystalline cells unless they are treated to lessen the impact. Cells have been treated with hydrogen, lithium, aluminum, arsenic, and phosphorous resulting in varying degrees of success but no treatment has solved the problem. [Benner and Kazmerski, 1999]

III-V Materials

Cells made from combining elements in the IIIB and VB columns of the periodic chart are also used in flat plate applications. These include Gallium arsenide (GaAs), gallium aluminum arsenide (GaAlAs), gallium indium arsenide phosphide (GaInAsP). Cells made of these materials have shown extremely high efficiencies, in the range of 30%-34%. [Johansson and Kelly et. al., 1993] The biggest drawback is cost. As such, the only flat plate applications of these materials as been in space where reliability and efficiency matter much more than price. Cells of these materials can and have been used individually in concentrator systems where very little material is needed.

Thin Films

The main thin film technologies include amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide (CIS), and crystalline thin-film silicon. In thin film manufacturing, semiconductor material is deposited on a rigid substrate in a continuous process. The manufacture (deposition) of thin films is more rapid, less energy intensive, less wasteful, and requires less handling than the manufacture of crystalline or polycrystalline silicon. [Johansson and Kelly et. al., 1993] These characteristics make thin film technologies perfect candidates for mass production. Most thin films absorb sunlight 100 times better that crystalline silicon. [Johansson and Kelly et. al., 1993] 50-100 microns of crystalline silicon will absorb 90% of the incident light whereas that same amount of light can be absorbed by a 1 micron thick thin film semiconductor. [Johansson and Kelly et. al., 1993] Thin films have significantly lower material requirements than standard cells. Thin films can be made of a single layer of material or multiple layers with different light-absorbing characteristics3. The latter are called multi-junction cells and are most commonly made of a-Si.

Amorphous Silicon (a-Si)

Amorphous silicon is a glassy alloy of silicon and hydrogen and is commonly used as semiconductor material in thin film PV cells. The electronic and optical characteristics of a-Si can be tuned over a wide range by alloying or adjusting the amount of hydrogen present in the material. By changing the characteristic bandgap of the material, different wavelengths of light will be absorbed which leads to higher efficiencies. Also, a-Si has a different chemical structure and therefore physics than crystalline and polycrystalline silicon, which makes a-Si 100 times more effective at absorbing sunlight. [Benner and Kazmerski, 1999] A 1 micron thick a-Si film can absorb as much light as a 100 micron think wafer of crystalline silicon. [Benner and Kazmerski, 1999] These different characteristics also make a-Si less reactive than crystalline silicon and therefore can be used with a wider variety of substrates including plastic and glass.

The largest stumbling block for a-Si is its instability. Cells made of this material suffer from the Staebler-Wronski effect; their output declines initially and then stabilizes due to exposure to light. The exact mechanisms that cause this degradation are not fully known but it is believed that it is at least in part related to the amorphous hydrogenated nature of the material. [Zweibel, 1997] This effect results in a 20% loss in output before stabilization. [Zweibel, 1997] One additional potential problem associated with the Staebler-Wronski effect is the risk of further drops in efficiency in the long term. [Zweibel, 1997] One of the best ways to mitigate this effect is to make multi-junction a-Si cells. Since changing a-Si characteristics is fairly easy, this is an effective way to increase efficiency. This is not a fix for the problem however; efficiencies of commercial multi-junction a-Si modules are only between 7%-9%. [Zweibel, 1997]

There are other factors that are believed to affect the efficiency of a-Si modules as well. Exposure to the atmosphere and temperature fluctuations can contribute to the degradation. Impurities and contaminates introduced in the manufacture of a-Si can reduce cell and module efficiency significantly. Taking into account all these issues, the best stabilized efficiencies today are around 8% for laboratory modules and 5%for commercial units. [Brennan, Palmer, et. al., 1996] Currently, a-Si is only thin film being used in commercial modules. Further work is needed if a-Si thin film cells are to be competitive.

Polycrystalline Thin Films

Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS) are the two main thin film technologies and can be broadly classified as polycrystalline thin films. Their structure consists of small-grained crystals, similar to polycrystalline silicon. They do not suffer from the Staebler-Wronski effect, mainly because of their structural characteristics. Although none of these materials are currently being used in mass production, they have significant potential to play a large role in the future of photovoltaics.

Cadmium Telluride

CdTe thin films are the next in line for large-scale commercialization. [Zweibel, 1997] They are currently used in many calculators and other small devices. They are also the easiest thin film to fabricate. The manufacturing process most widely used today provides an inherent benefit to CdTe cells. By treating the material in a cadmium chloride solution at high temperature, larger than average crystals are produced and the crystals are more densely packed. [Benner and Kazmerski, 1999] These factors reduce recombination losses and foster charge mobility in CdTe cells. [Benner and Kazmerski, 1999]

The biggest challenge facing CdTe is variability. Stability and efficiency varies from cell to cell and module to module. [Zweibel, 1997] As with most photovoltaics, CdTe modules are less efficient than CdTe cells and the variability aggravates this problem. The best laboratory cells have efficiencies around 16%. [Zweibel, 1997] Commercial prototype modules seem to be in the 6%-8% range. [Zweibel, 1997]

The exact reasons for the variations are not fully understood. It is believed that the p-n junction in CdTe cells contributes to the efficiency problem. [Zweibel, 1997] It is very difficult to optimize the junction because of the nature of the material used and the characteristics required for successful voltage generation. [Zweibel, 1997] There are many theories about what is causing variation in the stability. Unstable contact materials, oxidation, diffusion, and quality control are the most common. [Zweibel, 1997] More research is needed to understand these issues and correct for them in order for CdTe thin films to be a viable PV material for broad use.

Copper Indium Diselenide

CIS cells have achieved some of the highest efficiencies of any thin film. The best efficiency in 1996 was approximately 18%, which is close to that of polycrystalline silicon cells. [Zweibel, 1997] This has been achieved by adding other materials to the cells such as gallium and sulfur. These additives, along with some changes to the layering of the materials, increase the grain size and improve the electronic properties of the cells. [Zweibel, 1997] These changes widen the range in which cells can be constructed which has led to the high efficiencies seen in CIS cells. Another benefit of CIS is that the cells do not experience degradation over time.

The problems with CIS thin films seem to lie in the manufacturability of CIS modules. Problems stretch from fundamental properties to finding a viable production process. Irreproducible deposition of the CIS and poor adhesion to substrate material brought initial attempts to make modules to a halt in the early 1990's. [Zweibel, 1997] The added materials and deposition changes needed to achieve high efficiency add complexity to the manufacturing process which will need to be addressed if CIS is going to be competitive. Since CIS is known to have the capacity for high efficiency, investment in improving these technological issues is worthwhile.

Crystalline Thin-Film Silicon

Thin-film silicon is made by depositing silicon vapor onto an appropriate substrate. The efficiency of these cells should be able to compete with conventional wafer silicon cells. Currently, efficiencies vary widely - from 3% to 12% - depending on everything from what the silicon is alloyed with to what the material is deposited on. [Johansson and Kelly et. al., 1993] Processing hurdles such as required diffusion lengths, high temperature requirements and sensitivity to impurities all are current barriers to expanded use. [Zweibel, 1997] Technological enhancements that increase light trapping in these cells will be important in order for these thin films to have efficiencies competitive with wafer silicon cells3.

From a technological perspective, photovoltaics are a promising renewable energy source. Issues exist with materials processing and efficiency for current technologies but they are not insurmountable. The rising new thin film technologies have a great deal of potential due to the inherent benefits in their manufacturability and materials requirements. Much more work needs to be done on thin films to improve efficiencies in order for them to become the next generation photovoltaics.

III. Environmental Impact Review

There are three means by which photovoltaics can impact the environment. To get a true sense of the environmental benefits and costs of PV systems, one must look at all three. The areas are resource use, pollution potential and energy use. The latter of these is intrinsically related to carbon dioxide mitigation and climate change. These areas do overlap and each one depends on what part of the photovoltaic life cycle is in question. The interdependence will not be covered in depth here, nor will every aspect of the life cycle be looked at in every area. To be able to assess whether photovoltaics are 'environmentally friendly' and thus an appropriate renewable energy source to pursue, the benefits and drawbacks will be discussed on a broad scale.

Resource Use and Pollution Potential

Operation

One fundamental characteristic of photovoltaics that makes them more 'environmentally friendly' is the fact that they do not use any fuel during operation. This significantly reduces health and air pollution risks. PV systems also use no water during operation, which essentially eliminates water pollution concerns as well. Due to these characteristics, there is no waste generated from the operation of PV systems. Essentially, once a PV system is manufactured and installed, it has no environmental impacts whatsoever.

Manufacturing

Silicon is the basic raw material in most PV modules today. This is an abundant mineral and there is not expected to be issues with the use of this resource in the long term. Other module technologies such as thin films use other raw materials such as cadmium, selenide, and indium. Scarcity issues might arise with some of these materials such as indium if mass production of thin films becomes a reality. [Johansson and Kelly et. al., 1993]

There are hazardous feedstocks used in the manufacture of most PV modules therefore pollution risks exist in this part of the life cycle. CdTe thin films pose the most risks with CIS a close second. Cadmium is a suspected human carcinogen3. It poses a chronic risk to human health, not an acute risk. Therefore biomontioring (urine tests), proper materials management procedures, and monitoring equipment are appropriate means of minimizing risks. CdTe module production does generate waste as well. Material utilization in current processes is only around 80%. [Johansson and Kelly et. al., 1993] As well, 5% of all completed modules are rejects. [Johansson and Kelly et. al., 1993] A facility making 10MW worth of CdTe modules would generate approximately 250kg of cadmium contaminated waste per year. [Johansson and Kelly et. al., 1993]

Hydrogen selenide and cadmium are used in the production of CIS films. [Johansson and Kelly et. al., 1993] Hydrogen selenide is a highly toxic gas that poses significant human health and environmental risks. It is critical that proper storage and handling procedures are followed. Small quantities of cadmium are used so risks are small but it is still important that air and water monitoring is used to minimize potential exposures.

Other toxic gases are used in the manufacture of other thin films such as arsine, phosphine, diborane, and germane. [Johansson and Kelly et. al., 1993] The health and environmental risks from these are greater than from other hazardous materials used in thin films. The purification process used in the manufacture of crystalline and polycrystalline silicon uses fluorine and chlorine and results in releases of these materials to the air and water. [Phylipsen and Alsema, 1997] The magnitude of these releases, and therefore the health and environmental risks associated with them, are fairly minimal. 0.16kg of fluorine and 430kg of chlorine are released to the air and 1800kg of fluorine and 89,000kg of chlorine are released to water per TWhr energy generated by PV modules. [Phylipsen and Alsema, 1997]

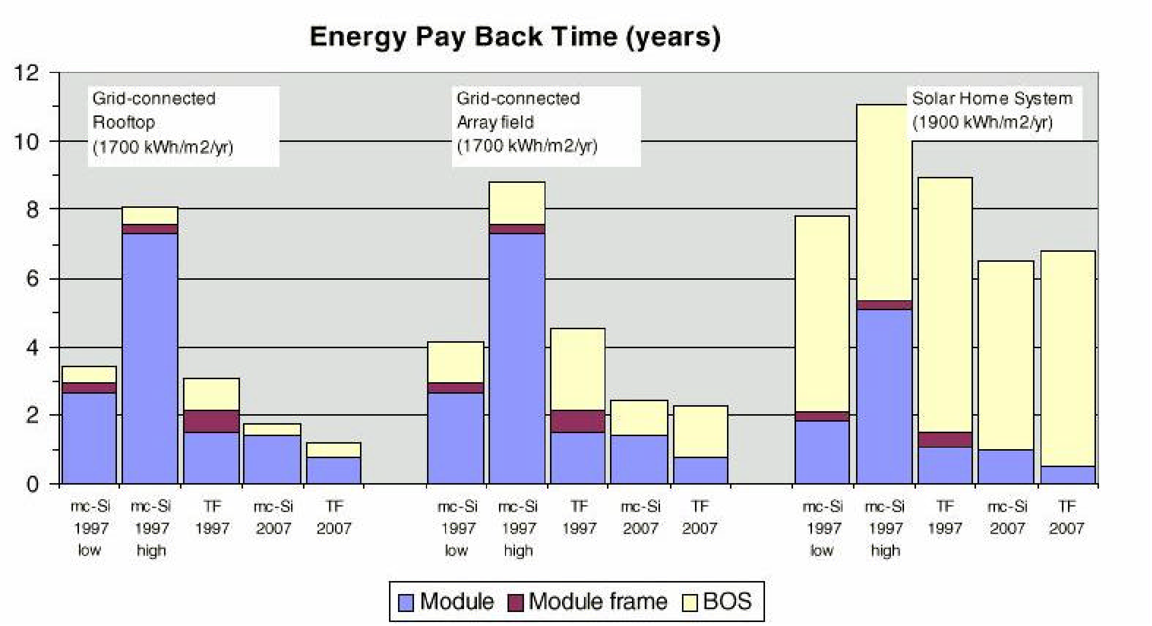
End-of-Life

For PV systems that contain certain polycrystalline or thin film modules, there could be disposal issues once the modules reach the end of their useful life. CIS modules contain on average 0.04 grams of cadmium and 6 grams of selenide per square meter. [Johansson and Kelly et. al., 1993] Selenide can pose a water pollution risk if the module was disposed of improperly but the cadmium is bound in such a way that it shouldn't be an issue. [Johansson and Kelly et. al., 1993] EPA TCLP tests (Toxicity Characteristic Leaching Procedure tests) have been done on these modules and the results have shown that the modules are non-hazardous by a factor of 10. [Johansson and Kelly et. al., 1993]

Energy Use

In order to produce PV systems, it takes energy. It is important that it does not take more energy to make the systems than can be gotten from the systems once they are in use. A common benchmark for evaluating PV in this light is called the energy payback time (EPBT). This is the length of time required for a module to generate an amount of energy equal to the amount required to produce it. [Lewis and Keoleian, 1997] It is important to point out that this type of analysis can not be done effectively for fossil fuel systems. They will never generate more energy than then consume (on a primary energy basis) because of the losses inherent to the generation methods. [Lewis and Keoleian, 1997]

Current estimates of the energy requirements for the production of crystalline and polycrystalline silicon modules are 5300-16500MJ/m^2 and 2400-7600MJ/m^2 respectively. [Alsema, Frankl, et. al., 1998] This wide range results from different assumptions for the energy requirements for the silicon feedstock. For a-Si thin films, energy requirement estimates are in the range of 710-1980MJ/m^2. [Alsema, Frankl, et. al., 1998] Differences in substrate choice and encapsulation materials are responsible for these differing values. The amount of energy produced by a system is dependent on the system efficiency, incident insolation, and module size. EPBTs for three different photovoltaic systems are shown in the chart below. Alsema, Frankl, et. al. compared polycrystalline silicon and thin film modules for three different applications. BOS and module frame energy requirements are also included.



Source: Alsema, Frankl, et. al., 1998

The results for polycrystalline modules were broken into high and low to account for the variations in silicon processing energies. Solar home systems have battery storage as part of the BOS calculations, which explains the significant increase in energy pay back time seen for these systems. It is also worth noting that although thin films have lower module production energies, larger surface area and other requirements increase BOS energies to the point where the module savings are negated. [Alsema, Frankl, et. al., 1998]

Results for crystalline silicon would be similar to the polycrystalline results shown though the EPBT for the modules would be slightly higher due to the increased energy required to process crystalline silicon. [Alsema, Frankl, et. al., 1998] The higher efficiency of crystalline silicon is not sufficient to overcome the excessive processing energy requirements. Similarly, thin film technologies would exhibit EPBTs comparable to those shown for amorphous silicon. [Alsema, Frankl, et. al., 1998]

Since processing energy requirements for most other thin films are slightly higher than for a-Si, module EPBTs would be slightly higher as well.

For PV technologies, the biggest opportunity for energy reduction in module manufacturing is in the material processing. This is particularly true of crystalline and polycrystalline silicon. If the PV industry moves away from relying on residual microelectronic grade silicon and develops independent processing methods, significant amounts of input energy can be saved. [Alsema, Frankl, et. al., 1998] For thin films, additional energy savings can be obtained by improvements in encapsulation and substrate materials. For all types of PV modules, production on a larger scale will help reduce overall input energy requirements.

Essentially all carbon dioxide emissions associated photovoltaics come from the generation of the energy needed for the production of PV modules. Therefore any technological advancements that improve the manufacturability or manufacturing process for PV systems will reduce CO_2 emissions. The potential for CO_2 mitigation comes from grid-connected PV systems. In grid-connected systems, the energy they generate is replacing energy that would have been generated by fossil fuels, therefore eliminating the CO_2 that would have been emitted in its generation. This is not true for off-grid PV systems for two reasons. First, most medium to large off-grid applications employ secondary systems that burn fossil fuel to meet energy needs when necessary. Second, virtually all off-gird systems require some form of energy storage and energy storage devices are incredibly energy intensive to make. There are greenhouse gases other than CO_2 that are emitted on a very small scale from the production of PV modules. The etching process use SF_6 and CF_4 - two fluorine-containing compounds that have higher global warming potential than CO_2. [Nieuwlaar and Alsema, 1997] 1kg of SF_6 gas emitted to the atmosphere is equivalent to 24,000kg of CO_2 and 1kg of CF_4 is equivalent to 6500kg of CO_2. [Nieuwlaar and Alsema, 1997] Though alternatives are being researched, there are no effective ones available at this point. It is imperative then that proper hoods and other vapor collection systems are used in conjunction with appropriate procedures to prevent the emission of these materials.

From the information above, it can be concluded that photovoltaic systems are 'environmentally friendly'. They use very few resources and those used in volume seem plentiful. There is very little pollution risk associated with PV system, with the exception of the air pollution from the generation of the energy needed to make the units. The energy life cycle of photovoltaics could be improved. Shorter EPBTs are needed in order to make the systems more attractive to consumers. Overall, PV systems pass the test and should be promoted as a clean energy alternative.

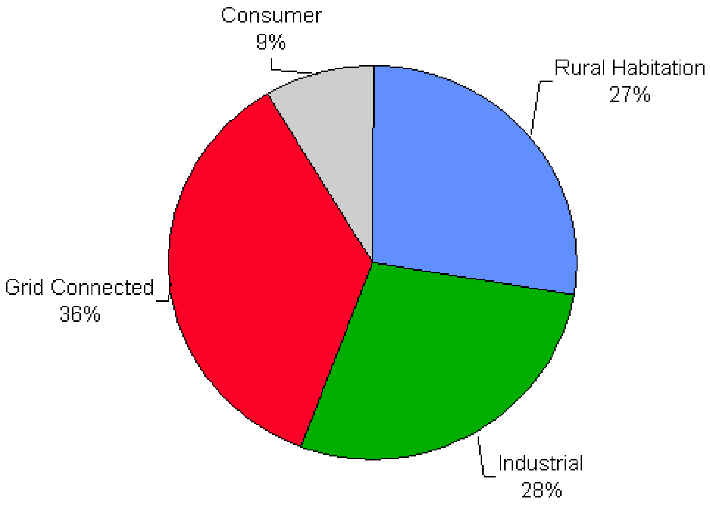
IV. Markets and Costs

Despite continuous growth in the PV industry over the last decade, photovoltaic energy is still a very small part of the overall US energy picture. In 1997, it satisfied less than one hundredth of one percent of the overall US energy consumption. [EIA, 1998] Due to the higher demand for PV units in other countries, 70% of the PV systems manufactured in the US are sent abroad. [EIA, 1998] Though this does help our economy, it does not help build the US market for photovoltaics.

Right now, photovoltaics are only filling niche markets in the US. The main reason PV systems are not playing a larger role is competition from fossil fuels. Over the past 10 years, fossil fuel prices have fallen dramatically. In March of 1998, the real price of oil hit an all-time low. [Serchuk and Singh, 1998]   The improved mechanization of coal mining, the deregulation of the natural gas industry, and OPEC's lack of success in maintaining market power have all contributed to this decline. PV power will continue to struggle until the prices of conventional energy sources reflect environmental and geopolitical costs.

Markets

Photovoltaic systems can either be connected to a transmission grid or can be used remotely. Off-grid applications can be broken down into three main categories; industrial, consumer, and rural habitation. Industrial uses include telecommunications, cathodic protection, telemetry, navigation systems, water pumping, and highway signs. Calculators, watches, and other small electronic devices fall in the consumer use category. Lastly, rural habitation includes remote homes and villages. Currently, more than 50% of the PV market is for off-grid applications and the largest market opportunity worldwide for PV is in rural habitation. [Worldbank, 1999] This includes both residential-scale and utility-scale applications of PV. The makeup of the world PV market in 1997 is shown in the chart below.



Source: Worldbank, 1999

Grid-connected PV systems can be used for both distributed and central power generation. Distributed generation includes residential (2-4kW) and commercial (30-100kW) roof or façade-mounted photovoltaics as well as installations at power substations other remote points on the transmission grid. That fact that PV can be used for distributed generation is very beneficial. It can help utilities lower loads at the distribution level and by combining PV with demand-side-management techniques such as conservation and energy efficiency efforts, they can save significant time, money, and trouble. Central generation consists of large multi megawatt facilities that transmit energy to the users through the grid. In the US, grid-connected systems have a great deal of market potential. The inherent flexibility in PV energy systems allows them to fit perfectly in the restructuring of the US electric power industry.

If the photovoltaic industry focused its strategy more on developing nations, where competition from conventional energy is minimal, the market for photovoltaics could be expanded substantially. [Serchuk and Singh, 1998] PV modularity is very beneficial in developing nations because of the small-scale widespread nature of their demand. The fact that it is easily scalable makes it easier for governments to keep pace with growth in demand. There are many reasons why the PV industry shies away from markets in developing nations today. Transportation issues, geography, fragmented governments, cultural differences, and regulatory barriers all play a role. [Serchuk and Singh, 1998] It is risky for private PV firms to put too much investment in these unsure conditions.

Residential versus Utility

As stated earlier, the vast majority of PV systems installed to date have been small-scale flat plate systems. Although concentrators are more efficient, they are not well suited for small-scale use due to their complexity and cost. They are better for utility-scale applications. Currently though, the use of photovoltaics in utility-scale applications is very small. In 1997, there were only four utility-scale plants using solar energy for power generation. [EIA, 1998] As such, sales of concentrator systems are less than 1% of the total worldwide sales of photovoltaic systems. [EPRI and EERE, 1997] The market for concentrator systems is clearly smaller and is growing slower than the market for residential-scale flat-plate units. The largest market for concentrator systems to day is space applications where cost and complexity do not matter and efficiency is very important.

The residential/commercial sector is a large potential market for PV systems. Currently over 10 million single-family homes that receive above average insolation in the US have suitably tilted roofs for the installation of PV systems. [EPRI and EERE, 1997] This is a 30+gigawatt market. [EPRI and EERE, 1997] Residential rooftop systems can be owned by the resident, the local utility, or an independent power generation company. Generally, utility or independent company-owned systems are part of a cluster called a neighborhood bulk system. Utilities in particular should see these 'customer-sited' PV systems as beneficial. For them, siting PV generation near the point of consumption reduces demand at peak load times and minimizes BOS costs associated with expansion by reducing site acquisition costs and eliminating the need for grid extension. [EPRI and EERE, 1997] Despite these benefits, there are very few power companies that operate customer-sited PV systems. New England Electric is one of the few utilities that own neighborhood bulk systems.

One last up-and-coming market for photovoltaics is building-integrated systems. As thin film technologies advance, there are more and more opportunities to make building materials such as shingles and roof tiles out of PV material. These inconspicuous lightweight applications will most likely play a substantial role in the future of photovoltaic systems.

Competition

Deregulation is slowly refocusing utilities on cost competitiveness. To do this, they are increasing their reliance on grid-connected distributed sources to meet power demands. [NREL, 1999] Right now, natural gas turbines are chosen most frequently and therefore are the stiffest competition for photovoltaics. Natural gas is similar to PV in that it is cleaner than oil and coal, it is quieter than other energy sources such as wind, it does not require any fuel storage on site, and it does not generate any waste. PV systems are superior in that they are emission-free during operation, they are completely noiseless, and they do not require any fuel at all. The problem that remains is knowledge. People in the power industry understand natural gas systems are better than photovoltaics. Natural gas turbines are easier to order and have installed as well. For PV to truly be competitive in the distributed energy market, greater understanding of total system benefits must become commonplace.

Off-grid applications of PV also face competition. Transmission and distribution grid extensions, primary disposable batteries, and gas and diesel generators all can replace PV systems. Photovoltaics do have their advantages though and for off-grid applications, the low operation and maintenance costs of PV provides a competitive advantage.

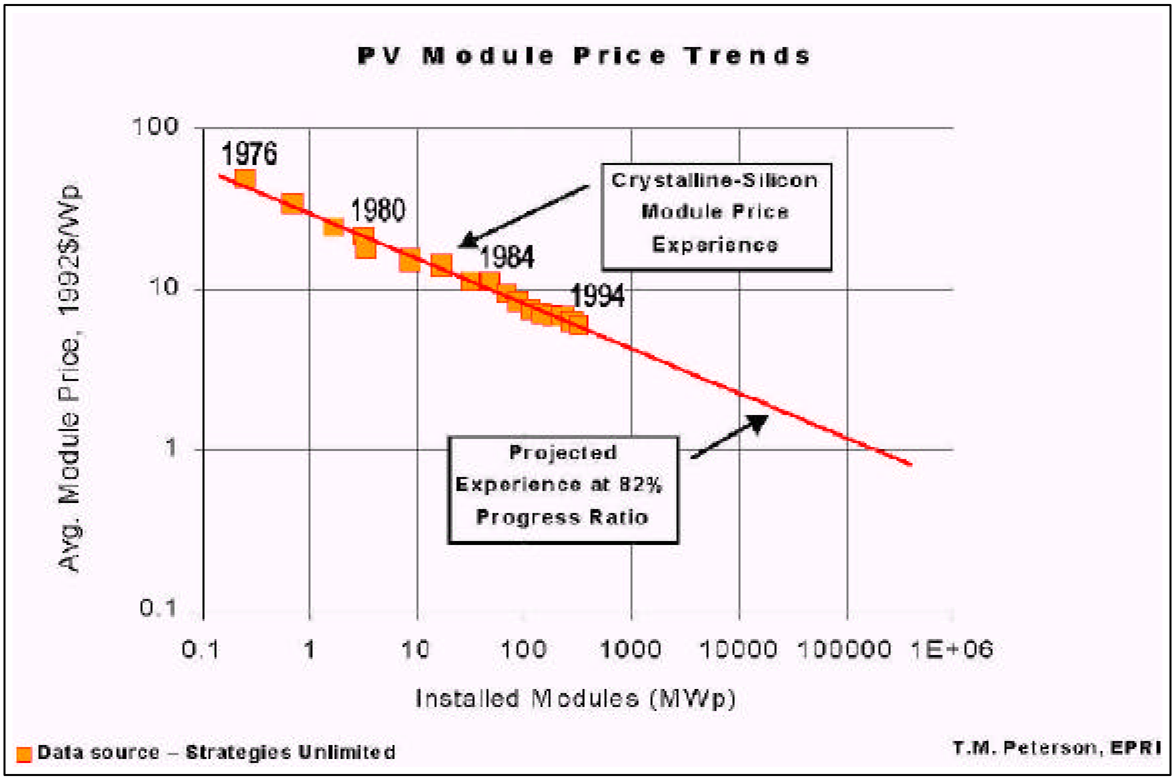
Costs

People invest in photovoltaic systems today because it produces clean energy that can reduce their grid-supplied energy bills. Utilities invest in PV systems to meet regulatory requirements or to minimize expansion costs. Though both of these markets are still small, prices of installed PV systems have fallen steadily over the past 15 years. Systems cost $17 per watt in 1984, $9 per watt in 1992, and $6 per watt in 1996. [Serchuk and Singh, 1998]

One of the biggest benefits to PV users of any scale is the minimal operation and maintenance costs. All PV systems have very low O&M costs. Flat plate systems O&M is slightly lower because they generally have no moving parts. Early kilowatt plants demonstrated O&M costs of $0.005 per watt. [EPRI and EERE, 1997] One study of the performance of a residential system over 10yrs of operation showed the system to have high reliability and very low annual O&M costs in the $52.00/yr. [EPRI and EERE, 1997] Utilities in particular can benefit from the use of PV systems. For utilities, electricity is most expensive to produce and distribute during peak load times. The full cost of delivering electricity to consumers during summer peak times can be as high as $0.40 per kWhr. [EPRI and EERE, 1997] By using PV systems as either customer-sited generation or as larger-scale distributed generation in place of system expansion, utilities could save a great deal of time and money. The cost of grid extension today is between $20,000 and $80,000 on average. [EPRI and EERE, 1997] Also, there is a lengthy permitting process required for the installation of new transmission and distribution networks. It can take several years to get upgrades approved. According to Pacific Gas and Electric, some utilities spend $1.50 to distribute power for every $1.00 they spend to produce it. [NREL, 1999] Utilities could use time-of-day pricing instead of the flat rate system used today to provide incentives for customers to install PV systems.

There are two costs that need to be considered when evaluating PV systems; module and BOS costs. Cost reductions in both areas are needed if PV is to become competitive with conventional energy. BOS costs account for a smaller portion of the overall system cost but it is still worth pursuing BOS cost reduction opportunities. A fairly large amount of BOS costs are wrapped up in the inverter and associated controls required to convert the DC output to usable AC current. [EPRI and EERE, 1997] 1993 cost of inverters and the required control equipment was $400-$1000 per kilowatt. [Johansson and Kelly et. al., 1993] Development work is being done to create a PV module with an integrated inverter which should substantially lower the inverter contribution to BOS costs. System design improvements and standardization in grid connection methods will reduce BOS costs as well.

In general, module costs are normally about 1/2 of total cost of a PV system. PV module output is directly proportional to the amount of solar insolation. Therefore the cost of PV modules is inversely proportional to the their efficiency. Module efficiencies and manufacturing costs are the largest determinant of PV system costs. Efficiencies are technical parameters and can't be directly affected by changes in module manufacturing. Module manufacturing costs are impacted by production but do not benefit from economies of scale as fossil and nuclear plants do. PV module manufacturing gains economic benefits from cumulative production, which can be measured by a learning curve. A learning curve plots cumulative production volume versus costs as in the chart below. [EPRI and EERE, 1997] The slope of the learning curve is the called learning curve factor or progress ratio. This value is the percent of cost remaining after a doubling of the cumulative volume produced. The chart below shows an 82% progress ratio, which means that module cost will reduce to 82% of the starting value when cumulative production doubles.



Source: EPRI and EERE, 1997

The 82% progress ratio has also been confirmed through a bottom-up analysis of the industry. [EPRI and EERE, 1997] Typical progress ratios for manufactured goods range from 70-90% which lends credence to this result. [EPRI and EERE, 1997] The data plotted on the chart represents several different technologies but the dominant driver for the learning curve has been the price-volume relationship for crystalline silicon modules. It is not unreasonable to apply this learning curve to other PV technologies in the near term. It would take the emergence and adoption of a fundamentally new technology to change the trend shown in the chart. Thin films have the potential to drive this shift if costs and manufacturing issues can be overcome.

The 15%-20% increase in module sales that has been seen over the past decade can be expected to continue due to learning effects. [EPRI and EERE, 1997] Combining the learning curve information with this annual projected growth in manufacturing gives a sense of the expected annual reduction in module costs. With an 82% progress ratio, price reductions should be on the order of 5% per year. [EPRI and EERE, 1997] Costs in the near term will still be too high for PV systems to be competitive. Increased production is essential to drive down costs and expand markets.

Cost Reductions for Specific Technologies

Since flat plate modules are the most widely used, it is important to identify potential near term cost reductions that will further their deployment. Flat plate PV system cost reductions can be achieved in two ways; by reducing cell manufacturing costs and by perfecting the manufacture of thin films. [Johansson and Kelly et. al., 1993] For silicon flat plate PV modules, the creation of the silicon ingots and processing them into wafers is 55%-75% of the total module manufacturing cost (assuming the most commonly used Czochralski process and inner-diameter saw cutting technique). [Johansson and Kelly et. al., 1993] Processing the wafers into cells is 10%-25% of the manufacturing cost and encapsulation into a completed module accounts for the remaining 10%-25%.[Johansson and Kelly et. al., 1993] New cutting techniques that are currently available can reduce material losses by half. [Benner and Kazmerski, 1999] Alternative ingot generation and cutting techniques are essential to achieve lower crystalline and polycrystalline silicon module costs. Alternative methods are being developed.

In 1997, thin film module costs were between \$3.5-\$5 per watt and overall system costs were between \$7-\$15 per watt. [EPRI and EERE, 1997] For thin films, the largest contributors to module costs are from the non-semiconductor substrate and encapsulation materials. The cost of the semiconductor material is the second highest contributor because thin films use very little material - 1/20 to 1/100 of the material required for traditional crystalline and polycrystalline silicon cells. [Johansson and Kelly et. al., 1993] The manufacturing methods used for thin films, such as chemical vapor deposition, seem to be better suited for automated large-scale production. Currently, the costs associated with these manufacturing methods are high and outweigh any cost savings from reduced materials requirements. All thin films have the potential for very low module cost (under \$50 per m^2) and for reasonable module efficiencies (13-15%) but so far none have made a significant showing in the market. [EPRI and EERE, 1997] The only thin film in production today is a-Si. All others are in various pilot stages but CdTe expected to be the next thin film to have notable market share. CdTe is less expensive to manufacture than a-Si because of the manufacturing process differences. CdTe is also less expensive to manufacture than CIS thin films because tellurium is 1/3 the cost of indium. Thin films are not expected to be cost competitive in the near term (3-10yrs).

Concentrators require less cell area by a factor of 1000 and therefor reduce module cost by the same factor. [EPRI and EERE, 1997] Point focus concentrators are more cost advantageous than other concentrator systems due to lower cell area requirements. Even though the cells in concentrator systems are very small, they still constitute the single most expensive component of the system. [Johansson and Kelly et. al., 1993] Concentrator markets will continue to suffer because of the inherently small volume of cells required. The small volume required makes large-scale production less likely and therefore costs will remain higher in the near and potentially in the long term.

Research and Development

Increased production and increased efficiencies of modules are necessary if photovoltaics are going to become competitive and meet the industry's goal of low costs for large-scale use. Research and development work is critical for photovoltaics' success. Further development is needed in three main areas; increased efficiency of modules, especially in thin films (current silicon modules are around 18% whereas thin film modules are less than 10%), optimization of manufacturing processes to increase yields, production rates, and material use, and increased long-term outdoor stability and reliability. [EPRI and EERE, 1997] The federal government plays, and should continue to play a large role in funding this important research, at least in the short term. Since most PV manufacturers are operating at a loss, they are not able to invest to the degree necessary to sustain, let alone grow the PV industry. Federal funding for photovoltaic R&D in 1997 was approximately $40M, half of which went to thin films. [EPRI and EERE, 1997] Additional funds are needed as well as new initiatives and policies at the state or federal level to move the PV industry beyond its current position.

Clearly, the biggest challenge for photovoltaics is cost. The technological hurdles discussed in the first section can be overcome and there are working suitable systems available today. From and environmental perspective, photovoltaics are head and shoulders above conventional energy systems. The most difficult obstacles the photovoltaics have to overcome are the ones that are, for the most part, out of the manufacturers' hands. Increases in market size must be achieved to drive down costs but creating the incentives to increase demand is not an easy thing to do. It can be done, with help from public interest groups, environmental organizations, the government and other entities that see the benefits to using photovoltaic power.

V. Present and Future Policies

Existing policies and legislation, particularly at the federal level, tend target renewable energy sources, not specifically photovoltaics. PV systems do have much in common with other non-hydro renewable energy sources so it is important to understand how the policies on renewables are structured. Policies will impact photovoltaics and other renewables in similar ways. There are some current initiative programs underway for photovoltaics, most notably the Million Solar Roofs program being sponsored by the federal government. The program calls for the Department of Energy to facilitate the installation of one million solar units (60% photovoltaic, 40% hot water) on rooftops by they year 2010. A lofty goal that, if successful, should give the photovoltaic market a solid boost.

Federal Government

Government incentives for sustainable energy essentially began with the passage of the Public Utilities Regulatory Policy Act (PURPA) in 1978. PURPA has been the main instrument for promoting renewables at the federal level. [Paulos and Dyson, 1996] The intent of PURPA was to force utilities to diversify their energy generation portfolios by requiring them to purchase electricity from certain types of independent power producers at the same price it would cost them to generate it themselves ('avoided cost'). When it was passed, it was generally believed that energy prices would continue to rise so avoided costs were set high. This made renewable energy look competitive. Since then, particularly over the past 10 years, energy prices have actually dropped, lowering avoided costs, and making renewable energy less attractive.

The Energy Policy Act (EPAct) of 1992 was the next significant piece of legislation to promote sustainable energy, and in particular, to clearly show support for solar energy. The EPAct opened transmission grids to wholesale power - a big step in the direction of deregulation. It also made a standing 10% federal tax credit on solar energy permanent, which sent a signal indicating government endorsement of this new source of power.

Another way the federal government supports renewable energy is through the National Energy Policy Plan. Part of this plan is the Comprehensive National Energy Strategy. This document outlines the US energy needs and goals as well as a plan for achieving them. It must be submitted by the President to the Congress as required under section 801 of the Department of Energy Organization Act. The 1998 version of this document directly and indirectly promotes renewable energy as part of the overall US energy portfolio. The strategy clearly supports improvements in the science of pollution and climate change as well as efforts to reduce greenhouse gas emissions. Any reference to pollution prevention indirectly supports renewable technologies. There are two specific sections in the 1998 strategy that directly refer to renewable energy sources.

> *Goal I, Objective 2, Strategy1:*
>
> "Provide federal technical support and leadership in adopting energy efficient and renewable technologies." [DOE, 1998]

This is primarily directed toward improved procurement mechanisms that promote the purchase of renewable technologies for federal agencies. The intended consequence of this is widespread adoption of renewables by setting an example for the private sector to follow.

> *Goal III, Objective 1, Strategy 3:*
>
> "Develop renewable electric technologies capable of economically doubling non-hydroelectric renewable generation capacity to a total of at least 25,000MW by the year 2010 and maintain the viability of existing hydropower sources." [DOE, 1998]

This is the closest reference to photovoltaics in the plan. This goal will be achieved through increased federal research and development efforts and voluntary cost-shared partnerships. The goals are improvements in efficiencies and affordability so that renewable energy can play a more substantial role in the competitive energy market. This also will help diversify the nations energy supply.

There are several other federal initiatives that support renewable energy. This Administration has put forth the Comprehensive Electricity Competition Plan which includes a requirement that a certain percentage of electricity sales come from non-hydro renewables. The Climate Change Action Plan has a section aimed at lowering the cost of renewable energy through the facilitation of aggregated purchasing. There are many joint programs supported by the federal government specifically for photovoltaics. These include TEAM-UP (Technology Experience to Accelerate Markets in Utility Photovoltaics), PV:BONUS (Building Opportunities in the US for Photovoltaics), PVUSA (Photovoltaics for Utility Scale Applications), PVMaT (Photovoltaic Manufacturing Technology project), PV4U (formerly Photovoltaics for Utilities, now Photovoltaics for You), and the Million Solar Roofs program.

The deregulation of the electric industry will have an impact on renewable energy. The increased use of natural gas turbines as distributed energy sources will spur the development of the essential system management and standardizations necessary to connect distributed resources to the grid, which will help photovoltaic energy sources tremendously. [NREL, 1999] On the other hand, restructuring could put renewable energy sources at risk because the strategic planning necessary to operate in competitive market requires acquiring the least-cost alternatives. [Brennan, Palmer, et. al., 1996] As shown here, renewables and particularly photovoltaics do not fall into this category. How current policies are implemented and how new policies are structured will determine the impact on photovoltaics.

The Role of the States

As the electric industry restructuring has progressed, most of the regulatory responsibility has fallen on the states. Most states have taken action to promote renewable energy as part of the electric industry, some with more success than others. Approaches vary from including renewables in the planning stages of power management to customer incentives. Many states' policies focus on requiring utilities to buy renewable power when it is cost-effective for them to do so. [Paulos and Dyson, 1996] This does nothing to promote photovoltaics; as pointed out in this paper, they are currently not cost competitive. Upstream planning approaches can be helpful but are not sufficient for the long-term growth of any type of renewable energy.

The most common upstream approach is requiring Integrated Resource Planning (IRP). IRP programs requires that renewable energy, conservation, and efficiency improvements be considered when utilities determine how to meet power demands. Some states' IRP programs do include social and environmental costs associated with generation, but it is usually in the form of externality charges on emissions. [Paulos and Dyson, 1996] Photovoltaics and many other renewables don't have emissions. Internalizing externalities in this way does not take into account to full set of benefits that renewables have to offer - things such as fuel diversity, employment opportunities, and trade implications are not considered. Though it is important to include renewables in the planning process, better methods to account for true costs and benefits of energy sources are needed to make a fair comparison.

Current downstream policy options can be put into five categories; set-asides, funding mechanisms, regulation, market approaches, and customer incentives. The first four are targeted toward utilities and independent power generators. These are all implemented on a state level, which leads to a great deal of variety from state to state. Experience has shown that no single option alone is capable of achieving the increased markets and lower costs that are necessary for renewables to play a substantial role in the US energy picture.

Set-asides are the most direct approach to promoting renewable energy. Set-asides are state mandates that require electricity suppliers to supply a certain portion of their power from renewable generators. The most popular form of set-aside is a 'renewable portfolio standard' which requires distribution companies to buy a set amount of renewable energy from electricity suppliers. [Paulos and Dyson, 1996] This approach favors only least-cost renewables. Photovoltaics do not fall into this category. Additional requirements are needed to ensure that the more expensive renewable technologies are not excluded.

Funding mechanisms include taxes (emission, carbon, and BTU), rebates, direct subsidies and system benefit charges. States use these and other schemes to collect money to fund renewable energy deployment. A system benefit charges is an access fee that would be levied for the use of the transmission grid. These are touted as a good approach because it addresses the distributional equity issue - everyone would have to pay to promote renewables. [Paulos and Dyson, 1996] On the flip side, the charge does not discriminate between polluters. Coal plants would have to pay as much as natural gas. Also, concerns have been expressed that the charge might not be sufficient to cover the true cost of promoting renewable energy. [Paulos and Dyson, 1996]

Rebates, buy-downs, and 'feebates' are methods of defraying the cost of implementing renewable energy. Buy-down programs use public funds to make up the difference between the price of renewable energy and the price of grid power. [Wenger and Herig, 1997] These are commonly administered through programs such as TEAM-UP. Feebates are revenue-neutral public/private tax/rebate schemes that charge generators based on their level of emissions. Rebates are then given to the low emitters to compensate for their higher abatement costs. These do not directly impact renewables as most don't have emissions from their operation. It does encourage utilities to use renewables as distributed sources to reduce overall emissions.

Regulation involves implementing statutes that promote renewable energy by constraining fossil fuel-burning facilities. These mechanisms include expansion of the current emission regulations, incorporation of externalities into operating costs, and 'cap-and-trade' systems. The latter sets a limit on the amount of emissions a generating facility can have in order to access to the transmission grid. A company that reduced emissions below that limit could trade those credits with other firms.

Market mechanisms include any government incentive or credit programs that use markets to drive renewable energy. The most common approach is 'green pricing' which can take many forms. [Paulos and Dyson, 1996] The basis for green pricing is that consumers are provided the opportunity to pay a premium on their energy bill to ensure that some amount of energy in the grid is contributed by renewable energy sources. Green pricing has the potential to increase the share of renewables in the marketplace. Recent willingness-to-pay surveys of utility customer behavior show that nearly 30 percent of utility customers would be willing to pay a 10% premium for renewable energy. [Paulos and Dyson, 1996] As of 1996, the largest green pricing program used 960kW of photovoltaic energy. [Paulos and Dyson, 1996]

The final category is consumer incentives. This includes net-metering, low-interest loans, energy-efficient mortgages, and consumer tax exemptions (property, income, sales, etc.) as well as other programs that encourage individuals to purchase renewable energy systems. These are particularly important for photovoltaics because of the high initial cost of purchasing a PV system. Net-metering is the most popular methods of providing consumers incentive. Currently it is being used to varying degrees of success in more than 20 states. [Wenger and Herig, 1997] Consumers are billed for the net electricity purchased from the utility over the billing period and additional electricity produced by the consumer's system is purchased by the utility. The problem with net-metering is the inconsistency with which it is applied. Most states do not buy the electricity back at retail rates and some have extraneous fees as well.

Future Policy and Incentives

Further policy development is needed to increase the role of photovoltaics in the current US energy picture. There certainly has been a start, as outlined in the previous section, but given the dynamic state of the energy sector and the increasing pressures of a market economy, it is important that future policy is set such that renewable energy is supported, not hindered. There are several actions and policies in particular that will help meet this goal.

- Additional information should be collected about the near term market opportunities and strategies for how to harness them should be developed. [Serchuk and Singh, 1998] This will help guide the PV industry in the right direction and will provide much needed incentives to manufacturers. In addition, it can increase the level of knowledge of photovoltaics throughout the electricity sector.

- Serious education is needed at all areas if photovoltaics are going to be adopted as a viable distributed energy source. Utilities, independent power generators, transmission and distribution companies, builders, architects, building inspectors, real estate appraisers, and consumers all need to have a better understanding of photovoltaics and their benefits over power generated by conventional fossil fuel systems. [Serchuk and Singh, 1998] Public interest groups, environmental organizations, and companies using photovoltaics should be promoting this education. The information must be in line with the goals of the PV industry so that the markets move in the right direction.

- Aggressive coordinated procurement of photovoltaic systems by the government will significantly increase production volumes, spur market growth, and reduce prices. If the federal government installed enough PV systems at its facilities to generate just 1% of its total energy consumption, it would require more than 330 megawatts of new PV capacity. [Serchuk and Singh, 1998] This is six times as much capacity as the US PV industry shipped as a whole in 1997. These procurement programs must be in line with private sector markets. Otherwise, special deals and special technologies will lead the PV industry astray. To implement these programs, new legislation will most likely be required and existing government procurement policies would need to be changed.

- Financing of the photovoltaic industry must progress from public to private funding. It is imperative that the government continue to strongly support research and development in photovoltaics in the near term but for the long term, investment in PV manufacturing must come from the private sector.

- Existing institutional barriers must be removed. The lack of supportive financing options for consumers, certain building codes, homeowner covenants, and inconsistent and non-existent grid connection requirements all hamper the deployment of photovoltaic systems. [Wiser, 1999] As mentioned, the increased use of natural gas turbines as distributed energy sources will help the development of the necessary grid connection standardization. The other issues must be addressed through local, state, and federal policies.

- Further legislation that supports distributed energy and stronger policies that foster photovoltaics and other renewable energy sources in the marketplace are essential. It is critical that the market rules that are established as part of the energy sector deregulation encourage overall price competition in the long run. [Wiser, 1999] Ultimately it is cost that drives consumer behavior. Statutes or guidance documents that facilitate the deployment of PV systems, that strengthen and standardize net-metering, that require uniform interconnection protocols, and that prohibit both unwarranted fees and restrictive homeowner covenants should be advocated.[Serchuk and Singh, 1998] In the near term, federal and state buy-down programs that stimulate technological advancement will increase the incentive for private investment in the industry and will begin to institute the infrastructure needed to support large-scale deployment of photovoltaics. [Serchuk and Singh, 1998]

In implementing the goals above, many factors must be considered. Caution is needed when combining policy actions. Some policies do not interact linearly and therefore the results might not be as good as what was intended. For example, the value of tax credits is dependent on the purchase price of photovoltaics. The value in buy-down programs is in reducing purchase price. The effects of these policies offset themselves and therefor the benefits of the programs are not additive. [Hoff, Wenger, et. al., 1993] A more in-depth evaluation of the policy options and how they interact is important to prevent the possibility of harming instead of helping the market for renewables. Also, it is probable that the inherent inertia in the incumbent utilities will affect the progress and outcomes of sector restructuring. [Wiser, 1999] Their position will make it less likely that consumers will switch to new sources of energy. Incentive programs should consider this when deciding how to distribute credits. Electric industry restructuring efforts should focus on the benefits of retail competition as well as wholesale competition to obtain the most benefit from distributed generation. [Wiser, 1999] Methods to ensure credibility need to be considered as well. 'Green' power should be certified somehow to make sure no one is able to take advantage of the system. And lastly, there needs to be a balance. As policies are developed and implemented, all stakeholders should be considered. Incentives should be set for both generators and consumers. Upstream programs should try to improve competitiveness but not at the expense of a particular industry.

VI. Summary and Conclusions

Based on the technological and environmental advantages outlined here, photovoltaic systems certainly have the potential to be a larger part of future US energy picture. The biggest roadblock for PV today is cost. As the US moves toward a deregulated competitive market structure in the electric industry, this is going to become more of an issue. Photovoltaics seem to have the 'chicken-and-the-egg' syndrome. In order for costs to come down, production and therefore PV markets must increase. Market share increases as costs decrease. How then can PV become a bigger player in the US electric industry? As outlined in this paper, government intervention in the form of research and development funding as well as supportive policymaking is critical to break this cycle. Technological advances are still needed to make photovoltaics more cost effective and less energy intensive to manufacture. A shift in how energy is valued is also needed to ensure that conventional power reflects all the true costs associated with it. Stronger policies on the state level and additional policies on the federal level that take into account the necessary concerns will spur this change as well as promote a friendlier atmosphere for renewable energy in general.

Since so much seems to be riding on the amount of government intervention, it will be interesting to see how the future of photovoltaics and renewables in general plays out. There is an election coming up this November and the two candidates have very different positions on energy issues. One, who is more conservative, speaks out little in support of renewable energy and support further fossil fuel exploration. The other, who is more liberal, is a self-proclaimed environmentalist. The future of photovoltaics will be affected by, but not necessarily decided by, which one is chosen. Photovoltaic energy is a strong and growing source of energy and should be able to take what comes.

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