Technological Innovation and Public Research & Development Policies: A Case Study of the Photovoltaic Industry

by

C. Bradley Nilson
B.A., Washington University, 1992

Submitted to the Department of Urban Studies and Planning in partial fulfillment of the requirements for the degree of

Master in City Planning

at the

Massachusetts Institute of Technology

June 1998

Signature of Author ______________________
Environmental Policy Group
May 21, 1998

Certified by ______________________
Vicki Norberg-Bohm
Thesis Supervisor

Accepted by ______________________
Lawrence Bacow
Chair, MCP Committee
Department of Urban Studies and Planning

Technological Innovation and Public Research & Development Policies: A Case Study of the Photovoltaic Industry

by

C. Bradley Nilson

Submitted to the Department of Urban Studies and Planning
on May 21, 1998 in partial fulfillment of the requirements for the degree of
Master of City Planning

Abstract

Efforts to reduce global carbon emissions have led to calls for increased use of renewable energy technologies for electricity generation. These technologies are, for the most part, not yet cost competitive with traditional methods of generation. Solar, or photovoltaics (PV), is one of the most popular renewable energy technologies, but it is widely believed that further advances in the technology are necessary to enable it to be cost competitive for utilities. Indeed, public resources continue to be spent towards this end. This paper presents a detailed look at the technological and policy history of the development of photovoltaics in the United States. The primary conclusion is that, while photovoltaics have not yet been widely commercialized for utility-scale electricity generation, supply-push policies such as publicly funded research and development (R&D) have been successful and have generated numerous important innovations. Furthermore, government R&D efforts have been successful in avoiding some of the problems associated with public sector commercial technology development programs. Nonetheless, this thesis proposes a number of recommendations as to how to further improve the federal PV R&D program.

Thesis Supervisor: Vicki Norberg-Bohm
Title: Assistant Professor of Environmental Policy, Department of Urban Studies and Planning

Table of Contents

Tables and Figures

Chapter 1
Why Photovoltaics?

The energy crisis of the 1970s signaled that the U.S. could no longer expect an inexpensive and reliable supply of petroleum to fuel economic growth. As oil prices increased and shortages emerged, the U.S. government acted on numerous fronts to address the problem. One response was to invest in renewable energy research to meet domestic energy needs and reduce dependence on foreign energy sources. The 1970s were also a time of increased environmental awareness and concern focused on the environmental impacts associated with the use of fossil fuels. Solar energy, and specifically solar-electric or photovoltaics (PV), was seen as a viable solution to both the energy crisis and current environmental problems. Government responded with numerous solar research and development (R&D) programs. Predictions were made about a "solar economy;" but by the 1980s, energy prices decreased, and the technological challenges faced by solar energy proved greater than expected. Hence, public and private interest in the technology lessened.

Today, as the 21st century approaches, there is a renewed interest in the way energy affects the environment, and yet again, solar energy has emerged as a potential solution to the problem. The way the U.S. generates electricity continues to have an impact on the environment. While SO_2 emissions are on the decline, other concerns such as greenhouse gas emissions are on the rise. With the Kyoto summit recently completed, nations are refocusing on how electricity is generated and its impacts on the environment. The fear that CO_2 emissions are slowly increasing the planet's temperature, and the impacts that this may have, is an overriding reason as to why solar energy has emerged on the national agenda again.

Energy-environment issues are not just the concern of the U.S. and other developed countries. Less-developed countries are also looking to renewable energy technologies such as solar energy as a prime source of electricity generation. Solar energy has the potential to bring electricity to remote areas where transmission and generation costs are so high that hopes of grid-connected electricity in the near-term is unrealistic. Solar can bring electricity to these areas, where even a few watts of power can be used for a single light, radio, or refrigerator for vaccine storage. These possibilities mean that millions of peoples' standards of living could be increased with single PV units instead of waiting for large-scale power generation facilities to be constructed.

While energy security issues have faded into the background, they are by no means gone. OPEC still controls a large amount of the world's oil reserves, and the U.S. relies on imports for a majority of its petroleum supplies (EIA 1996). While PV is not currently cost competitive for utility scale electricity generation, a large amount of public funding has been invested in this technology. Significant progress has been made in photovoltaic technology in the last 25 years. This thesis looks at the history of the technology's development and describes the major innovations in PV over the last 25 years. It also looks at the various public policies affecting PV over the same timeframe, mainly those in the form of government funded R&D. Many different types of R&D programs have occurred in the history of the U.S. PV policies. These programs are described and evaluated in terms of their effectiveness in producing technical change. From this standpoint, I draw general conclusions as to how environmental technology R&D programs could be structured. These recommendations could be applied to other federally sponsored commercial technology development programs.

Specifically, Chapter 2 describes photovoltaic technology and its different uses. It also presents the technical challenges facing PV, and a description of how sunlight is converted into electricity. Measurements for quantifying technical progress are also introduced, as are some potential negative environmental impacts of photovoltaics. Chapter 3 discusses the relationship between public policy and technological change in order to frame the photovoltaic-specific policies described in Chapter 5. The history of photovoltaic technology is the subject of Chapter 4. Significant innovations in the different types of photovoltaic technology are detailed, including the source of these innovations. Chapter 6 includes an analysis of the R&D programs described and makes recommendations as to how they can be improved.

Chapter 2
Photovoltaics in Brief

This chapter presents an introduction to photovoltaic (PV) technology and its uses. It begins with the history of PVs followed by a brief description of how PVs work, and the main components of PV systems are also summarized. Included in this section is a review of the many different applications of PVs. The chapter concludes with a discussion of some of the environmental impacts associated with PVs.

2.1 An Abbreviated History of Photovoltaics

The idea of using the Sun as an energy source is as old as history itself. The discovery that electricity could be generated from sunlight with certain materials, the photovoltaic effect, is credited to Frenchman Edmond Becquerel in 1839. Becquerel found that when certain materials were exposed to sunlight they produced a small amount of electrical current. Little work to explore the photovoltaic effect occurred until the 1950s. This was partly due to the fact that quantum mechanics had not been developed, which was fundamental to explaining the photovoltaic effect.

The groundbreaking work that started photovoltaics on their modern day progress occurred at Bell Telephone Laboratories. Researchers were studying semiconductors -- materials whose electrical properties are somewhere between that of conductors and insulators (Boyle 1996). In fact, only a few years before Bell Labs had developed the first transistor, which was a semiconductor. Bell scientists were subsequently studying the effect of light on semiconductors and created a silicon solar cell with an efficiency of six percent. Efficiency is defined as the portion of the energy in sunlight that is converted into electric energy. These first solar cells were extremely expensive and did not produce very much electricity.[1] During much of the 1950s and 1960s few photovoltaic modules were produced. The technology, however, caught the attention of the infant U.S. space program of the 1950s. In fact, solar cells in their first major application were used as a backup power source on Vanguard I in 1958. This signaled the beginning of a very important period in the development of photovoltaics.

Ever since that first use of solar cells on Vanguard I, PV has been a major part of the space program. This resulted in technological progress in the amount of electricity produced from them throughout the 1960s and 1970s. Progress also occurred in the weight of solar cells. These two drivers moved the technology forward greatly, but cost was not an important factor; hence, interest and use of photovoltaics for terrestrial applications remained extremely limited until 1973.

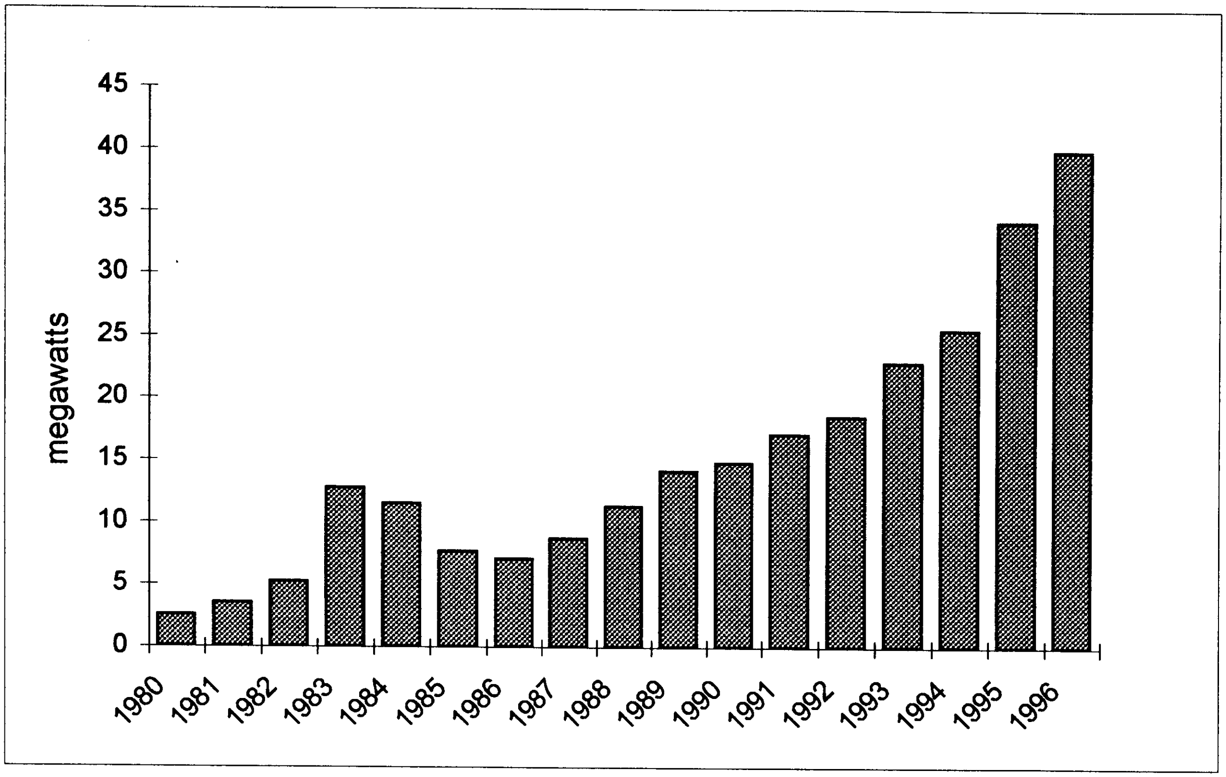
PV cells were first manufactured specifically for the terrestrial market in 1972. These modules did not need the reliability and radiation hardening required for space applications. Hence their cost per kilowatt-hour was lower than space modules, but still substantially higher than the cost of power from electric utilities. The market for terrestrial PV cells was initially limited to niche markets such as ocean buoys, oil platforms, or remote mountaintop radio repeaters.

The energy crisis of the 1970s and growing environmental concerns prompted the search for alternative energy sources. High on this list was photovoltaics. Solar energy could provide a secure source of energy if only the cost could be lowered. R&D in the technology skyrocketed and whole new government laboratories were created just to develop the technology. Many of the major oil companies such as Mobil, ARCO, and BP entered, and helped create, the terrestrial photovoltaic industry.

1 It has been reported that the cost of PV cells for the first spacecraft were $200,000 per peak watt (Boyle 1996).

The cost of photovoltaics decreased substantially during the 1970s and 1980s as a result of research and development efforts. The rise of the microelectronics industry also provided the photovoltaic industry with a pure and reduced cost material for the fabrication of photovoltaic cells (crystalline-silicon). The decrease in price led to expanded use in other applications, such as calculators and remote power generation. Overall interest in photovoltaics declined in the 1980s as oil prices retreated.

Figure 2-1: U.S. PV Module Shipments



Source: Watts and Smith 1988; Golob and Brus 1993; Kozloff 1993; DOE 1996b.

In the last five to ten years interest in and production of photovoltaics has increased substantially, for two reasons. First, the cost of photovoltaics has been reduced to a level where they are cost-competitive in many niche markets and are approaching competitive levels for utility-scale electricity generation. Second, the environmental benefits offered by photovoltaics are valued more due to concerns of global climate change. An example of the increased interest for niche markets is the fact the 75 percent of the photovoltaics manufactured in the U.S. in 1996 were exported to other countries, with much of that used for remote power generation (DOE 1997). Climate change interest in PV is exemplified by the U.S. government's recent Million Solar Roofs initiative.

2.2 Applications for Photovoltaics

Photovoltaics can be used in a variety of situations. Several different characteristics of PV systems make them desirable for a wide range of applications. These features include, electricity generation with little impact on the environment, no moving parts to wear out, modularity -- the ability to be sized according to need, and most importantly, the only fuel needed is sunlight. Applications for photovoltaics were originally very limited, but as this chapter shows they have expanded into a multitude of different areas.

2.2.1 Space Applications

The first commercial use of photovoltaics was in space. While this paper focuses on photovoltaics used in terrestrial applications, it is important to note the importance of the first use of photovoltaics. Space applications have slightly different requirements for operation than terrestrial PV cells. Space cells must be able to withstand higher levels of ultraviolet radiation than cells used on Earth. Furthermore, PV cells for space place a premium on reliability, efficiency, and weight, rather than cost and are much more expensive than terrestrial cells. Production of PV cells for space rose quickly to 10 kW/year creating a young photovoltaic industry (Linden 1977). Demand for space PV cells continued to rise during the 1960s to a level of 70 kW/yr. The PV space industry is currently experiencing rapid growth due to the explosion in the number of communications satellites being launched worldwide.

2.2.2 Consumer Products

The are currently millions of small PV systems used in consumer products such as calculators, watches, and radios. These systems usually produce only a few thousandths of a watt or even less of power. Consumer products are typically made of thin-film amorphous silicon material.

Cordless, handheld calculators have been a commercially available product since the early 1970s. Solar powered calculators first appeared commercially in 1977, at the same time as solar powered wristwatches. Hand-soldered crystalline-silicon cells powered the earliest PV calculators and wristwatches. These simple, four function calculators cost between $80 to $160, and operated well in sunlight but poorly under fluorescent light. Current photovoltaic powered calculators use thin-film silicon cells. Thin film silicon cells are inherently more responsive to indoor, fluorescent light, and also perform well under general sunlight.

Explosive market growth for handheld calculators has driven prices to very low levels, now averaging less than $3 for business card size units and up to $60 for fancy desk models. U.S. annual cordless calculator imports are currently in excess of $400 million, over 90 percent of these are now solar powered. Virtually all solar calculators are manufactured outside of the U.S., mainly in the Asian Pacific region, using predominantly Japanese-manufactured thin films. Mainland China exports the most calculators to the United States (SolarDome 1996).

2.2.3 Remote Power Generation

The largest application of photovoltaics today is in situations where it is inconvenient or too expensive to use grid-supplied electricity. These applications include remote radio repeater stations, streetlights, and traffic signals. Photovoltaics can also be a household source of power for locations not connected to a traditional grid system. This has taken on major importance in developing areas that are increasingly relying on photovoltaics to supply power for water wells and electricity for a single appliance or light source. A reliable, maintenance-free, and inexpensive power source in areas without electricity grids has enormous potential to improve the quality of people's lives. The United States and World Bank have initiated several programs to promote the use of photovoltaics in lesser-developed countries.

2.2.4 Grid-Connected PV Systems

Photovoltaics are generally not cost-competitive with conventional sources of electricity generation and few utility-scale grid-connected systems have been built. The Sacramento Municipal Utility District (SMUD) has, however, installed two one-MW plants in California. These systems cost about $6 per watt installed in 1995 as opposed to the $3 per watt level that is thought to be needed to be competitive (SEIA 1995).

Grid-connected PV systems need not be centralized at a single power plant. Many rooftop PV arrays have been connected to electricity grids as part of demand-side management efforts. In these situations, when more PV electricity is being generated than is used, the surplus is fed back into the electrical grid. Likewise, when not enough electricity is being produced by the local system, the extra amount needed is drawn from the grid. It is possible to meter this transaction in a manner called "net-metering", where only the net amount purchased is billed by the utility.

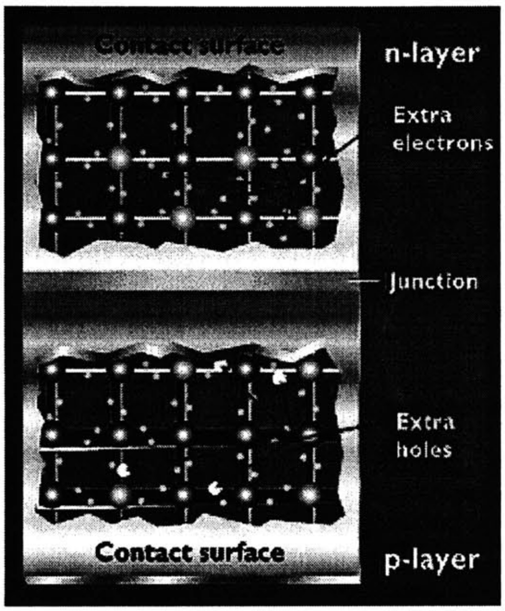
2.3 How Photovoltaics Work

In their most basic form photovoltaics are semiconductors that convert sunlight into electricity. Photovoltaics can be composed, designed, and fabricated by a variety of methods. While there are many unique features to individual photovoltaic modules, they all rely on the photovoltaic effect to convert sunlight into electricity.

2.3.1 The Photovoltaic Effect

Before describing the photovoltaic effect it is critical to understand the key design element of photovoltaic materials that makes the effect possible. In the simplest terms, photovoltaics are semiconducting materials made of two different layers, a p-layer and an n-layer. The p-layer is composed of a pure semiconducting material, such as silicon, to which a small amount of impurity has been added. The impurity added to the p-layer is one that causes the material to have a deficit of free electrons, hence the term positive or p-layer. The n-layer is exactly the same except a small amount of impurity with a surplus of electrons has been added. These layers come together to form the p-n junction.

Figure 2-2: The P-N Junction



Source: DOE 1998.

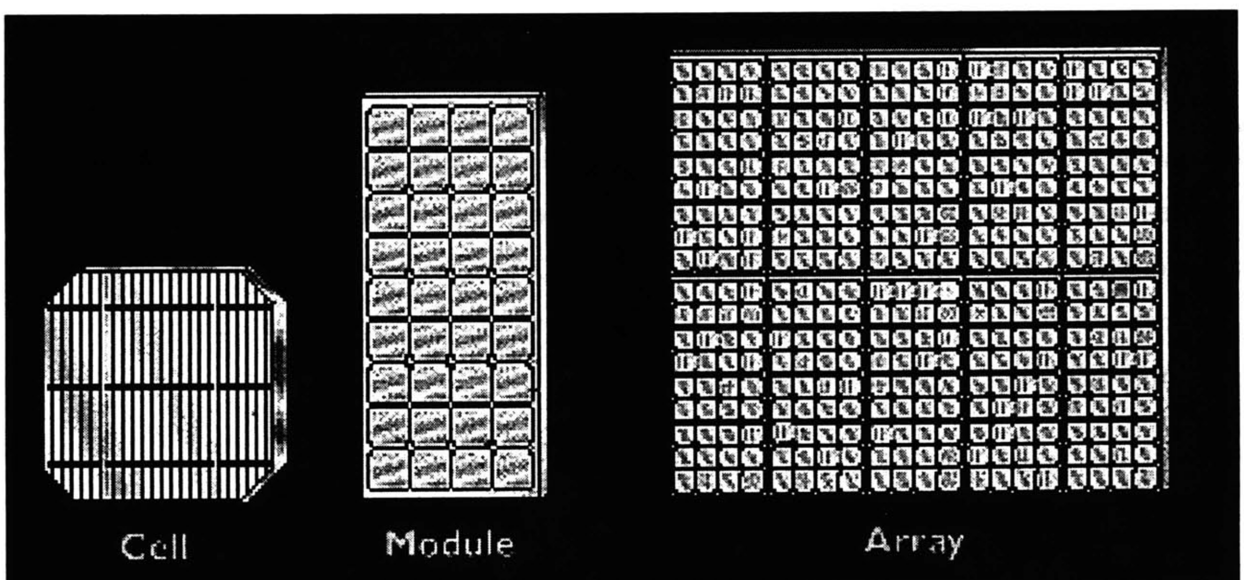
When these two different semiconductors are joined they create an electric field. Negatively charged particles tend to move in one direction, and positively charged particles tend to move in the opposite direction. The photovoltaic effect occurs when light falls on the p-n junction. Sunlight is composed of photons or packets of solar energy. These photons contain different amounts of energy that correspond to the different wavelengths of the solar spectrum. When photons strike the front of PV cells, they can be reflected, absorbed, or pass through the cell. The absorbed photons generate electricity. The energy of a photon is transferred to an electron in an atom of the semiconductor device. With its newfound energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor to become part of the current in an electrical circuit. The built in electric field generated by the p-n junction provides the voltage needed to drive the current through an external load (DOE 1991; Boyle 1996).

2.3.2 Photovoltaic Cells, Modules, Arrays, and Systems

The photovoltaic cell is the building block and the smallest practical unit able to produce electricity. Photovoltaic cells can be manufactured with a variety of different materials. The first, and currently most common, material used in the manufacture of commercial cells is silicon. Other semiconducting materials, such as cadmium telluride, copper indium diselenide, and gallium arsenide are also used in the production of photovoltaic cells. Cells are important because they are the first unit to be examined in the laboratory for efficiency. While this number is important in the research and development phase, it is not equal to what the efficiency of a photovoltaic module will be once it is in commercial use.

An individual photovoltaic cell produces about 1 or 2 watts of power. This amount is rarely enough for most applications. Cells can be connected together to increase the total amount of power output. This can be done either in series or parallel, depending on whether increased current or amperage is desired. The connections between cells are very sensitive and must be able to withstand environmental stresses over a long period of time. Once cells are connected they are sealed with a laminate and covered with glass to form a PV module.

Figure 2-3: PV Cell, Module, and Array



Source: DOE 1998.

A single photovoltaic module may not be large enough for some applications. Modules can be connected together to form arrays. An array, however, is not a complete PV system. Other parts such as mounting structures, converters to change the direct current generated into alternating current, and storage batteries can all be part of what is called the balance-of-system (BOS). Mounting structures must be able to withstand all types of weather including hail, wind, and snow. These structures can be constructed so that the arrays mounted on them track the sun in order to increase the amount of sunlight captured. Power conditioners, or converters, change the electricity generated by the array into a form that can be used by almost any application. This technology is fairly standard, but it must be sized according to the system it is connected to. Storage devices are not required for the majority of PV systems, which are grid-connected, but are useful for stand-alone systems when power is needed when the sun is not shining. The downside of batteries is that they decrease the efficiency a PV system because all the electricity stored is not recovered. Batteries also increase the cost of a PV system and have some environmental impact. Several types of batteries have been designed specifically for PV systems, the most common being lead-acid batteries and nickel-cadmium batteries (DOE 1993).

2.4 Technical Challenges in Photovoltaics

Photovoltaics face numerous technical challenges that must be overcome before they reach widespread terrestrial use. This section describes these challenges which have been organized into three categories. While these three categories do not encompass all barriers to market diffusion, they represent areas which most R&D efforts focus upon. It is impossible to summarize all of the technical responses or innovations to these challenges, but many of the major innovations are discussed in Chapter 4.

2.4.1 Cost

The greatest impediment to PV becoming commonplace has been cost. Cost in photovoltaics can be measured at three levels. The first is the cost of generating electricity from a PV cell. This is the least common measure of PV costs, since cells are not commercialized in themselves. The more common cost figures are for electricity generated from modules and for PV systems that usually include balance-of-cost systems. Cost numbers for PV systems are given in dollars per kilowatt-hour ($/kWh), while costs for PV modules are expressed in dollars per peak watt ($\$/W_p$). Systems costs are in dollars per unit of energy, while module costs are given in dollars per unit of power. How costs are calculated is discussed further in Chapter 4 in the context of technology diffusion.

PV electricity costs have always been higher than costs for conventional methods of utility-scale electricity generation. The main driver of cost is the amount of semiconducting material used to fabricate the cell. As noted before, PV costs have declined dramatically in the past 25 years. This is due to new materials, designs, and more efficient cells. The specifics of this technological progress are the subject of Chapter 4.

2.4.2 Efficiency

Efficiency is the amount of electricity produced divided by the amount of sunlight energy striking the surface of the PV cell. Efficiency is an important factor that determines costs, but increased efficiency does not necessitate lower PV costs because increased efficiency may be the result of more expensive design or manufacturing. Data about efficiency must be specified for which subsystem it applies to, because there is a consistent drop-off in efficiency from the cell to the module to an array.

Many factors affect how much light is converted into electricity in a PV cell. Most important is how the material composing the cell can absorb much of the light. Different materials are better than others in capturing light depending on how their chemical composition interacts with different wavelengths of light. All materials have a different theoretical maximum efficiency. There have been a number of different technology philosophies about how to increase the amount of light captured by a PV module, which is the focus of Chapter 4.

2.4.3 Stability

Another technical challenge faced by photovoltaics is reducing the amount of degradation or loss of stability that occurs when modules are first exposed to the sun. Some modules when first exposed to sunlight lose several percent in efficiency. This occurrence is specific to the type of material used in the fabrication of the cell and the subject of a large amount of technical work to understand why this happens.

2.5 Negative Environmental Impacts of Photovoltaics

From an environmental point-of-view, photovoltaics have minimal negative effects. There are, however, a few minor issues that should be addressed. These include some of the toxic materials used to manufacture photovoltaics, and in some cases, the amount of land used in utility-scale PV systems.

2.5.1 Hazardous Materials

Solar cells made of silicon pose no toxic threat in their material composition, but other types of cells do contain small amounts of hazardous materials. Cells made of cadmium telluride or copper indium diselenide (CIS) could pose a small hazard via inhalation if they are consumed by fire. Although the chances of this occurring are remote, it is a possible hazard if these types of cells become more prevalent and are installed on rooftops.

During the processing and manufacture of many photovoltaics some hazardous materials are used. Hydrogen selenide, for example, is used in the manufacture of thin-film CIS cells. If this material is handled properly there is little safety risk. Many of the processing issues related to silicon cell production are similar to those faced by the integrated circuit industry and have solved (Mazer 1997). The U.S. Environmental Protection Agency has conducted tests of CIS cells. After grinding the cells and suspending them in water, it was found the leaching of the materials was within acceptable limits (Ahmed 1994). Another concern is with the cadmium contained in cadmium telluride (CdTe) thin-film cells. The amount of cadmium potentially released into the environment from PV cells is small compared to the amount currently released by batteries and fertilizer.[2] Recycling of CdTe cells is currently being explored. Disposal of used CdTe and CIS, as opposed to crystalline-silicon, modules could, never the less, becomes an important issue if they are used in large numbers. These modules, however, last on average 30 years and research and infrastructure to recycle these modules could be put into place by then.

2.5.2 Land Use and Visual Impact

PV arrays can have some visual impact on the environment. Rooftop arrays have some aesthetic impact, but "PV-shingles" are being developed in the effort to blend PV into roof structures better. Large grid-connected PV arrays are usually installed in land specifically designated for this purpose. They usually take up areas less than other electricity generation facilities of similar power generation capabilities. Furthermore, some grid-connected systems have had nature reserves located near them and small-scale agriculture can be practiced between PV arrays (Boyle 1996).

[2] For example, in the U.S. 1,000 tons of cadmium enters the waste stream yearly from discarded batteries; this is equivalent to the amount that would be created from 20 billion watts of discarded PV modules.

Chapter 3
Public Policy and Technological Innovation

The role of public policy is to improve the welfare of a country's citizens. This welfare includes economic and environmental standard of living. In the United States, a large portion of our country's economic productivity has been the result of technological innovation. Since Solow's groundbreaking paper on the role of technological change in productivity growth, there has been a realization of the importance of innovation in economic growth and the welfare of humanity (Solow 1957). Correspondingly, governments have acted to increase the rate of technical change within societies through a variety of public policies. In the United States there has recently been an emphasis on assisting the private sector innovate to compete in the global marketplace. Furthermore, there is an increasing interest in the role of technical change in making further strides to minimize the impact of economic activity on the environment and moving towards a sustainable society (Norberg-Bohm 1997).

3.1 Public Policy and Technological Innovation

In this paper, a common taxonomy of technical change is used. Change is composed of three stages. Invention refers to the development of a new technical idea, innovation is the first practical or commercial application of the invention, and diffusion is the adoption of the innovation by those who did not develop it. Sometimes a user will make significant changes to a technology in adopting it, which may then be considered an innovation.

Public policy responses have occurred to stimulate each of these stages of technical development. Invention has been encouraged by the introduction of patents and financial support for basic scientific and technological research. Government policy with regard to innovation is related to the fact that innovation is subject to supply and demand. As a result, there are policy mechanisms that attempt to increase both the supply of, and demand for, innovation. These are known as "supply-push" and "demand-pull" policies. "Supply-push" policies foster the creation and development of new innovations. The most common types of "supply-push" policies are R&D tax credits and federally funded R&D. "Demand-pull" policies create or expand the market for a particular technology or set of technologies. Government procurement or subsidies of a product can increase demand for the product and result in technical change. Regulation is also an important "demand-pull" policy.

This chapter focuses on the justification for, and types of, "supply-push" policies. It explores in further detail the history and ways federally sponsored R&D has been carried out. It goes on to describe some of the most important problems and concerns with federally sponsored R&D which will later be used to evaluate PV R&D policies in Chapter 5. The chapter finally describes how federal R&D programs should be designed with respect to different market failures and the stage of technological development.

3.2 Justification for "Supply-push" Policies

The reasons for public policies concerning technological innovation are numerous, but they are most often justified by some market failure. There are three types of market failures particularly relevant to this discussion: 1) those associated with public goods, 2) appropriability problems, and 3) risk.

Frequently, technological innovation is deemed necessary to meet some type of pressing societal need or goal to accomplish a specific mission. Some such special needs include national defense, space exploration, economic growth, and environmental protection. Market failure can prevent these goals, which are public goods, from being achieved. This most common type of market failure is the one related to public goods. Because there is not an adequate private market for these goods, a less than optimal amount of R&D takes place. This can also be the result of externalities not being internalized.

A part of this market failure, and justification for government assisted innovation, is when the benefits of an innovation reside in **both** the public and private sectors. According to Branscomb and Parker (1993), it is appropriate to subsidize R&D of technologies that have mixed public and private markets. An example of a set of goods that fits this description is renewable energy technologies. While the end product of these technologies, electricity, is a private good, current methods of producing electricity have many environmental or public sector effects. Public values may justify an acceleration of development efforts beyond what the market would elicit.

A second type of market failure, which leads to an insufficient amount of R&D to be undertaken by the private sector, is the appropriability problem. This failure frequently stems from the fact that the private sector is unwilling to undertake certain types, or amounts, of R&D because it would be unable to obtain enough benefit to offset the cost of the R&D. Because no single individual or firm can be excluded from enjoying the benefits of a good, they in effect become free-riders. Since these individuals do not have the incentive to pay for what they receive, a less than optimal amount of R&D takes place.

A third type of market failure can occur when a project contains an extraordinary amount of risk and is not pursued. Frequently, technologies are very far from commercialization, very expensive to develop, and hence, very risky. Nonetheless, the technology may have societal benefits that outweigh the costs of development. In these situations government funding of R&D is justified (Wright 1983).

3.3 How Should Government Be Involved?

One option for correcting these market failures is to have government enact "supply-push" public policies. Two types of "supply-push" policies exist: indirect and direct. Indirect methods use economic policies such as R&D tax credits to influence the amount of R&D undertaken by the private sector. Direct methods entail direct investment of federal resources into R&D. Indirect methods have the advantage of leaving private firms in control of investment decisions and are relatively easy to administer. On the other hand, they can be expensive. Direct methods come in many different forms and can be carried out by many different entities. This paper focuses on direct R&D in the PV industry and evaluates its effectiveness.

3.3.1 Indirect "Supply-push" Policies

As noted above, the most common indirect "supply-push" technology policy is R&D tax credits. These credits allow private firms to deduct a portion of R&D costs or increased costs from their tax burden. Over the years the specific details of tax credit policies have changed, but they have existed in some form since at least the 1950s. One of their advantages is that they interfere with the marketplace less than direct supply-push policies, and allow firms to respond to real demand, as opposed to government created demand (Bozeman and Link 1984). This may be an important point for those who feel that government should not be in the business of deciding which technologies should be singled out for development by potentially biased government officials.

There are, however, some criticisms of R&D tax credits. These include the fact that private firms may be benefiting because of work they would have undertaken with or without the presence of tax credits. Others criticize this policy mechanism because it can be extremely expensive and can undermine budget control (Bozeman and Link 1984). Furthermore, R&D tax credits are not a precise policy instrument. The size and location of increased R&D due to the credits is rarely predictable, controllable, and it is difficult to measure its effectiveness after-the-fact.

3.3.2 Direct "Supply-push" Policies

One of the most important types of "supply-push" government policies is federally funded research and development. The U.S. has historically spent a higher amount on public and private R&D than any other country in the world. Of this amount, approximately one-third has typically been publicly funded. Levels of federally funded R&D have remained near the 1996 level of $63 billion over the last ten years. In terms of percentage of GDP, the U.S. has spent approximately 2.5 percent over the last 10 years, which is very similar to levels spent by Japan and Germany (NSF 1996).

There are three general types of publicly sponsored R&D: 1) that which the government is both producer and consumer of the technology, 2) basic research in science and technology, and 3) work to assist in the development of a technology for commercial use.

The type of R&D where government is both producer and consumer of innovation has a long history. Defense R&D is the most prominent example of this type of situation. With this type of technology development, government determines the supply, through funding and at times performance of R&D, and the demand for technological innovation at the same time. Government, therefore, coordinates technological capabilities of the producer and the needs of the user. This close coordination results in continual feedback from the consumer as the technology evolves and increases the probability of successful technology development (Rothwell 1981; Nelson 1982).

A subset of this type of R&D is what are commonly referred to as "big science" efforts. In these projects government spends a large amount of funds to develop a technology of which it is both the producer and consumer. The subject of the project is usually defined as a highly visible and politically attractive societal goal, such as the space program or Manhattan project. These types of efforts have been well studied because they have traditionally consumed the largest portion of the federal R&D budget.

Funding of basic research in the U.S. has widely been considered an important, appropriate, and successful government role (Dertouzos et. al. 1989). Basic research can be defined as research that "expands human opportunities and understanding" (Branscomb 1997).

The benefits of basic research are often diffuse and it is very difficult for private firms to reap the benefits of this research. This uncertainty is one of the defining characteristics of basic research, and the knowledge generated from basic research is often the building blocks of future commercial technologies (NSF 1968). In recent times basic research has become the forte of government. At one time, however, a number of private research organizations such at Bell and RCA Labs were heavily involved in basic research. This research, as will be seen in Chapter 4, was extremely important in the development of photovoltaics. But in recent times the private sector has substantially reduced its participation in basic research. In 1996 only 5.1 percent, as opposed to 6.4 percent in 1973, of privately funded R&D could be classified as basic research (NSF 1993). While substantially more funds have been spent by the public sector on basic research, that amount has leveled off or is actually increasing only slightly. Government support for basic research in 1993 was almost $10.9 billion compared to $9.0 billion in 1987 (constant 1987 dollars) (NSF1996).

While there is a long history of publicly funded basic research and development in the United States, only in recent times has publicly funded research included work to commercialize technologies for use in the private sector. This effort to support industrial technologies largely emerged in the late 1980s in response to concerns that the U.S. was losing ground economically to other countries whose governments actively supported industrial R&D (Heaton et. al. 1992).

3.4 Issues Associated with Direct "Supply-push" Policies

Whenever government affects the way in which the market operates there are important issues to be addressed. As expected, there are issues and criticisms related to federally funded R&D programs. When government tries to remedy one of the previously mentioned market failures with funding R&D, several of the following issues or problems can arise.

3.4.1 Pork-Barrel Spending

A frequent criticism of government funded R&D is that it constitutes "pork-barrel" spending. By allocating government funds to special interests, industries, or firms, politicians may only be furthering their own narrow political interests. This is seen as giving individual private firms an advantage, or subsidizing work that they receive a large return in profits. Others argue that government should not be in the business of commercial technology development. The private sector should be the only determinant as to what technologies should be commercialized. Market forces should determine how much investment should occur in a new technology.

Government is also open to the criticism that it is unfairly selecting the "winning" and "losing" firms within an industry. By funding the development of a technology, government may be speeding the advancement of a technology unfairly and potentially not developing the best technology. Only the firms and technologies that receive government funding "win," when the market should only be the determinant of "winners" and "losers."

Another "pork-barrel" problem is the fact that those coordinating the research face a different set of incentives than those in the private sector. The politicization of the R&D process and a focus on maintaining budget levels, rather than developing technology for commercial use can be problematic (Gates 1988). Government agencies that only spend money, and do not produce technology development, can also be seen as "pork-barrel" spending.

3.4.2 Technology Transfer

Another major issue associated with government supported R&D is how the technology is transferred to the private sector -- the ultimate users of the technology. The signals and incentives to which a researcher is responding often determine the success of an R&D program.

The success of a civilian technology development program relies on a feedback loop between the producers of innovation and the end-users of the innovation.

Even once a technology has been developed there may be problems transferring that knowledge to the private sector. Technology includes the knowledge and skills held by those involved in the creation of a new technology. Transferring this knowledge is critical to the success of a technology after it leaves the laboratory.

3.5 Solutions

The answers to these issues lie in how an R&D program is structured. Broadly, these issues can be addressed by deciding who should perform the R&D, who should pay for it (cost sharing), and how technologies for R&D should be chosen. Specifically, the use of public/private partnerships, competitive bidding for funding, peer review, and industry constoria can mitigate corporate welfare or "pork barrel" criticisms. Public/private partnerships are also beneficial in that they reduce technology transfer problems.

3.5.1 Pork-Barrel Solutions

The "pork-barrel" or corporate welfare problem is related to who performs the R&D. In most cases the private sector performs the work, which is funded publicly. This issue has been responsible for many debates within the Congress about who should perform R&D work. "Pork-barrel" criticisms can be addressed, in part, by implementing cooperative projects that require the private firm contribute a portion of the project's funding. Criticism can also be addressed by the use of competitive procurement for the performance of the R&D work by the private sector. This ensures that only the most technically qualified firms receive funding for R&D work. A final solution to the problem of “over-supporting” a single private firm is for government R&D programs to work with industry consortia.

3.5.2 Technology Transfer Solutions

The problem with some federally sponsored R&D is that it insulates the research from its ultimate producers, who are more knowledgeable about the technology's use in the private sector. One method of overcoming this problem has been the use of public/private research partnerships. Public sector R&D managers better understand private market signals through partnerships with the private sector. This problem can be solved, in part, by public/private partnerships and cost-sharing arrangements. A well-designed partnership allows for the private sector to contribute in the decision of which technologies or projects should be funded. When a private firm performs the actual work they are best able to address how that technology could be used in the marketplace. They are also best able to identify problems and benefits of the technology to be addressed or expanded upon.

3.6 Program Design in Context

The questions of who performs the R&D? how are partnerships arranged and costs shared, if at all? and how are technologies chosen for R&D? are all important in trying to avoid the problems associated with publicly funded R&D. These are most certainly three of the most important variables to analyze when designing a publicly funded R&D program. These questions lead to general prescriptions that do not apply to all cases. To avert "pork-barrel" or technology transfer problems, two other factors must be taken into consideration when designing an R&D program. First, it must be determined what type, or types, of market failure is associated with the lack of R&D in the technology. Second, and most importantly, at what stage of development is the technology? Is it in the early exploratory stage and dependent on basic research, or is it more fully developed, but manufacturing problems still exist? These two variables, type of market failure and stage of technology, interact to determine the main features or components that lead to a successful R&D program.

3.6.1 Type of Market Failure

Determining what type of market failure has occurred in a given situation is important because R&D programs should be designed with this failure in mind. Government action to address a market failure must, therefore, first correctly identify the market failure. In those cases where the market does not undertake a socially efficient amount of R&D, because of public goods, appropriability problems, or high risk, government can directly intervene. Patent protection, for example, will alleviate some of the appropriability problem, but not all. Direct government funding is the most common method of increasing levels of R&D.

3.6.2 Stage of the Technology

When deciding what type of assistance government should provide, not only should the nature of the market failure be taken into account, but the state of the technology and associated industry should also be considered. Mueller and Tilton have described a four-stage process by which a technology and an associated industry evolve. This process starts with the innovation stage where large amounts of technical and commercial uncertainty exist. Once these uncertainties are overcome, and an innovation is produced, the imitation phase is reached. Here private-sector R&D is directed towards copying an innovation and technological uncertainty is reduced and the potential for appropriable benefits increases. After this phase an industry has been created and the technological competition stage is reached. During this phase many different firms and organizations exist with detailed knowledge of the technology. This creates barriers to firm entry because of the high start-up cost of obtaining the necessary information to compete with this "mature" industry and technology. Finally, a standardization stage is reached where price of the technology becomes extremely important and less emphasis is placed on the technology and the focus is on process and cost reductions. These phases in sum compose an important model for the evaluation of the state of a technology.

An industry, and a corresponding technology, can be at the innovation, imitation, technological competition, or standardization phase. At each of these stages there is a corresponding government commercialization strategy (Mueller and Tilton 1969). At the standardization stage government policy intervention should be limited to maintaining competition within the industry producing a technology. During the imitation and technological competition phases government should set standards and assist in the exchange of information. When a technology and an industry are at the innovation stage government commercialization strategies should take into account this weakness and seek to support it with direct R&D support, R&D tax credits, and other policies directly influencing innovation, rather than diffusion of the technology. It is essential that government commercialization strategies match the stage of evolution of the target industry and its associated technology. Although this may seem obvious, government policy has not always matched the status of a technology (Roessner 1984). Improper assessment of an industry and technology's status can lead to policies which try to commercialize a technology before it is ready (market competitive or market accepted) and wastes federal funds.

Another way to look at where a technology is in its development is to classify the R&D work needed to commercialize it as either concerning basic, applied, or manufacturing research. Obviously there is a continuum between these three areas, but it is helpful to try to determine where the most R&D work is needed. Basic R&D work can be composed of both process and products. Often, as is in the case of photovoltaics, basic research concerns materials. New ways to make the material and completely new materials may be needed to work towards commercialization. As a technology progresses through these stages, depending on the market failure, R&D programs should adjust in terms of the who, how to allocate dollars, and technology selection questions.

Cost Sharing

When public/private partnerships are used to perform federally sponsored R&D the main question is, what portion of the project should be government funded vs. privately funded?

Government programs rarely have as much funding as administrators would hope for, and any way to increase the amount of R&D performed is looked for. By forming cost-sharing arrangements, federal R&D programs leverage their funding and increase the total amount of R&D completed. How the funding split is determined should be a function of what type of work is being performed. In general, basic R&D work is far from commercialization and hence, should be more subsidized by government. Furthermore, much of this work is undertaken by universities that have less interest in commercialization than the private sector does. On the other hand, manufacturing R&D should be more heavily funded by the private sector, since it is closer to commercialization and profiting from the R&D (see Figure 3-1).

Figure 3-1: R&D Program Design and Stage of Technology Development

Who Performs R&D?	More Universities and National Laboratories		More Private Firms
Cost Sharing?	Little	Some	A lot
How Technologies Selected?	More University/Lab Input		More Private Sector Input
⟸		***Stage of Technology Development***	⟹
	Basic Research	*Applied R&D*	*Manufacturing R&D*

The risk market failure is a very important one. A technology becoming closer to commercialization does have an impact on the who, allocation of funding, and technology selection variables that are important in the design of an R&D program. Figure 3-1 summarizes this concept in a qualitative manner. As the technology matures, the who should change from laboratories and universities to private firms. This is because they are the ones who will be selling the technology and better understand the market for which the technology is being developed. The allocation of funding for partnerships should be weighted more to the private sector as the technology progresses. While there still may be significant risk associated with a technology in the manufacturing stage, it is less than it was during the basic research phase. This dictates that the private firm should be willing to increase its portion of the funding of the project. The technology selection variable is similar to the who question. The group closest to the end market best understands what will and won't work, and therefore, the private sector should have more input in selecting technologies for development when the technology is fairly mature.

Technology Choice

Another important component of any R&D program is how are specific technologies selected for investigation and funding. This question exists on two levels -- political and technical. The political issue concerns the goals of the program. For example, if government is trying to develop renewable energy technologies, are the technologies that are to be funded for R&D work focused on use by utilities, or for use in developing countries in single family homes. These goals will affect what type of problems to solve, and what should be the technical specifications of the commercialized technology. Technical selection issues are also important no matter what the goals of the program. A valid assessment of which technology pathway is most promising is often risky and can be biased. These issues all play out in the selection process and who is involved in the decision making process.

Not only is how what technology is chosen important, but the number of different technologies pursued is equally relevant. A program may choose to pursue one technology with a large amount of funding and move quickly towards development. This strategy has risks though. If that technology ends up being a dead-end, a large amount of valuable time and funds may be wasted. It is also possible to pursue several different technological pathways when it is unknown which technology will "pan out" and push all of them forward at the same time. This "parallel paths" strategy, while more expensive and slower, is less risky and avoids "putting all your eggs in one basket" -- an issue that many risk adverse government R&D managers find appealing (Nelson 1961).

3.7 Summary

There are instances when government intervention into the process of commercial technology development is warranted. The way in which government responds to this need must, however, be carefully examined to avoid "pork-barrel" criticisms and technology transfer problems. Furthermore, the way in which federally sponsored R&D programs are designed is critical to the success of the program. The project must examine the type of market failure occurring, and the status of the technology under development. Once these features are known there are ways to structure who does the R&D work, how partnership funding is divided, and how technologies for research are selected that lead to more successful federal R&D programs.

Chapter 4
Photovoltaic Technology

This chapter presents a closer look at the technological development of photovoltaics. In doing so, numerous technological innovations within photovoltaics are presented. The source of these innovations, and parties bearing the cost that led to the innovation, are identified. Sources can be from within or outside the photovoltaic industry, as can be the party funding the research. A brief history of the most popular types of photovoltaic cells is also presented.

Chapter 2 described the technical challenges faced by photovoltaics and categorized them as relating to cost, efficiency, and stability. In the following discussion, it is more appropriate to group innovative responses according to the type of PV technology and construction phase in which they occurred. While there are many different types of photovoltaics (e.g., thins-films, crystalline-Si, and concentrators), all photovoltaics go through a similar construction process. All must have some sort of material formation, cell construction, and module fabrication stage. Grouping technical innovations by manufacturing phase is important due, in part, to the fact that many innovations can be considered a response to more than one technical challenge. For example, the development of new PV materials is a response to both cost and efficiency concerns. Furthermore, the PV industry has not pursued a single design philosophy. Innovations are described in each one of these PV design types. The purpose of this chapter is not to describe or explain the entire PV manufacturing process, but rather to relate some technical innovations which are repeatedly noted as important in the history of technological change in photovoltaics and organize them by the phase in which they occur. Table 4-1 shows the innovations described in this chapter along with their applicability to the categories of challenges described in Chapter 2.

Table 4-1: Photovoltaic Innovations and Categories of Technical Challenges

Innovation	Efficiency	Cost	Reliability/Cell Degradation
Czochralski process	X		
Float-zone process	X		
Wire saw		X	
EFG (edge-defined, film-fed growth)		X	
Dendritic web		X	
Anti-reflection coatings via APCVD	X		
Surface texturing	X		
Hydrogen passivation	X		
Screen printing		X	
Laser-buried groove cells	X		
EVA for module encapsulation		X	X
Ce glass module			X
Laminated modules			X
"low-cost wet chemical" deposition in CdTe cells		X	
Splitting of CdZnS layer	X		
Selenization	X		
Gallium in CIS	X		
Amorphous silicon		X	
Frensel lens	X	X	
Tracking systems	X	X	

4.1 PV Design Philosophies

Before describing the individual technological innovations that have taken place in the PV industry, a brief history of the most popular PV design philosophies is presented. Photovoltaic designs can be divided into three categories: 1) flat-plate cells using single-crystalline and polycrystalline silicon, 2) flat-plate cells using thin-films, and 3) arrays using concentrators. Crystalline-silicon photovoltaic cells try to maximize efficiency with a photovoltaic material that is somewhat expensive, but has been used for a long time. Thin-film photovoltaic cells take the philosophy that a reduction in the amount of photoactive material used, and hence cost, is preferable even though efficiencies are lower. Finally, PV concentrator systems represent the position that the smallest amount of photoactive material should be used, but that material should yield the highest efficiencies possible, and a large amount of sunlight should then be focused on that material. Historically, all three of these design philosophies have been pursued with great interest and with predictions of each becoming the "champion" of photovoltaics. In 1995, approximately 85 percent of the world's solar cell modules produced were made from crystalline silicon (57 percent single-crystal, 25 percent cast polycrystalline, and 3 percent polycrystalline ribbons), 14 percent were made from thin-films (13.5 percent amorphous silicon), and less than one percent were of the concentrator design (Mazer 1997; Kurtz 1996).

4.1.1 Crystalline Silicon Photovoltaic Cells

The first commercially produced photovoltaic cells were made of crystalline silicon which continues to be the "workhorse" of the PV industry today. Bell Telephone Laboratories produced the first silicon cell in 1954, and silicon cells were the first to be used in both space and terrestrial applications. Since that time, silicon cells have demonstrated a high degree of reliability, and its basic properties have been extensively studied in other industries, such as microelectronics. Cost, however, has been a major limitation in the diffusion of the technology. Today, innovative efforts are focusing on lowering the cost of producing high quality silicon feed-stock, as well as, increasing cell efficiency with innovative cell designs.

Manufacturing Silicon PV Cells

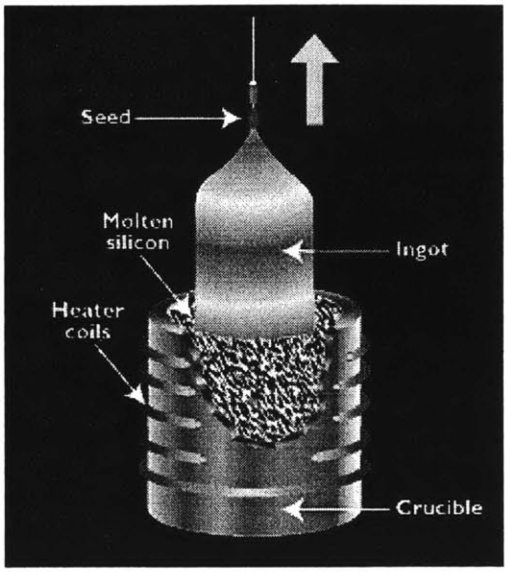
Crystalline silicon cells are produced in three basic steps. Innovation and progress in the production of photovoltaic modules is assessed in each of these steps. The three phases of crystalline-silicon PV cell production are: wafer production, cell fabrication, and cell encapsulation/module construction.

Wafer Production

Pure silicon is required as the starting material for the production of photovoltaic cells. The first solar cells produced were made from single-crystalline material. Because the production of high-grade silicon material is costly, numerous innovations have occurred in the creation of silicon for solar cells. A large amount of crystalline silicon is produced for the microelectronics industry. Some of this material, however, is either leftover or does not meet the purity quality standards for integrated circuits and is discarded. This silicon can be used in solar cells and is the main source of solar cell material. The solar industry has benefited from the economies-of-scale at work with regard to silicon because of the microelectronics industry.

The first solar cells were developed in the 1940s and 1950s with silicon produced from the Czochralski (CZ) process which produces single-crystal silicon. The Czochralski method was originally developed for the microelectronics industry, but has been used for the production of single-crystal silicon for photovoltaic cells since their beginning in the 1950s. The Czochralski process converts polycrystalline silicon into its single-crystal state. In the Czochralski method, a seed of single-crystal silicon is dipped into a reservoir of molten polycrystalline silicon and slowly drawn from it to form a large cylindrical ingot of single-crystalline silicon under careful cooling conditions (Green 1993). Since its first use in photovoltaic cells, substantial efforts have been undertaken, in part with federal support, to improve the method. Numerous incremental improvements have led to the production of purer CZ ingots, and therefore, more efficient photovoltaic cells.

Figure 4-1: The Czochralski Process



Source: DOE 1998.

Other methods beside the Czochralski process have been developed in order to find a method of producing purer single-crystal silicon ingots. The most popular alternative method to the Czochralski method is the float-zone (FZ) technique which produces purer crystals than the Czochralski method. This is primarily due to the fact that FZ crystals are not contaminated by the crucible as are Czochralski produced crystals. This method has higher capital costs than the Czochralski method, but produces crystalline silicon with better PV cell efficiencies which many think justifies the higher capital costs (Green 1993). This process consists of a rod of polycrystalline-silicon placed above a single-crystalline seed. The rod is lowered through an electromagnetic coil, which creates an electric field in the rod, and in turn, heating and melting the point of contact between the rod and seed. Single-crystal silicon is subsequently formed, which resolidifies at this point, and grows upward as the coils are raised. Although the basic features of this process were revealed in the 1950s, much of the work to use the process for the production of single-crystal silicon was not accomplished until the 1970s and 1980s with support from the Jet Propulsion Laboratory (JPL) and the Department of Energy (DOE) (Keller 1981).

Once an ingot of crystalline silicon is produced it must be sliced into wafers. Another significant cost and research focus of photovoltaics is the slicing of ingots into wafers. One reason for this high cost is that a large amount of silicon is lost in the sawing process. Up to 70 percent of the valuable silicon material can be lost as sawdust, or kerf (Surek 1993). In fact, a study by the Jet Propulsion Laboratory found that the slicing process accounts for 15 to 35 percent of the total cost of manufacturing a PV module (Green 1990). Silicon ingots were first cut using an inner-diameter slicing technique originally developed for the microelectronics industry. A major breakthrough in reducing the amount of silicon lost in the cutting process occurring in 1980, with the development of cutting silicon ingots by wire saw. This type of cutting reduces wafer thickness (about one-half of what could be achieved via inner-diameter cutting) and prevents excessive cutting loss, which means more wafers can be produced per ingot (Green 1993). Investigation of the use of the technique was funded by JPL specifically for use in photovoltaics. Shortly after this early investigative work, wire saws were quickly adapted for use in slicing silicon ingots for PV cells and are now used throughout the photovoltaic industry (Anderson 1980).

Both the Czochralski and float-zone methods of producing single-crystal silicon require highly skilled operators, and are labor and energy intensive (Boyle 1996). In response to these challenges other methods of producing crystalline silicon have been developed. In order to bypass the highly inefficient cutting process, it was thought that crystalline silicon could be grown, not in ingots, but in thickness equal to what is needed for photovoltaic cells. One of the earliest methods developed for producing silicon in sheets or ribbons was the dendritic web approach. By controlling the temperature of a pool of molten silicon, two single-crystal wire-like seeds or dendrites, which are separated from each other by several centimeters, will form. As they are drawn from the melt, a thin sheet of molten silicon is trapped between them and subsequently solidifies into good crystallographic material. The high quality of the silicon sheet, however, is offset by the method's exacting temperature requirements and low throughput (Green 1993). The idea of using the dendritic web process to produce silicon for photovoltaic cells was first entertained in the mid-1960s, but halted because of a lack of market for photovoltaics. Interest in the method was rekindled and developed largely by Seidensticker and co-workers at Westinghouse Research Laboratories in the 1970s. Much of this development work was performed for JPL as part of the Low Cost Solar Array Project, which was sponsored by DOE and NASA (Seidensticker et. al. 1978).

Another more rugged method of producing crystalline silicon in sheets is the edge-defined, film-fed growth technique (EFG). The idea of using EFG for fabricating silicon sheets for solar cell manufacture originated with Mlavsky and co-workers in the early 1970s (Taylor 1987), but it was not until 1985 that a quality commercial product was produced using EFG. EFG is a process where an octagon-shaped, thin-walled tube of single-crystal silicon (approximately 10 cm on a side and 300 microns thick) is grown to lengths of about 5 meters. These tubes are produced when molten silicon moves by capillary action between two faces of a graphite die and a thin sheet is drawn from the top of the die. Individual silicon wafers are then obtained by cutting the tube with a laser. The EFG method was almost entirely developed by the Mobil Solar Energy Corporation (now ASE Americas, Inc.) in the 1970s and 1980s. In fact, Mobil Solar patented the process and several other firms in the PV industry currently using the technique. Mobil's development work was supported in part with federal funding from NSF, JPL, and DOE (Mackintosh 1978).

Cell Design and Fabrication

After the crystalline-silicon wafer has been manufactured, the photovoltaic cell is created. While there are many different cell designs, many share some of the most important innovations in the effort to increase cell efficiency. Significant innovations have occurred in the structure of the surface of the cell, reducing material defects in the cell during cell processing, and the structure of. and the process of forming, the metal contacts on top of the cell.

As explained in Chapter 2, one of the most important factors in producing a highly efficient PV cell is to capture as much light as possible. In the effort to increase cell efficiency, several important innovations have occurred in the cell's structure to increase the amount of light captured. Silicon is a shiny material and the surface of a PV cell can reflect more than 30 percent of the light that strikes it (DOE 1991). Therefore, the surface of the cell is treated with antireflective materials in order to minimize reflection. This is usually done by applying a thin layer of silicon monoxide or titanium dioxide to the surface of the cell, which reduces reflection to about 10 percent and is why solar cells appear to be a dark color (DOE 1991). Finding a cost effective method of applying this layer, however, has long been the subject of much technical work. The cost of applying this layer was reduced substantially by using a process called atmospheric-pressure chemical vapor deposition (APCVD). This process was originally developed for use by glass coating manufacturers. In early 1980s, with funding from DOE, the process was adapted for use in crystalline-Si cells. The process in now commonly used in the production of thin-film photovoltaics (von Roedern 1998).

The first PV cells developed had flat surfaces from which reflected a portion of incident light. In order to effectively increase the capture of incidental light, cell surfaces have been textured. By making the surface of a PV cell textured, light which is initially reflected from the cell surface, strikes a second surface before it can escape. Texturing has become a routine process in the production of high-quality solar cells (DOE 1991). The roughness of the surface is created by chemical etching which makes a pattern of cones and pyramids. This major technical innovation was pioneered by COMSAT in 1974 for use in space cells, but was quickly adapted by manufacturers of terrestrial cells. Much of this work was funded by JPL (Chitre 1978).

When polycrystalline silicon, instead of single-crystal silicon, is used as the base material for photovoltaic cells there is a reduction in efficiency. This is because polycrystalline materials have many crystal boundaries that can degrade efficiency. Polycrystalline silicon, however, is less expensive to produce than single-crystal silicon. Typically there is a 1.5 to 2 percent difference in efficiency between single and polycrystalline silicon cells (Kelly 1993). A large amount of effort has been directed at how to reduce this loss of efficiency. A major breakthrough towards this end was the realization that the broken bonds at grain edges could be filled with hydrogen. This process, called hydrogen passivation, reduces the electronic activity of grain boundaries and defects and increases cell efficiency (Green 1993). It was first recognized that hydrogen passivation of defects in silicon could increase cell efficiency in 1979. The work was funded largely by JPL and DOE's photovoltaic programs.

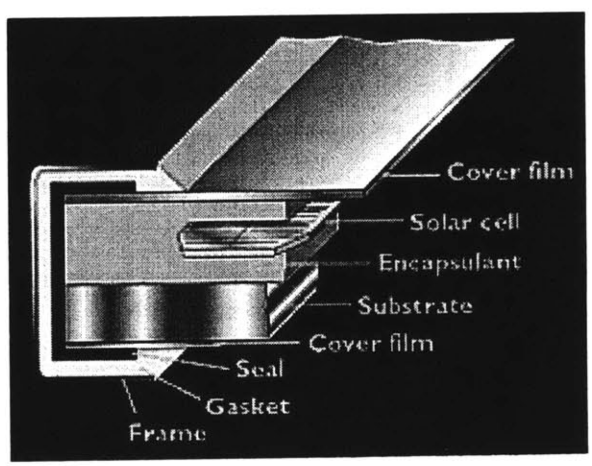
A photovoltaic cell must be part of an electrical circuit. This is the function of electrical contacts attached to PV cells. Contacts must be placed on both the front and back on the cell. Several different types, and designs of contacts, as well as methods for forming and attaching these contacts have been pursued. The following describes some of the most important technical changes in cell contacts.

The contacts on the front of a PV cell are much more difficult to design and attach efficiently than the back contacts. When the cell is placed in sunlight current is generated all over the surface of the cell. In order to create the circuit, as many of these electrons must be gathered. To do this a grid of metal contacts is placed on the top of the cell. However, the larger the grid is, the more of the cell surface is blocked from the sunlight and the cell's efficiency declines. How this grid is attached to the cell has been the subject of several technical breakthroughs. Metal contacts in the mid-1970s were initially placed on the cell by either evaporation of the metal onto the cell in a vacuum or by electroless plating where a grid-mask is placed on the cell and the contacts are then plated onto the cell in layers. These methods, however, proved to be very expensive and a new technique was sought to place contacts on the cell. The most important innovation in forming front contacts was the use of direct screen-printing onto the cell surface. Here, a mask containing the desired grid layout is placed over the cell and the metal is applied to the cell through the patterned screen in paste form. Screen printing was a traditional industrial technology that existed since the beginning of the 1970s (Jins et. al. 1996). The advantages of screen printing, compared with evaporation and plating techniques, include the suitability for automation, relatively simple and continuous processing, and low capital investment (Frisson 1983). Screen printing was first used in laboratory photovoltaic cells in the late 1970s and later used for the first time in large volumes for purchases by JPL in 1975-6. By the mid-1980s, screen printing had established itself as the preferred technology for most cell manufacturers (Green

1991). The technique was studied and applied on a commercial scale in the early 1980s with support from JPL and DOE.

In the late 1980s another major innovation occurred in the forming of the front metal contacts, which significantly increased cell efficiencies. Researchers at the University of New South Wales in Australia invented and patented the laser-grooved, buried grid solar cell in 1985. The LGBG process uses lasers to create grooves in the cell, which are then filled with contact material. This process reduces the amount of cell surface obscured from the sun by the contacts and also increases the amount of contact surface area. BP Solar found the technology promising in terms of cost and effectiveness, licensed it, and began developmental work to use the process in commercial manufacturing of PV cells in 1985 (Mason 1991). The technique was first commercially used in the 1990 World Solar Challenge, where the winning car using these type of cells finished the race nearly a day ahead of the rest of the field. Today, the laser-grooved, buried grid cell technology is comparable in cost to the screen printing of front contacts and has been licensed by several major cell manufacturers (Green 1995).

Figure 4-2: A Photovoltaic Module



Source: DOE 1998.

Encapsulation and Module Construction

To produce power, cells must be connected together into large units to form modules, which can then be connected together into larger units called arrays. Modules are formed because photovoltaic cells are fragile and need to be protected from the adverse effects of being moved around, environmental elements, and to protect others from the electrical current generated by the cell (Green 1982). Most importantly, encapsulation helps protect the cell from degradation by ultraviolet radiation. After a group of cells is connected, they are assembled into their final layout. The interconnected cells are placed in a stack consisting of a glass superstrate, a layer of encapsulant of laminate material, the interconnected cells, another layer of laminate, and then a backing layer (Green 1995).

In the early days of photovoltaics for terrestrial application, a good laminate or encapsulant material was not available. Although polyvinyl buteral had been used, it was somewhat expensive and difficult to store. DOE, therefore, invested research and development resources through JPL in an effort to find a suitable material in the late 1970s. Ethylene-vinyl acetate (EVA) was developed specifically for this purpose and subsequently adopted throughout the PV industry (Green 1995). This novel material represented a breakthrough because it was low-cost, easy to work with, and did not impede light from reaching the cell's photoactive material (Mazer 1997). It was observed, however, in the late-1980s that PV modules exposed to sunlight for long periods of time began to exhibit discoloration of the EVA material and reductions in module efficiency of up to 10 percent were reported (Kazmerski 1997). In 1990 SERI initiated a cooperative research program to investigate why this was happening and to develop solutions to the problem (Czanderna 1996). Since that time federally sponsored research has developed an understanding of how ultraviolet radiation degrades EVA over long periods of time. Furthermore, this effort has recommended that glass using cerium be used to cover the modules and filter UV to prevent EVA degradation. Shortly after this recommendation one of the major suppliers of glass to PV manufacturers began delivering glass containing cerium (Czanderna 1996).

4.1.2 Thin-film Photovoltaic Cells

Thin-film PV cells were developed with the intent of creating a PV cell that uses a small quantity of photoactive material, and therefore less costly to produce than crystalline-silicon cells, while having a greater potential for large-scale manufacturing than crystalline-silicon cells. Thin-film photovoltaic cells are composed of semiconducting materials that absorb sunlight much more effectively than crystalline silicon. Because these materials can absorb sunlight better, much less material is needed to manufacture the cell, which results in the creation of a less expensive photovoltaic cell. Thin-films are typically 0.001 to 0.002 mm thick, as opposed to 0.3 mm for typical crystalline silicon cells.

Thin-film PV cells are manufactured much differently than crystalline-silicon cells. Photovoltaic thin-film cells are made from a number of layers of photosensitive materials, including silicon. Thin layers of different materials are deposited sequentially, on top of each other on a glass, metal, or plastic substrate. This process starts with deposition of the back electrical contact, then the semiconducting material, then an antireflective coating, and finally the front electrical contact. After sheets of this film are created they are divided into individual cells with a laser. Thin-film layers are typically applied using a wide variety of deposition methods. Deposition of thin-films can be much more rapid, much less energy intensive, and done on a larger scale than the manufacture of thick crystalline silicon (Zweibel and Barnett 1993). The first thin-films used a Cu_2S/CdS material and were developed for space missions, which were looking for a lightweight power source. Since that time other photo-sensitive materials have been used for thin-film cells, each which has its own benefits and problems. Another positive feature of some thin-films is that they are very stable in environments outside the laboratory. The most popular materials for manufacturing thin-films are reviewed below with significant innovations within each material emphasized.

Cadmium Telluride

In the late 1950s, Cadmium Telluride (CdTe) thin-films were one of the first thin-films to be studied. CdTe cells have an extremely high theoretical efficiency and have been the focus of a large amount of developmental research. CdTe devices are created by the deposition of CdTe on a substrate and are then heat-treated to become active (Zweibel 1993). During the late-1970s and early-1980s four companies (Kodak, Monosolar, Matsushita, and Ametek) tried to commercialize CdTe photovoltaics cells. Matsushita was the only company of these four to successfully commercialized CdTe cells (in the early-1980s) and still working with CdTe cells. The technology, however, advanced greatly due to the efforts of all of these firms, and several other companies are now ready to commercialize CdTe cells. Many of the innovations in CdTe since the 1970s have been a result of research performed by the Matsushita company of Japan. Matsushita uses a screen printing method to deposit the CdTe on the substrate to form cells for use in calculators. Other CdTe research at BP Solar and Ametek progressed rapidly during the 1980s, but the most significant innovation occurred at Photon Energy, Inc.

Photon Energy was formed in 1984 after the collapse of its predecessor and was focused on developing "low-cost wet chemical methods" of deposition. Photon Energy subsequently achieved impressive results with this method as demonstrated by increased cell efficiencies at low cost. In 1986, the company won a "cost-shared" subcontract from SERI and DOE to further this progress. In 1989, Photon received an award from the PVUSA to produce 20 kW of modules by 1991. In 1991, Photon Energy, Inc. and SERI won an award from *R&D Magazine* for their low-cost CdTe modules. A problem, however, with all CdTe cells is an inherent degradation in efficiency. This issue is being addressed by new methods of cell encapsulation.

Copper Indium Diselenide

Much of the pioneering work with copper indium diselenide (CIS) thin-films occurred from 1973 to 1975 at Bell Laboratories. CIS has an extremely high absorptivity that allows 99 percent of the available incident light to be absorbed in the first micron of the material. That is not, however, the only reason that CIS is attractive for PV devices. It also has shown very good stability in outdoor tests, which is an important criterion for commercialization. Although research and development efforts on CIS started late in the thin-film arena, it emerged as the leading thin-film in the 1980s (Zweibel 1993; DOE 1991).

During the mid- to late-1970s research at the Boeing Corporation showed that by using a thin-film deposition method called vacuum evaporation, thin-film CIS cells could be created which exhibited efficiencies of at least 9 percent. Boeing scientists created the basic structure of CIS devices with support from DOE. During the 1980s, thin-films composed of CIS emerged as a very promising thin-film material. The creation of CIS thin-films of comparable efficiency to single-crystal CIS cells was a major event in the technology's development. Furthermore, CIS cells exhibited more stability than other thin-films being developed at that time such as a-Si. Further research into CIS manufacturing occurred in the late-1970s with the support of SERI at Boeing and other research facilities. This work has continued into the 1990s with other government research facility/private research efforts (Zweibel 1993).

One of the most important innovations in CIS thin-films was the replacement of the single CdZnS layer with two layers. This innovation, developed and patented by ARCO, improved efficiencies by nearly 20 percent. Since that time other CIS researchers have adopted the same approach to create cells of similar efficiencies.

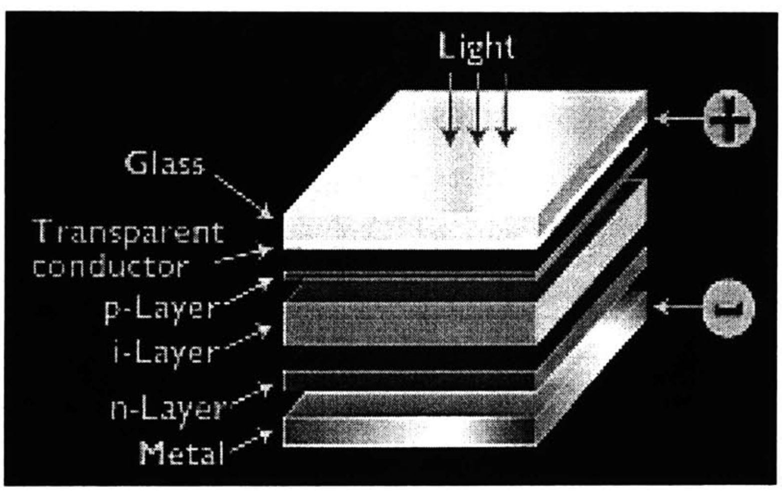
Aside from the issue of efficiency, the other major challenge facing CIS thin-films has been the question of whether modules could be manufactured in large sizes using low-cost processes. An innovation specifically addressing this challenge occurred in the mid-1980s with the creation of the low-cost fabrication process called selenization. This process is a two-step CIS deposition technique which produces CIS layers with grains that are larger and better ordered than those created via traditional vacuum evaporation methods. Selenization entails first depositing copper and indium through a sputtering method. The copper-indium layer is then exposed to a selenium-bearing gas, such as hydrogen selenide, at very high temperatures. This process is fast and allows scientists to fabricate large CIS modules that show efficiencies very close to the best CIS cells -- 88 percent. Much of the work to develop selenization was performed by Arco Solar and its successor, Siemens Solar Industries, with support from SERI (Zweibel 1993).

Another important innovation in the history of CIS cells was the addition of small amounts of gallium to the layer of CIS. This boosts the band gap of CIS, which in turn improves the voltage and therefore the efficiency of the cell (DOE 1991). This work dates back to Boeing's work for SERI in the 1980s. Since 1988, CIS efficiencies have continued to improve because of increased material quality. As of 1993, CIS modules were not available commercially. Low-cost manufacturing techniques are lacking, and attention is being focused on better utilization of materials, process simplification, and the elimination of hazardous materials in cell processing (Surek 1993).

Amorphous Silicon

Amorphous silicon (a-Si) was regarded as an insulator until 1974 when it was demonstrated to be a semiconducting material. (Ahmed 1994) The discovery by Carlson and Wronski at RCA Laboratories that by modifying a-Si's composition slightly, it becomes suitable for use in photovoltaic devices was an exceptionally important innovation in the thin-film field. The potential of a-Si cells for solar conversion on a large scale was recognized immediately, and the development of a-Si technology was taken up world-wide (Carlson and Wagner 1993). Since that time amorphous silicon has become a very popular material for consumer devices, such as calculators. In fact, amorphous silicon composed almost 14 percent of the world PV market in 1995. In recent years the efficiency of amorphous silicon PV devices has incrementally increased to almost 13 percent in 1989 (DOE 1991). A-si was first introduced as a commercial product in 1980, and is now used in a wide range of applications spanning from calculators to portable electricity (Carlson and Wagner 1993).

Figure 4-3: Structure of an Amorphous Silicon Cell



Source: DOE 1998.

Amorphous silicon absorbs light 40 times more efficiently than single-crystal silicon and can be easily deposited on low-cost substrates. As a result, a film only about 1 micron thick can absorb 90 percent of the useable solar energy (DOE 1991). This reduction in material use is what makes a-Si such an attractive option as a low-cost photovoltaic cell. However, a-Si modules face the problem that after being first exposed to sunlight, their conversion efficiency is decreased by 10 to 20 percent (DOE 1991). Thereafter, their performance is relatively steady. It is this instability that has hindered a-Si use in the production of bulk power and has stimulated the effort to find other more stable thin-film materials.

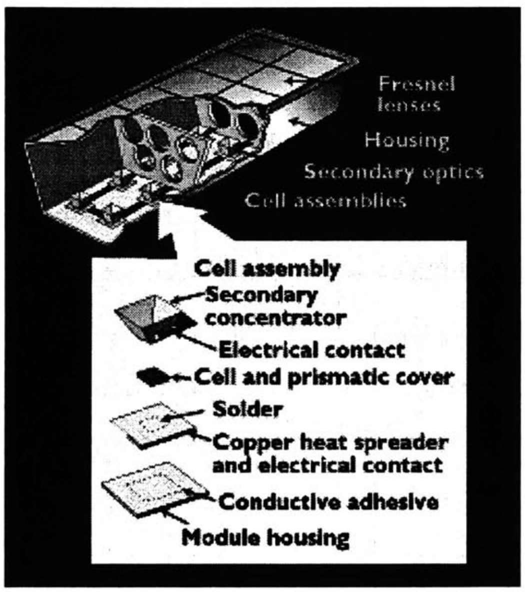
4.1.3 PV Concentrator Systems

The high cost of PV materials has stimulated research into others methods to reduce total photovoltaic costs. The third design philosophy within photovoltaics is the concentrator system. Concentrators use mirrors or lenses to concentrate light onto a smaller-area PV cell. The primary reason for using concentration is to decrease the amount of solar cell material being used in a system. It is often more cost-effective to use less cell "surface-area" and more expensive cells which collect more light (Boes and Luque 1993). A concentrator uses relatively inexpensive materials (plastic lenses, metal housing, etc.) to capture a large area of solar energy and focus it onto a small area, where the solar cell resides. Concentrators use both crystalline-silicon and crystalline-gallium arsenide as cell material. One potential negative aspect of concentrators is that, unlike other PV systems, they require direct sunlight. This means that insolation at a site is very important in determining the effectiveness of concentrators.

A typical concentrator unit consists of a lens to focus the light, a cell assembly (the mechanism that houses the lens at one end and the cell at the other), a secondary concentrator to reflect off-center light rays onto the cell, a mechanism to dissipate excess heat produced by concentrated sunlight, and various contacts and adhesives. (see figure 4-6)

As of the late 1980s, the most promising lens for PV concentrating optic applications was the Fresnel lens. The lens is a sheet of plastic that is flat on the upper side and has sawtooth grooves on the bottom. If the grooves are etched in parallel they concentrate light along a line when the PV cell is placed. Acrylic Fresnel lenses perform well because they have been shown to be weather resistant, stable, and light. Fresnel lenses were first developed for lighting in theatre production, and later adapted for use in PV concentrator systems.

Figure 4-4: A Basic Concentrator Unit



Source: DOE 1998.

The concentrator systems which concentrate light the most use complex, and expensive sensors, motors and controls to allow them to track the sun in two axes, ensuring that the cells always receive the maximum amount of solar radiation. Other systems exist which only track the sun on one axis and are less complex and expensive (Boyle 1996). Development of these tracking systems has been the subject of a large amount of federally sponsored research and development. Federal demonstration projects of solar-thermal systems have provided valuable experience for improving the design and maintenance of tracking structures (Kelly 1993). This work has led to large reductions in the cost of concentrator systems.

4.2 Incremental Innovation

Most of the innovations just described involved radical changes or breakthroughs in photovoltaics. But this is only a small part of the story and could be misleading if taken out of context. That context is that technical change in photovoltaics is as much due to incremental innovation as it is radical innovation. As in Abernathy and Utterback's model there are typically a few incremental changes that lead up to a radical innovation, and a flourish of incremental improvements after the initial breakthrough (Abernathy and Utterback 1978). This is exceptionally important, and true, in the photovoltaic industry due to the extreme pressure on cost and efficiency. Changes which shorten a process by a few minutes result in more throughput. Minor increases in efficiency result in cents off the cost of the module. The success of photovoltaics is dependant on the minor improvements, as much as they are major breakthroughs. It is, however, much more difficult to research and describe incremental innovations than radical innovations.

4.3 Diffusion of Technologies

PV is one of many technologies for generating electricity. It would be possible to look at the diffusion of the technology as a whole into the electricity marketplace, but this has been quite limited with PV only accounting for less than one percent of electricity generation in the U.S. in 1993 (EIA 1993). Furthermore, photovoltaics are used in a number of different applications, such as consumer goods, radio repeaters, and valve control in remote locations, and measurement of the contribution of PV to grid-connected commercial power generation would greatly underestimate the diffusion of the technology. Other methods of measuring the diffusion of the technology are therefore required.

It may be more useful to look at the diffusion of particular innovations. While this has been done in a limited fashion in the discussion of a few innovations previously described, detailed information is extremely limited and in most cases does not exist. Most importantly, several of the innovations previously described appear to have a significant impact on a portion of a PV technology, but because other aspects of the technology are not well developed, the system as a whole has not been commercialized. Therefore, to examine diffusion of innovation within PV technology overall, two different methods will be used. The cost of electricity from photovoltaics is presented, first, followed by data on the efficiency of different types of PV cells.

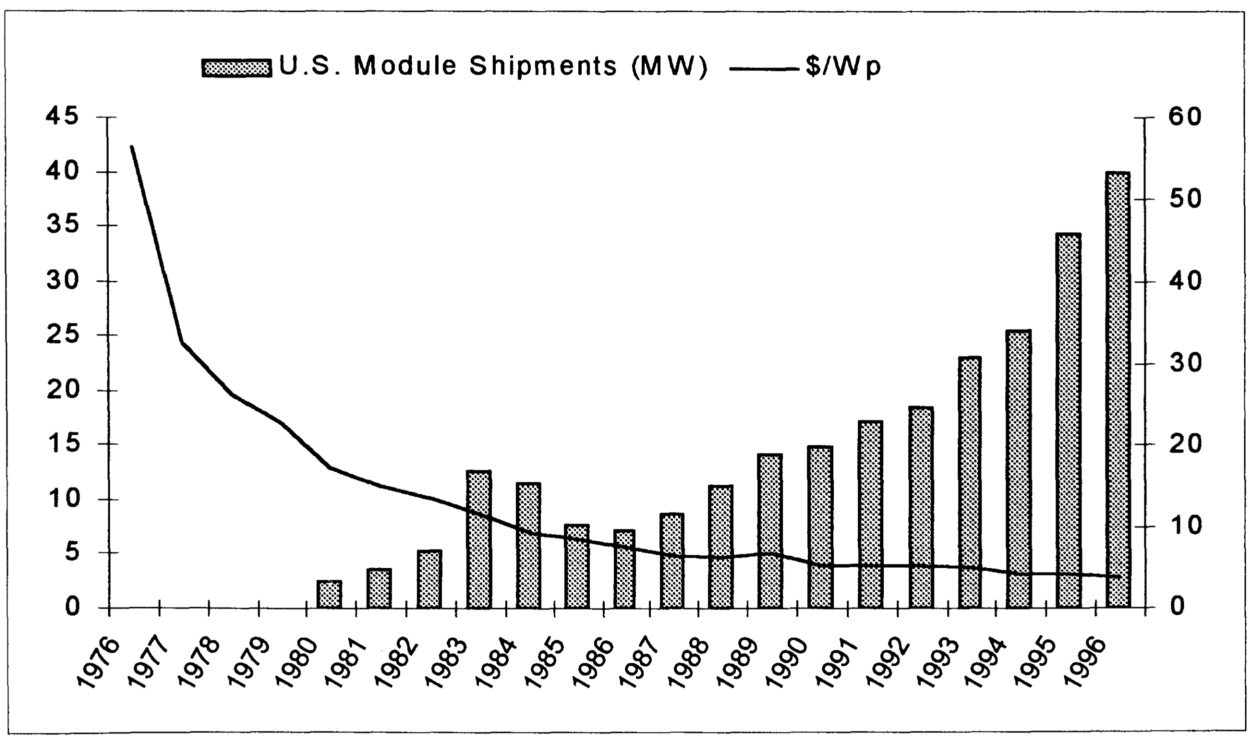
4.3.1 Cost of Photovoltaics and Electricity

When analyzing costs associated with photovoltaics there are typically three types of cost data referenced: module costs, balance-of-system (BOS) costs, and the cost of electricity generated from a PV system. Module costs refer to the cost of creating an actual PV module. BOS costs include the devices needed to create a complete PV system, such as supporting structure and storage batteries. PV electricity cost is the final cost of the electricity generated from a PV system that takes into account module and BOS costs, as well as several other site and system specific factors.

4.3.2 Module Costs

Module cost data are typically reported in dollars per peak watt ($\$/W_p$). When comparing costs over time it is important to note whether costs are given in current or constant dollars. Module costs do not include BOS costs such as mounting and storage.

Figure 4-5: Crystalline-Si PV Module Costs and Annual U.S. Shipments



Source: Winter 1991; DOE/IEA 1995-7; Figure 2-1.

Module costs are highly dependent on the manufacturing technique used to create the module, the size of the module, and the size of the system order. There is a direct relationship between cell cost and cell efficiency. For example, although some thin-film CdTe cells have been created with efficiencies of over 15 percent, most recent CdTe cells use a less expensive glass encapsulate which lowers efficiencies several percent. Module prices also vary greatly between several watt orders and megawatt orders due to economies-of-scale.

As seen in Figure 4-5, the cost of single-crystal silicon modules decreased between 1976 and 1996 from over $55/Wp to under $4/Wp (in constant 1992 dollars). During the 1980s PV was the most economical choice of power for remote terrestrial applications where small amounts of power were required. European firms focused PV applications in the 1980s on electrification in Third World countries. The Japanese during the 1980s took a much different approach towards PV. Japanese R&D was focused on very small cells used to power consumer products such as calculators. In 1985 Japan moved ahead of the U.S. in total PV shipments. This was due to the Japanese market dominance of PV for consumer goods (Watts and Smith 1988). At this time the U.S. maintained a clear lead in the PV power module sector. Also, during the mid-1980s the price of power modules for large quantities of PV decreased from about $17/Wp in 1980 to $7/Wp in 1987 (in constant 1992 dollars). Single-crystal silicon modules continued to decline in price during the 1990s to a price of just under $4/Wp in 1996 (in constant 1992 dollars). The first thin-film modules for non-consumer electronic use appeared on the scene in the late 1980s. These thin-film modules cost $10/Wp in 1992, but since that time they have decreased to a level of about $4/Wp in 1996 (Zweibel 1997).

4.3.3 Balance-of-System Costs

Balance-of-System (BOS) typically refers to items such as supporting structure, power converters, wiring, batteries for storage, and other devices needed for installation of a PV system. Unfortunately, what exactly constitutes the BOS differs from citation to citation. BOS costs also vary according to the type of PV system in use. A PV system for a residential home has much different BOS requirements than a radio relay or utility system. These differences make it even more difficult to compare BOS costs, and in turn, PV electricity costs. However, it is generally agreed upon that BOS costs account for 40 to 60 percent of the capital costs of a PV system (Ahmed 1990). BOS costs are also typically reported in dollars per peak watt ($/Wp).

4.3.4 PV Electricity Costs

The final cost of electricity generated for a PV system is dependent upon several factors, many of which are site-specific.

- Insolation at the site. The amount of sunlight striking the Earth's surface at a particular point varies from point-to-point. This factor determines the amount of electricity potentially generated from a PV system. For example, if PV electricity could be produced at 6¢/kWh in Kansas the same system would produce electricity at 8¢/kWh in New York State and at 4¢/kWh in the desert Southwest (Zweibel 1997).

- Module efficiency. This factor refers to the amount of sunlight converted to electrical energy. These values have increased over time and are usually 75 to 85 percent of PV laboratory cell efficiencies.

- Module cost. Materials, manufacturing technique, order size, and module size all factor into module costs.

- BOS costs. Other devices to complete a PV system play an important part of PV electricity costs.

- System life. The amount of time the system is expected to produce electricity plays an important role in the final cost calculation. PV systems are typically assumed to have lives of 30 years, but past experience has shown that 15 to 20 years should be assumed for current PV systems.

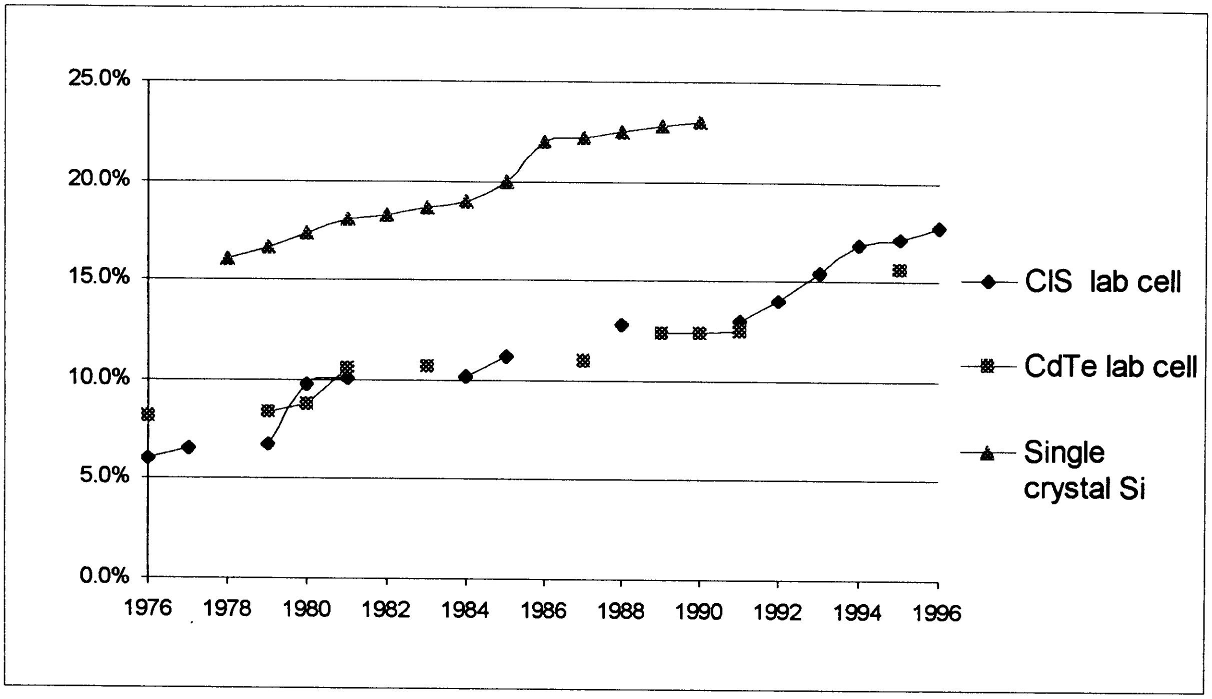
- Interest rate. This plays an important role in determining electricity cost due to PV systems' high capital and zero fuel costs.

Given the many different factors which can be used to calculate the cost of electricity produced by photovoltaics, no single chart could be constructed that portrayed electricity from comparable systems to compare cost. There is, however, a significant trend in PV electricity costs over the past 25 years -- PV generated electricity has fallen dramatically over the last 20 years. Furthermore, PV electricity costs have fallen substantially even during the last 10 years. PV electricity in 1991 costs about 55-60 ¢/kWh, that amount has fallen to the 35-40 ¢/kWh range in 1995 (in current dollars). This trend is expected to continue, but predictions vary greatly about by how much and when.

4.3.5 PV Efficiencies

While cost numbers are the most important in terms of competitiveness for generation of electricity, efficiency numbers are just as, if not more, important in determining technical change within the industry. As mentioned previously, efficiency data should not be compared between technologies (i.e., thin-films vs. concentrators), but should be compared within the same technology over time. Figure 4-8 shows the steady improvement in efficiencies overtime. It is important to recognize that each technology has a theoretical maximum in efficiency, and as cells approach this maximum it will at some time become more difficult to increase efficiency marginally.

Figure 4-6: PV Laboratory Cell Efficiencies



Source: DOE 1993, 1994, 1996, 1998.

4.4 Summary

The photovoltaic technology has advanced greatly over the last 25 years, in all phases of production and in the different types of PV technology. Numerous significant innovations have caused efficiencies to increase and costs to decrease. Table 4-2 summarizes these innovations for further examination and are listed in order of construction phase. It is important to note that almost all innovations had some sort of public sector funding involved in their development. This is consistent with the claim that the technology lacks investment from the private sector. The types of innovations are almost split evenly between product and process innovations. Finally, it is interesting to note the almost all innovations originated through R&D specifically focused on PV technology. Many of the challenges facing photovoltaics are unique to the industry and do not benefit from R&D in related technologies such as integrated circuits. There are reports, however, that the integrated circuit industry is benefiting from R&D work specifically for photovoltaics (von Roedom 1997).

Table 4-2: Characteristics of Photovoltaic Technology Innovations

Innovation	Unit effecting	Outcome of innovation	Source of innovation	Source of funding	Type of innovation	Originating industry
Czochralski process	Material	Produced good single-crystal Si	Universities	Public	Process	Micro-electronics
Float-zone process	Material	Produced purer single-crystal Si	Bell labs/universities	Public	Process	PV
Wire-saw	Material	Reduced wafer thickness and kerf loss	Universities	Public	Process	?/PV
EFG (edge-defined, film-fed growth)	Material	Produced thin sheets of crystalline Si	Mobil Solar	Private and Public/Private	Product	PV
Dendritic web	Material	Produced thin sheets of crystalline Si	Westinghouse Research labs.	Public	Product	PV
Amorphous silicon	Material	Discovery of new low-cost thin-film material	RCA labs.	Public/Private?	Product	PV
Anti-reflection coatings via APCVD	Cell	Increased amount of light captured	?	?	Both	PV
Surface texturing	Cell	Increased amount of light captured	Micro-electronics/ COMSAT	Public/Private	Product	Micro-electronics
Hydrogen passivation	Cell	Reduced poly-Si crystalline defects	Universities	Public	Product	PV
Screen-printing of front contacts	Cell	Reduced cost of making front contacts	Universities	Public	Process	Standard industrial process
Laser-buried groove cells	Cell	Increased cell efficiency	University	Public	Product	PV
"low-cost wet chemical" deposition in CdTe cells	Cell	Low-cost thin-film deposition method	Photon Energy	Private?	Process	PV

Splitting of CdZnS layer	Cell	Substantially increased cell efficiencies	ARCO solar	Private?	Product	PV
Selenization	Cell	Allowed high-volume, low-cost manufacturing of thin-films	ARCO solar	Public/Private?	Process	PV
Gallium in CIS	Cell	Improved CIS cell efficiencies	Boeing	Public/Private	Product	PV
EVA for module encapsulation	Module	Lowered cost/increased quality of laminate	Universities	Public	Product	PV
Ce glass module	Module	Reduced laminate degradation	University/ Private firms	Public/Private	Product	PV
Laminated modules	Module	Improved durability of modules	Siemens Solar	Private	Product	Auto industry
Fresnel lens	System	Low-cost durable lenses	?	?	Product	?
Tracking systems	System	Increased sunlight captured	Sandia/Private firms	Public	Product	PV/Solar thermal

Chapter 5
Photovoltaic R&D Policies

The policy history of photovoltaics has primarily been focused on R&D. This is due to the fact that the cost of electricity generated from photovoltaics has been so much higher than other forms of commercial electricity generation, and demand-type policies such as subsidies would have been less appropriate at this stage and required exorbitant amounts of funding.

Annual levels of public R&D funding have risen and fallen greatly as interest by Congress and the Executive branch in the technology has ebbed and flowed. Cumulative PV R&D funding up to 1995 totaled approximately $1.2 billion in the public sector. Energy R&D has historically been the responsibility of the private sector, but geopolitical events have, at times, created a role for public involvement in the commercialization of energy technologies. This chapter is a review of the legislative and programmatic history of PV R&D policies. The chapter concludes with a discussion of how various PV technologies were selected for public R&D funding.

Over the last 25 years U.S. PV R&D programs have changed substantially. The focus of much of the work has moved from basic materials research to manufacturing R&D. The programs have matured as the technology has matured. Furthermore, the amount of private sector input into these programs has also increased. This chapter gives a more detailed look at these changes and how they related to the development of the technology.

5.1 Justification for PV R&D

Following the rapid increase in petroleum prices after the Arab oil embargo of 1973-1974 a societal goal became clear for the U.S. government – that of providing affordable energy.

Market prices of oil before the embargo did not reflect the true cost of importing oil from an unreliable source. The United States greatly depended on oil imports, and the rapid decrease in supply became a national crisis. This circumstance created a well-defined "mission" for the U.S. government to pursue, of which R&D was a key first step. Speeding up the development of renewable energy technologies was seen as a justifiable action of the government. In affect, cheap and reliable energy was a public good, and pursuing renewable energy R&D was one option that could accomplish this mission.

This "mission" justification for government R&D of PV is another way of highlighting the public good market failure. The fact that few private firms were unwilling to undertake the large amount of R&D necessary to commercialize PV is a function of the fact the some of the benefits of the technology were public goods. While, electricity is a private good, its environmental impacts are clearly in the public realm. Emission costs from most energy sources are not fully included in the market price of electricity. Reliable renewable energy supplies would also increase national security, which is not accounted for in current energy prices.

A closely related justification for federal efforts to commercialize photovoltaics is the appropriability problem. As noted before, appropriability refers to a private firm's ability to capture the benefits accruing from a technology development project. The basic research needed to commercialize a technology is the most obvious area in which private firms will not have the incentive to undertake the R&D. This is no different for PV. The private sector has not been willing to fund basic research into PV related topics.

An additional, and particularly relevant, market failure occurring in PV, which justifies government support of R&D, is the issue of risk or uncertainty. PV poses large risk problems for potential private investors in the technology. It was, and is, very difficult to predict where the technology is headed and how long it will take for costs to become competitive. In the 1970s, PV electricity costs were on the order of \$500/Wp. To be commercially competitive they must reach the \$3/Wp level. The technology has relied greatly on basic R&D work, which is risky, and not guaranteed to result in a commercially viable technology. Furthermore, PV R&D

requires an extremely large amount of funding. Energy technologies in general require large investments, and bias a large amount of private R&D funds towards smaller incremental projects, rather than R&D on "big-ticket" radical projects.

PV during the early 1970s was at a stage when its commercialization for utility-scale use needed the assistance of R&D by the public sector because of several market failures. Without this "kick-start" it was unlikely that the private sector would have undertaken the R&D necessary to commercialize the technology, yet the benefits of such research could outweigh the costs to society.

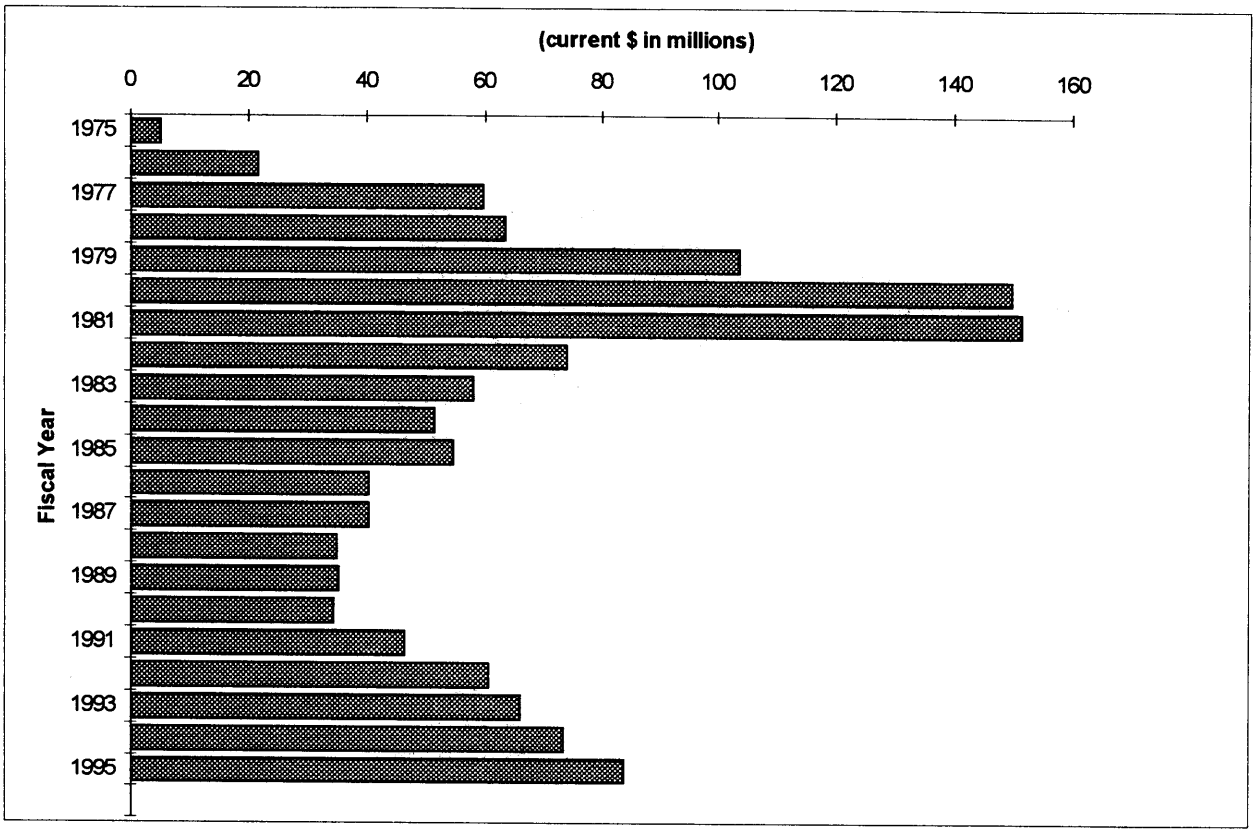
5.2 History of PV R&D Supply Policies

As shown in Figure 5-1, appropriations for photovoltaic R&D grew rapidly in the last half of the 1970s. They proceeded to decline almost as dramatically in the 1980s, and in the last decade they have slowly increased. The Flat-Plate Solar Array (FSA) program of the 1970s was a driving force in the development of terrestrial photovoltaic technology. The 1990s have seen the appearance of many R&D programs that rely on cost-sharing arrangements with the private sector.

5.2.1 Solar Legislation

Federal photovoltaic research began in the 1950s in order to find a suitable power source for satellites. As noted earlier, the first PV cells to enter space were installed on Vanguard I in 1958. The first PV R&D programs were focused on photovoltaics for space applications. As the space program developed through the late 1950s, the need for photovoltaics for space applications grew. Space photovoltaics needed to be both highly efficient and reliable. The cost of these cells was not particularly important when compared with the cost of transporting them to their destination. As a result, research into solar cells for use in space was focused more on efficiency and weight, than cost per peak-watt or kilowatt-hour. During this time research continued into other potential PV materials such as cadmium sulfide. Much of this work occurred in military laboratories with the assistance of private firms. Nearly all PV cells sold until 1972 were silicon based and designed specifically for space applications.

Figure 5-1: U.S. DOE Photovoltaic Research and Development Spending



Source: Frankel 1986; EIA 1993; DOE 1994, 1996b.

1974 Solar Energy Research, Development, and Demonstration Act

The Solar Energy Research, Development, and Demonstration Act enacted one of the first federal research efforts into terrestrial photovoltaic cells in 1974. The purpose of the act was:

> to authorize a vigorous Federal program of research, development, and demonstration to assure the utilization of solar energy as a viable source for our national energy needs, and for other purposes.

The legislation created the Solar Energy Coordination and Management Project. The Project was composed of six members from the National Science Foundation, the Department of Housing and Urban Development, Federal Power Commission, NASA, the Atomic Energy Commission, and a presidential designee. The project and its members were responsible for management and coordination of national solar energy research and development. At the time the act affected many different agencies performing solar R&D. The Jet Propulsion Laboratory was conducting, while the National Science Foundation was funding, most of the research concerning photovoltaics. The act also created the Solar Energy Research Institute (SERI) which later consolidated all of these efforts.

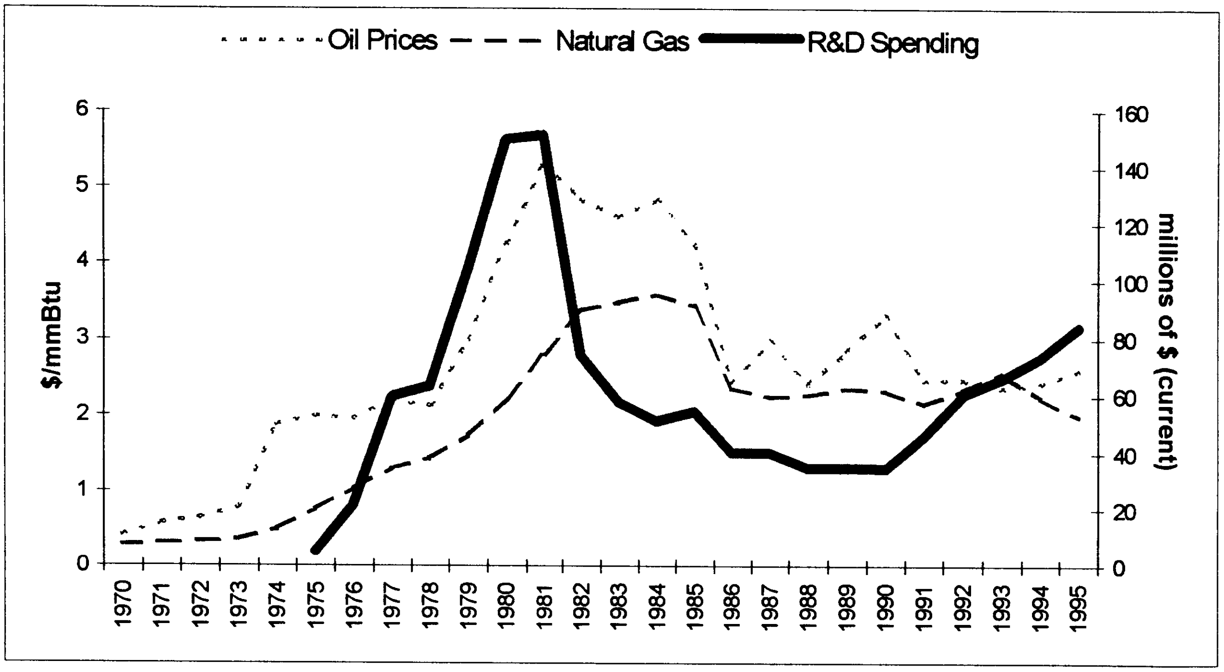
Although much of the research focus of this act was on flat-plate solar heating, some R&D efforts were PV-specific. From 1975 to 1980 cumulative federal expenditures for the U.S. photovoltaic program totaled nearly $450 million. This entire amount was focused on R&D. Specifically, $95 million for advanced R&D, $163 million for technology development, and $99 million for testing and applications (Roessner 1984).

1978 Solar Photovoltaics Research Development and Demonstration Act

This act set the stage for the rapid increase in PV R&D during the Carter administration that peaked at $151 million in FY 1980. The act established a 10-year, $1.5 billion program whose goals were to establish, "an aggressive research development and demonstration program..." for photovoltaic systems to produce electricity "... cost competitive with utility generated electricity." (Pub. L. 95-590, Sec. 2, Nov. 4, 1978, 92 Stat. 2513) Funding for the program decreased substantially with the new administration in 1980, and a philosophy of limited government involvement in the development of domestic energy supplies.

The election of President Reagan in 1980 marked a fundamental shift in the role of government in energy policy and the technology development efforts of government. Technology commercialization was considered to be the role of only the private sector. Furthermore, environmental issues were less of an administration priority, and oil prices were declining (see Figure 5-2). Government funding of photovoltaics declined substantially over the next ten years. During this time, however, several government R&D projects did continue. Almost all demonstration and commercialization activities were stopped, with government funds only being applied to R&D. Government PV efforts were consolidated and centralized at Sandia National Laboratories (SNL) and the Solar Energy Research Institute (SERI), which was renamed the National Renewable Energy Laboratory (NREL) in 1992.

Figure 5-2: Federal PV R&D Spending and Fossil Fuel Prices



Source: EIA 1996; Frankel 1986; EIA 1993; DOE 1994, 1996b.

5.2.2 Solar R&D Programs

Flat-Plate Solar Array Project

The first photovoltaic development program was the Flat-Plate Solar Array (FSA) project. Table 5-1 gives a general overview of some the most prominent PV R&D programs over the past 25 years. The FSA program was funded at $228 million over the period 1975 to

1985 and managed by the Jet Propulsion Laboratory (JPL). The project's goal was to produce a crystalline silicon-based terrestrial PV technology. The development programs were focused on PV materials, cells, modules, manufacturing processes, and field testing of PV systems. The program set the precedent of using cooperative joint technology development with the PV industry, universities, and national laboratories (Wallace 1995). Specific efficiency and cost goals were laid out at the beginning of the project. These goals were to be met primarily through the development of new materials and material processes. As discussed earlier in Chapter 4, several important new silicon technologies were developed as a direct result of the FSA project. These included EFG and dendritic web growth of crystalline silicon. Other progress occurred in the development of new methods of attaching the front contacts of crystalline silicon cells. Substantial progress was achieved with regard to the three technical challenges faced by photovoltaics. Costs decreased from $\$75/W_p$ to $\$5/W_p$ (1985 dollars); efficiency increased from 5 to 15 percent and manufactures of PV modules introduced 10-year warranties -- all as a result of the FSA program (Wallace 1995). In summary, the FSA project produced a wealth of information and progress in all aspects of silicon cell technology and economics.

Table 5-1: Overview of Federal PV R&D Programs

Program	Date	Administered	Funding (million)	Work completed by:	Goals/strategy set by:	Who selected technologies	How technologies selected	Cost-share %
Flat-plate Solar Array Project	1975 - 1985	JPL	$228	sub-contracts	JPL	JPL		rare
a-Si Research Project	1982 - 1992	SERI	$40	sub-contracts	SERI/DOE	SERI	yearly planning meeting	increasing
Thin-film PV Partnership	1994 - present	NREL	over $100	sub-contracts	NREL/DOE	NREL	yearly planning meeting	some
PVMaT	1990 - present	NREL	$118	sub-contracts	industry/ NREL	NREL	best proposal	large amount
CRADAs	since 1992	NREL/ Sandia	$24	private industry	NREL/private industry	NREL/ Sandia	best proposal	large amount
Concentrator Alliance	1997	NREL	?	Sandia/ subcontract	Sandia/DOE	Sandia	best proposal	some

Source: DOE 1994,1995, 1996a; Gates 1988; von Roedern 1998.

An important component of the FSA project was the periodic purchase of PV modules by JPL. While this is what is typically considered a demand-pull type of public policy, it was very important in the technology development process. These periodic purchases and demonstrations allowed the group requesting the technology, the government in this case, to have interaction with those actually developing the technology. JPL tested the modules, and gave direct feedback to the manufacturers, who used the information to optimize the technology. This technology transfer process assisted in the commercialization of several new material technologies developed through the FSA project.

Amorphous Silicon Research Project

Another important federal PV R&D program was the Amorphous Silicon Research Project (ASRP), which was established at SERI to coordinate amorphous silicon (a-Si) research. The project began in 1982 and ended in 1992 with a cumulative budget of approximately $40 million dollars (von Roedern 1998). The goal of the project was threefold: to foster a viable amorphous silicon PV industry in the U.S.; to develop cost-effective a-Si technology; and to help industry achieve a PV program goal of 10 percent efficient commercial thin-film modules by 1995. All of these goals were part of the effort to create a cost-competitive a-Si technology for the utility power sector (Stafford, et. al 1991). Efficiency goals were for stabilized modules, instead of initial performance. This represented an important change by NREL, and a refocusing of industry and university researchers to minimize performance degradation (Surek 1992). While the best a-Si cells exhibited efficiencies of 10.9 percent in 1995, the best modules only achieved 8 percent stabilized (DOE 1996b and 1998).

Cost-shared, multi-year subcontracting to pursue applied R&D in industrial laboratories was introduced by the ASRP. This method of "direct technology transfer" from government labs to the private sector helped shorten the time between lab research to pilot production, and then prototype manufacturing. Government laboratories would investigate the photovoltaic potential of the material and then share their findings with private firms that were primarily involved in the creation of pilot production facilities. The multi-year nature of these contracts also provided stability useful for project planning. During the history of the ASRP project, a-Si cell efficiencies increased from less than 5 to 11 percent. The specific technical achievements which accounted for this increase included better metal oxide contacts, a-Si alloys, and large-scale manufacturing techniques such as plasma-induced chemical vapor deposition.

Wallace notes that the ASRP's "Cost-shared, multiyear subcontracts with industry and coordination with internal, national laboratory, and university research have impacted the design of subsequent technology development programs" (Wallace 1995). A current example of this phenomenon is NREL's ongoing Thin-film Project.

Thin-film PV Partnership Program

DOE formed the Thin-film PV Partnership Program in 1994. The project is an R&D program that is approximately two-thirds publicly funded. The objective of the program is to develop a thin-film technology that has reasonable efficiency (15 - 20 percent), very low cost (about $\$50/m^2$), and long-term reliability (30 years). The collaboration seeks to develop prototype products largely based on amorphous silicon, cadmium telluride, copper indium diselenide, and thin-layer crystalline silicon technologies.

DOE has awarded contracts to a large number of industrial partners and even more research partners in universities. Each of the partners, including universities, contributes 10 to 50 percent of the value of these contracts. University researchers, including those at the DOE PV Center of Excellence at the Institute of Energy Conversion (University of Delaware), play key roles in this work. The program focuses its funding on cost-shared contracts with companies called "Technology Partners" that are involved with bringing thin-film technology to pilot production. The program also funds NREL's R&D, as well as that of other organizations (called "R&D Partners") contributing to making thin-film technologies successful. A large amount of progress has been achieved by the Project in terms of increasing efficiencies through a greater fundamental understanding of materials and device structures (Surek 1992).

The program is divided into four teams to address issues in the following areas: amorphous silicon (a-Si), copper indium diselenide (CIS), cadmium telluride (CdTe), and environment, safety, and health (ES&H). The team approach tries bring together people involved in research and industry to discuss issues common to a certain technology. For example, when a manufacturer is having trouble with encapsulating cadmium telluride, a research scientist is available to diagnose the problem and offer solutions. An easy and frequent flow of information produces solutions to problems faster than it would take without the collaboration. Furthermore, thin-films are thought to be the leading technology in the future of photovoltaics. By assembling and combining the knowledge of scientists and members of the thin-film industry it is thought that the industry will position itself better for the future.

The teaming approach does, however, face some resistance from a few members in the industry. Some firms are reluctant to share information concerning their manufacturing processes for fear of loosing a competitive advantage. The importance of proprietary issues varies by thin-film technology. For example, in a-Si, where a large portion of the industry has reached the conclusion that the only way that current challenges will be overcome is to pool resources and knowledge, proprietary issues are less important. In areas such as CIS, some firms feel they have a technological edge on competitors and do not feel the need to work in teaming arrangements.

Photovoltaic Manufacturing Technology Project

The Photovoltaic Manufacturing Technology Project (PVMaT) also uses multiyear, cost-shared subcontracts with industry. These contracts are awarded through competitive solicitation open to all U.S. PV manufacturing companies (Surek 1992). The project funds both proprietary research at individual companies and nonproprietary teamed research on generic manufacturing technologies. The Project, initiated in 1990, was entering phase 4A in 1997. The goal of the project is to help the PV industry improve manufacturing processes and lower costs while increasing production capacity. PVMaT projects are cost sharing arrangements where DOE and a subcontractor jointly fund research and development projects. To meet the project's goals the program was structured in five phases. Table 5-2 details the PVMaT initiative.

Table 5-2: The PVMaT Initiative

Phase	Objective	Contracts
1	Identify specific PV manufacturing problems.	22 small contracts to members of the PV industry.
2A	Researching process-specific module-manufacturing problems.	Phase 2A consisted of seven contract awards with two going companies involved with crystalline silicon technologies, three with companies working with amorphous silicon technologies, one company involved with concentrator modules, and another company working with another thin-film technology.
2B		Phase 2B contracts also focused on improving module manufacturing processes and equipment to increase commercial module performance and reduce the module manufacturing costs. Two phase 2B contracts were awarded to firms involved with cadmium telluride module technologies, on with crystalline silicon, an one other with a firm developing a novel photovoltaic technology.
3A	Teamed research on generic or common problems in PV manufacturing.	One contract to a group of companies to work on automation of the assembly and encapsulation of PV modules. Another contract was awarded to a group of companies to develop better encapsulation materials.
4A1	Broadened the scope of the project to include balance-of-system (BOS) components.	Three companies received two-year contracts for research on inverters, two for the development of AC modules, and two others for standardization and deployment of system work.
4A2		Five three-year subcontracts for module manufacturing work.

Source: DOE 1996b.

As of the end of 1995, a total of 48 subcontracts had been awarded out of more than 100 proposals submitted (DOE 1996a). When phase 4A is completed, total funding of the PVMaT project will have been about $118 million. Of this amount industry accounted for nearly 43 percent of the funds. A team including representatives from the PV industry, government, and the national laboratories developed the project's concept, general management, and procurement approaches.

In 1995 DOE and the Solar Energy Industries Association completed an assessment of the PV's industry's views of the DOE PV program. The review consisted of detailed interviews with 22 PV companies, most of which had participated in the PVMaT program. The project was considered by all companies "to be the best and most helpful government assistance they could hope to have available in this period" (DOE 1996a). It should be noted that at the time of the survey, federal PV funding was under strong pressure from Congress to be significantly reduced.

PVMaT represents the changing nature of federal R&D efforts. Early programs such as FSA were focused on novel materials, processes, and cell designs. While these are still a part of federal R&D efforts, there has been a new emphasis on support of, and cooperation with, the photovoltaic industry in their production technology, which started in 1990. PVMaT is a prime example of this transition. The reason for this change in structure, balance, and technology development focus has been two-fold. First, funding for the U.S. PV program has been experiencing modest increases in the past five years. Second and most importantly, the status of the technology has been changing. Photovoltaics are becoming a more mature, from a cost perspective, technology with more technical challenges appearing in manufacturing processes.

While a number of different PV technologies were created in the 1970s and 1980s, substantial cost difficulties remain. The PV industry faces high manufacturing costs due to labor-intensive production lines, old processing equipment, and small plant capacities. The technical challenges faced in manufacturing of photovoltaics are large and the benefits of incremental progress in innovation will not be met with substantial reward in market growth and profits. As a result of this situation little R&D effort has been focused on PV manufacturing technologies. This problem only recently received DOE's attention and was a force behind the creation of the PVMaT initiative.

Basic Research

Federal R&D efforts have continually included work on materials and cells. Behind all of this work is the knowledge gained by fundamental research. This basic science is what allows incremental technical advances in new materials and devices that result in increased cell efficiency and lower PV costs. Government funded basic research has been performed at universities, national laboratories, and industrial laboratories. This research has had a significant impact on the development of photovoltaics. For example, NREL is currently funding research into the basic characteristics of silicon. The work is focused on trying to understand how defects and impurities affect, and are introduced into, crystalline silicon. It is hoped that a better fundamental understanding of silicon will allow higher efficiencies of crystalline silicon PV cells to be achieved.

Cooperative Research and Development Agreements

Another approach to R&D that integrates work with the private sector are Cooperative Research and Development Agreements (CRADAs) that assist member of industry bring promising technologies to the marketplace. Under a CRADA, NREL or Sandia National Laboratories and an industrial partner contribute facilities, personnel, and/or property to a project, and each participant funds its own activities. The facilities of the national laboratories are also available for analyzing projects and materials supplied by the industrial partner. To date, NREL has contributed $23.6 million to CRADAs and industry partners have contributed $62.1 million, bringing total funding to $86 million. NREL's share of this amount is 27 percent, while industry's share is 73 percent (DOE 1997). These types of projects are another way in which DOE leverages its funds and facilitates R&D, and transfer technology from the lab to the marketplace.

5.2.3 Technology Selection

How technologies are selected for development work is a very important question because funds are limited and risk is high as to which exact technology will be a successful commercial product. Furthermore, technology selection that is not based on technical merit leaves the PV program open to political criticisms.

In the 1980s, many of the technologies and proposals selected for funding were done so without a heavy reliance on the technical merits of a proposal. Many of the researchers funded had reputations known to R&D managers and were the only ones working in an area or on a specific problem. There was little competition, and R&D managers had a much stronger hand in determining who would complete a project. This situation has slowly changed as there are more participants in the field and competition has increased. It is more common that a request for proposals will be released, and several proposals will be received. Technical capabilities and research plans are now much more carefully examined, and the exact "who" is not known before an RFP is released. An example of this process is the PVMaT initiative. The initiative does not select projects to fund because they are of a certain type of technology (i.e., thin-film or concentrator). Any technology is open for funding, and there are no predetermined requirements as to what type, or how many projects, should be funded. Proposals are judged solely on the merits of the technical approach and the importance of the problem targeted (von Roedern 1997).

5.3 Summary

The history of public policy related to PV has included a variety of different "supply-push" efforts. There has, however, been a set of constant market failures that have justified government support of PV R&D. Many of these programs spanned long periods of time, even though yearly funding fluctuated greatly. This support led to R&D in several different PV technologies. Over time, research programs evolved as the technology matured, and today focus more on manufacturing R&D rather than new materials and basic research. The implications of these findings are the subject of Chapter 6.

Chapter 6
Analysis, Conclusions and Recommendations

The preceding chapters have attempted to identify the important factors behind the development of photovoltaic technology in the U.S., both from a technical and policy standpoint. Drawing from these findings, this chapter seeks to answer the question of which policies and components of R&D programs were most successful. The issue of which technologies were selected for R&D is addressed first, followed by an evaluation of how the R&D programs changed over time. The success of a "parallel paths strategy" and the fact that federal R&D programs evolved as the technology matured are the primary findings of the research. Weaknesses in R&D programs are also described followed by some recommendations for future PV R&D policies and programs.

6.1 The Federal PV Program Has Generated Key Innovations

As described in Table 4-2, many of the most significant technological innovations in the PV program have been either partially or substantially funded with federal R&D money. These innovations were focused on new materials during the 1970s and 1980s, while R&D programs have been focused more on manufacturing innovations during the 1990s. This reflects the fact that large cost reductions have taken place and it is thought by many federal officials and members of the private sector involved with PV that at this time the commercialization of PV depends more on improved manufacturing techniques, than novel materials (von Roedom 1997). This assertion seems reasonable considering how close crystalline silicon cells are to their theoretical maximum and the cost reductions observed in similar manufacturing industries such as integrated circuits.

The Flat-plate Solar Array (FSA) program was a major contributor to the knowledge about the materials and photovoltaic effect. The program also was extremely successful in developing the first demonstrations that PV could be used as a remote power source. The biggest successes in knowledge gained were concerned with how terrestrial PV modules and photoactive materials worked and could be used in terrestrial situations. This knowledge set the stage for future experiments in the effort to increase cell efficiency and the design of new cell and module structures.

The national PV program has also been responsible for the testing and verification of output and efficiency of PV modules. This has led to a standardized testing regime that includes characterizing and measuring performance of modules made by NREL researchers, industry partners, and universities. NREL conducted more than 17,000 measurements in 1997 (NREL 1998). Researchers analyze materials, characterize device performance, evaluate fabrication problems, and model solar cell and module performance with computers. SERI and NREL have primarily carried out this work. The standards work started in 1978 and continues today. NREL serves as an independent neutral third party that can verify claims of module efficiency. This is important because there are so many different variables in a PV module and a uniform standard and testing facility allows for comparison of modules produced by many different researchers and manufacturers.

6.2 The Parallel Paths Strategy Has Worked So Far

The federal PV program has been organized in such a fashion as to minimize the risk of technological failure and increase the chance of producing a commercially competitive technology for electricity generation. While the federal PV program has not produced a technology commercially competitive for utility scale electricity generation, it has made substantial progress in decreasing the price of PV electricity. Furthermore, and more importantly, the federal PV program has avoided many of the pitfalls of other federal renewable energy R&D programs.

The federal government has traditionally engaged in commercial technology development programs of the "big-science" variety. Renewable energy projects have been no different. For example, in its early years the federal wind energy program placed half of its efforts into developing a "cost-competitive, mass-producable, utility-scale" wind turbine (the Mod Program) (Lioter 1997). This effort suffered from several problems, among them the fact that the effort invested in a single technology. Several things made this strategy risky. One, the technology being pursued could end-up not being viable, or two, there could be some change in the market for the technology that the technology could not adapt to, and result in a black-hole project. Furthermore, the Mod program has not been successful partially because of a lack of communication between the private sector and the public R&D managers. Placing a large amount of funding into a single technology has not been a successful strategy in some renewable R&D energy programs.

The U.S. federal PV program has been focused on the development of several different PV technologies, each sufficiently different so that if one should not reach commercialization another is still being pushed forward. The idea is similar to Nelson's parallel paths strategy where total risk of technology failure is lowered, but cost of development is increased. The PV R&D programs since 1975 have pushed crystalline-Si, several different types of thin-films, and a-Si, all forward at the same time. While none of these technologies have been commercialized for utility-scale use, they have all made significant gains in terms of cost and efficiency.

Throughout the history of the PV program the parallel paths strategy has shown its flexibility. During the 1980s when domestic PV manufacturers felt the pressure of a potential Japanese breakthrough in a-Si technology, U.S. federal R&D efforts focused more heavily on a-Si. While this technology did not progress as rapidly as expected, the federal PV program had still funded crystalline silicon R&D. While the amount of this R&D was substantially reduced from early times, it continued to promote the technology on a limited scale. The result of this was that crystalline silicon technology was not abandoned and was able to maintain a large percentage of market-share in the U.S.

While a parallel paths strategy has worked to avoid technological dead-ends, it may have done so at the expense of higher cost and slower technological progress. It can be argued that if all of the funds for the different types of PV technologies had been focused on a single technology, then that technology could have been commercialized already. Although this is possible, the argument requires that the technology which could "win" was known. This has proven to be a very difficult problem to answer and it would have been luck if the right technology was chosen.

6.3 PV Program Cost-sharing Has Increased

The Department of Energy has leveraged federal funds and encouraged the commercialization of photovoltaic technologies by requiring industry and other partners to share in the R&D costs. During fiscal years 1996 and 1997, private industry and other groups' cost sharing ranged between 13 and 92 percent of the cost of the research projects. The cost-share apportionment depended on the size of the firms involved and the phase of the R&D. The cost-shares were in the form of cash or in-kind contributions, such as salary or equipment costs or a combination of both and are generally established during the initial solicitation for partners. Cost-share contributions by partners from private industry are generally higher for projects in the later phases of R&D. For example, the industry's cost-share percentages for the photovoltaic program are 24 percent for the basic and applied R&D phases and 92 percent for technology development.

The importance of cost-sharing in the PV R&D program has been two-fold. One it increases the total amount of R&D undertaken by the PV industry. By leveraging private sector dollars more and larger PV R&D projects can be undertaken. Two, it is important for the private sector, which will ultimately use the technology, to be in close communication with the public

R&D managers who fund the work. The close interaction that results from cost-sharing arrangements facilitates the creation of a product that meets commercial preferences. For example, one cost-sharing R&D project concerns the design of PV arrays by attaching modules together. This process has many technical hurdles such as how to provide a constant power flow, which is related to the total amount power output of a single array. Private sector partners have been able to provide public R&D managers with information from their customers about the demand for different sizes of PV arrays. Currently, niche markets in radio transmitters and single unit living units in rural developing areas are a major source of PV array demand. By working together R&D is focused more directly on a future product for which there will be demand.

6.3.1 R&D Funding and Cost-sharing by Technology Stage

In fiscal year 1996 $9.9 million (16%) was allocated to basic research, $23.9 million (39%) to applied research/exploratory development, $22.7 (37%) million to advanced development/engineering development, and $5.0 million (8%) to operational tests/field validations.

In fiscal year 1996 100 percent of basic research R&D costs were borne by the government. Applied research/exploratory development activities were either split 70/30 between DOE and its partners or entirely funded by DOE. Advanced development/engineering development activities were split 50/50, 57/43, or 87/13 between DOE and its partners (GAO 1997). On average, the PV industry's cost-share percentages for the photovoltaic program are 24 percent for applied R&D work and 92 percent for technology development (manufacturing). As can be seen, the private sector's contribution to R&D partnerships increases for projects in the later phases of R&D (GAO 1997). Furthermore, over 95 percent of all procurements are awarded competitively. This data exemplifies the current pattern of funding for cost-sharing R&D activities in DOE R&D programs.

6.4 Weaknesses in Federal R&D Efforts

1) Funds have been spent poorly in terms of solving important technological problems. While Federal R&D funds have resulted in many significant technical innovations, they have not always been focused on technology development. Utility demonstrations were not helpful because the technology being used was so far from cost competitiveness that the demonstrations only took money away from R&D programs. Members of the PV industry agree with this thought since real market penetration into utilities will be the result to cost reduction through R&D, not subsidized demonstrations (DOE 1996). Likewise, many of the international demonstrations have been counterproductive.

2) Not enough funds dedicated to any one technology. Many different technologies exist under the "photovoltaic" umbrella and the technical challenges facing each of them were underestimated in the 1970s. This resulted in overly optimistic expectations of when solar would be commercialized and resulted in lower funding than could have been expected otherwise. This was especially damaging during the 1980s, when funds were spread out to between all PV technologies to keep them all viable resulting in a period of program maintenance, not technological progress (von Roedern 1997). Funding has also never been sustained at a high level and been subject to recissions and changing priorities within DOE.

3) Inadequate Attention Paid to Manufacturing R&D. While no one knows exactly what PV technology will eventually be commercialized on a wide scale for utility use, it will need to be manufactured in large quantities to be low cost. This requires that manufacturing processes be advanced greatly. Manufacturing of PV requires a focus on throughput—the rate at which PV materials or devices are passed through the processes of material deposition, preparation, encapsulation, and connection to electrical components. Examples of manufacturing R&D topics include, automating the assembly process,

reducing the number of steps in a process, and moving from batch processing to continuous processing (DOE 1998).

If the manufacturing issue is not addressed, the U.S. risks losing its lead in PV technology to the Japanese and Germans because they are currently investing more in manufacturing than the U.S. The PVMaT initiative has been an important *first step* to address this issue and is referred to very favorably by members of PV industry and called the "missing link" in past R&D efforts (DOE 1996a). PVMaT has also been successful because of the way the program is organized -- it identifies very specific technological problems and then develops a detailed research plan to be undertaken that is manageable and sets timetables that can actually be met. Furthermore, these efforts are supported with some federal funding and awarded competitively to those most qualified to complete the specific task.

6.5 Recommendations for Future Policy

The most important recommendation for future PV policies is that publicly sponsored R&D continue and be increased. There is no doubt that further technological change is needed for PV to be competitive. Currently PV electricity costs of 35 to 40 cents/kWh are not competitive and demand pull policies will either be too expensive to implement or create an industry reliant on subsidies. PV manufacturers are leery of efforts that "artificially" increase the demand for PV and can be ended just as quickly as they started. The industry is interested in creating a cost competitive technology not dependent on the political mood of Congress or the Executive Branch. The best way to do this is to continue federal R&D programs. This being said, there are some specific recommendations as to how these programs could be improved.

1) *Increase funding of PVMaT and create other programs similar to PVMaT.* Not only is this program successful in terms of the focus, manufacturing, but its structure should be a model for other PV R&D programs. Industry members consistently give the program high marks when compared to previous initiatives (DOE 1996). The creation of other

programs focusing on manufacturing are vital to the future of PVs. Furthermore, the industry is composed of many small firms and PV manufacturing lines are extremely expensive and firms have little ability to conduct their own R&D.

2) *Form a consortium among small PV firms to offset the counterproductive "hyper-competitive environment" that currently exists in the industry.* Small firms dominate the PV industry. Almost of all these firms have a different method of material production, or cell design and guard this proprietary information closely. As a result, there is little information sharing between firms. This is, however, counterproductive because there are many common technical problems faced by all firms. A government-sponsored consortium could facilitate information flow and prevent the duplication of research and development efforts. The program would be open to international firms with the stipulation that knowledge gained through the effort only be used in manufacturing plants based in the U.S. The focus of the consortium would be on pre-competitive technologies where all members of the industry face the same issue. The work would be careful to not take away any competitive advantage a firm currently has and work on mutually agreed upon topics.

3) *Form a better review-board to gain a "more independent" method for awarding contracts and "technology selection" in general.* One of the strengths of the PV industry is the fact that there are many different technological pathways being pursued in the industry. Each firm has a strategy as to what it thinks will be a viable low-cost technology. The federal PV program has supported this process by funding many different PV technological pathways. This has, however, created an unfortunate problem. When competitive contracts are awarded, it is difficult to find independent reviewers of technology that do not have a bias towards a certain technology, such as a-Si, CIS, or CdTe. This leaves federal managers unable to consult outside private sector input in the assessment of project proposals. This problem could be better addressed by creating review boards composed of past NREL program managers who are now industry analysts. Although

there are not a large number of these types of individuals, they would be more independent and better able to see the "big picture" in the industry and where future R&D efforts should be directed.

6.6 Further Research

The conclusions of this paper could be expanded upon and reinforced with further research into the history of each of the PV innovations described in the thesis. Given the complexity of the technology and its basis in materials science, there is much to be learned from the origin of PV innovations. The paper could be developed further with additional conversations with those in the field, who have a better context in which to place innovations and the history of federal R&D policies. Furthermore, private sector work of the late 1970s has no doubt has a large impact on today's PV technology, but private sector R&D data and efforts are difficult to investigate.

References

Abernathy, W. J and J. Utterback (1978). "Patterns of Industrial Innovation." *Technology Review* **80**: 40-47.

Ahmed, K. (1994). *Renewable Energy Technologies: A Review of the Status and Costs of Selected Technologies*. World Bank, Washington, D.C.

Anderson, J. (1980). *Wire Saw for Low Damage, Low Kerf Loss Wafering*. 14th IEEE Photovoltaic Specialists Conference, San Diego, CA, IEEE.

Boes, E., and A. Luque. (1993). Photovoltaic Concentrator Technology. *Renewable Energy: Sources for Fuels and Electricity*. H. K. Thomas Johansson, Amulya Reddy, Robert Williams. Washington, D.C., Island Press.

Boyle, G. (1996). *Renewable Energy: Power for a Sustainable Future*. Oxford, Oxford University Press.

Bozeman, B. and A. Link (1984). *Strategic Management of Industrial R&D*. Lexington, MA, Lexington Books.

Branscomb, L. (1993). *Empowering Technology*. Cambridge, MA, MIT Press.

Branscomb, L. (1997). "From Technology Politics to Technology Policy." *Issues in Science and Technololgy* Spring 1997 41-48.

Branscomb L. and G. Parker (1993) Funding Civilian and Dual-Use Industrial Technology. *Empowering Technology*. R. Branscomb, Cambridge, MA, MIT Press.

Carlson, D. and S. Wagner. (1993). Amorphous Silicon Photovoltaic Systems. *Renewable Energy: Sources for Fuels and Electricity*. H. K. Thomas Johansson, Amulya Reddy, Robert Williams. Washington, D.C., Island Press.

Chitre, S. R. (1978). *A High Volume Cost Efficient Production Macrostructuring Process*. 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., IEEE.

Czanderna, A. W., Pern, F.J., and S. Glick (1996). *PV Module Materials and Encapsulation Research*. 13th NREL Photovoltaics Program Review, Lakewood, CO, American Institute of Physics.

Dertouzos, M. L., et. al. (1989). *Made in America: Regaining the Productive Edge*. Cambridge, MA, MIT Press.

DOE (1991). *Photovoltaic Fundamentals*, SERI.

DOE (1996a). *U.S. Department of Energy (DOE) Assessment of the Photovoltaic (PV) Industry's Needs, Priorities, and Views Regarding the DOE Photovoltaic Program*. Department of Energy (DOE/GO-10096-258).

DOE (1996b). *Photovoltaic Energy Program Overview Fiscal Year 1995*. Department of Energy (DOE/GO-10096-257).

DOE (1997). *Photovoltaic Energy Program Overview Fiscal Year 1996*. Department of Energy (DOE/GO-10097-365).

DOE (1998). May 8, 1998. http://www.eren.doe.gov/pv/materials.html.

EIA (1995). *Annual Energy Review* 1994. Energy Information Administration (DOE/IEA-0384(94)).

EIA (1996). *The Changing Structure of the Electric Power Industry: An Update*. Energy Information Administration (DOE/EIA-0562(96)).

EIA (1993). *Federal Energy Subsidies--Direct and Indirect Interventions in Energy Markets*. Energy Information Administration (DOE/IEA -EMEU/92-02).

Frisson, L., et. al. (1983). *The Integral Screen Printing Solar Cell Technology in an Industrial Environment*. 5th E.C. Photovoltaic Solar Energy Conference, Athens, Greece.

GAO (1997). *Solar and Renewable Resources Technologies Program*. General Accounting Office (GAO/RCED-97-188).

Gates, W. (1988). "Federally Supported Commercial Technology Development: Solar Thermal Technologies 1970-1982." *Research Policy* 17 (1988) 27-42.

Golob, R. and E. Brus (1993). *The Almanac of Renewable Energy*. New York, H. Holt.

Green, M. (1982). *Solar Cells*. Englewood Cliffs, N.J., Prentice-Hall.

Green, M. (1990). Photovoltaics: Coming of Age. 21st IEEE Photovoltaic Specialists Conference, Orlando, Florida. IEEE.

Green, M. (1991). *Present Status of Buried Contact Solar Cells*. 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, Nevada. IEEE.

Green, M. (1993). Cyrstalline- and Polycrystalline- Silicon Solar Cells. *Renewable Energy: Sources for Fuels and Electricity*. H. K. Thomas Johansson, Amulya Reddy, Robert Williams. Washington, D.C., Island Press.

Green, M. (1995). Silicon Cells: Single Junction, One Sun, Terrestrial, and Single and Multiple Crystalline. *Solar Cells and Their Applications*. L. Partain. New York, John Wiley & Sons, Inc.

Kazmerski, L. (1997). "Photovoltaics: A Review of Cell and Module Technologies." *Renewable and Sustainable Energy Reviews* **1**(1/2): 71-170.

Keller, W. (1981). *Floating-zone Silicon*. New York, Marcel Dekker.

Kelly, H. (1993). Introduction to Photovoltaic Technology. *Renewable Energy: Sources for Fuels and Electricity*. H. K. Thomas Johansson, Amulya Reddy, Robert Williams. Washington, D.C., Island Press.

Kozloff, K. (1993). *A New Power Base: Renewable Energy Policies for the Nineties and Beyond*. Washington, D.C., World Resources Institute.

Kurtz, S. (1996). *Recent Developments in Terrestrial Concentrator Photovoltaics*. NREL/SNL Photovotlaics Program Review, Lakewood, CO, American Institute of Physics.

Linden, L. et. al. (1977). *The Solar Photovoltaics Industry: The Status and Evolution of the Technology and the Institutions*. MIT Energy Laboratory Report (MIT-EL-77-021).

Loiter, J. (1997). *Technological Change and Public Policy: A Case Study of the Wind Energy Industry*. Masters Thesis. Massachusetts Institute of Technology.

Mackintosh, B. H. (1978). *Multiple Silicon Ribbon Growth by EFG*. 13th IEEE Photovoltaic Specialists Conference, Washington, D.C. IEEE.

Mason, N. B., D. Jordan (1991). *A High Efficiency Silicon Solar Cell Production Technology*. Proceedings of the International Conference, Lisbon Portugal.

Mazer, J. (1997). *Solar Cells: An Introduction to Crystalline Photovoltaic Technology*. Norwell, Massachusetts, Kluwer Academic Publishers.

National Science Foundation (1968). *Technology in Retrospect and Critical Events in Science*. NSF.

National Science Foundation (1996). *Science and Technology Pocket Data Book*. NSF 96-325.

Nelson, R. R. (1982). Government Stimulus of Technological Process: Lessons from American History. *Government and Technical Progress: A Cross-Industry Analysis*. R. R. Nelson. New York, Pergamon Press.

Norberg-Bohm, V. (1997). *Stimulating "Green" Technological Innovation: An Analysis of Alternative Policy Mechanisms*. Massachusetts Institute of Technology (unpublished working paper).

Roessner, J. D. (1984). "Commercializing Solar Technology: The Government Role." *Research Policy* **13** (1984) 235-246.

Rothwell (1981). "Some Indirect Impacts of Government Regulation on Industrial Innovation in the United States." *Technological Forecasting and Social Change* **19**: 57-80.

SEIA. (1995). *Solar Industry Journal*. Third Quarter, 1995. Solar Energy Industry Association.

Seidensticker, D., et. al. (1978). *Computer Modeling of Dendritic Web Growth Processes and Characterization of the Material*. 13th IEEE Photovoltaic Specialists Conference, Washington, D.C.

SolarDome (1996). April 13, 1998. http://www.solardome.com/SolarDome19.html.

Solow, R. (1958). "Technical Change and the Aggregate Production Function." *Review of Economics and Statistics* **39**: 312.

Stafford, B. L., W. Luft, et al. (1991). *The U.S. DOE/NREL Amorphous Silicon Photovoltaics Program*. 22nd IEEE Photovoltaic Specialists Conference, Las Vegas, Nevada. IEEE.

Surek, T. (1992). *Overview of NREL's Photovoltaic Advanced R&D Project*, NREL.

Surek, T. (1993). *The State of the Art of Thin-Film Photovoltaics*. NREL.

Taylor, A. (1987). "Long Nonagons -- An Approach to High Productivity Silicon Sheet Using the EFG Method." *Journal of Crystal Growth* **82**: 134-141.

von Roedern, B. (1997) NREL. Personal Communication, December 18, 1997.

von Roedern, B. (1998) NREL. Personal Communication, February 28, 1998.

Watts, R. L. and S. A. Smith (1988). *Photovoltaic Industry Progress from 1980 through 1987*. Pacific Northwest Laboratory, Richland, Washington.

Winter, C. J. et. al. (1991). *Solar Power Plants*. Springer-Verlag: Berlin.

Wright, B. (1983). "The Economics of Invention Incentives: Patents, Prizes, and Research Contracts." *The American Economic Review* September: 691-707.

Zweibel, K. (1993). Polycrystalline Thin-film Photovoltaics. *Renewable Energy: Sources for Fuels and Electricity.* H. K. Thomas Johansson, Amulya Reddy, Robert Williams. Washington, D.C., Island Press.

Zweibel, K. (1997) *Utility-Scale Flat-Plate Thin Film PV Systems.* NREL.