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Solar Energy Research and Development in California

Brett T. Close
Pomona College

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Professors David M. Tanenbaum

and David J. Menefee-Libey

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Brett T. Close

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Pomona College

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Introduction

At the start of the nuclear era there was a saying that in the future, nuclear energy would be a clean source of energy that was so cheap that it "would not be worth metering." That optimistic forecast has turned out not to be true and is unlikely ever to become so. California, and indeed the entire United States, remains addicted to fossil fuels for all forms of energy, including electricity. As the hold of fossil fuels remains strong and even increases, evidence that use of fossil fuels is harmful to our economy, our health and our environment is becoming clear.

There is a growing awareness about energy issues in California. The energy crisis in 2001, continued high prices for gasoline and electricity, and record high temperatures are all keeping energy issues in the minds of Californians and Americans in every state. High prices for energy and power disruptions not only cause inconvenience, but also raise prices for nearly everything we buy, diminishing real disposable income and hurting economic growth. If climate change continues to increase as projected, heat waves and catastrophic wildfire are likely to increase. The problems are clear; the next step is finding and implementing solutions. The direct sunlight that falls on Los Angeles an average of 340 days per year has vast potential to mitigate the negative effects of high energy prices and climate change. By turning sunshine into electricity, using both solar photovoltaic and solar thermal generation, we can reduce dependence on fossil fuels, increase energy security, help the environment and the economy, and improve public health. Unfortunately, many scientific and technological barriers remain to widespread

deployment of solar power. What should the state of California do regarding research, development and demonstration to increase the amount of solar energy generated effectively and in a fiscally responsible manner?

In the following paragraphs of this introduction I will outline the problems in California that solar power could address and the ways in which solar power could address them, noting current limitations of solar energy. Then I will explain the policy analytic model I will be using. Finally I will explain the methodology and analysis of this study.

The Problems

There are many problems facing California today. These include climate change, with it associated shifts in weather patters, increase in severe weather and drought, sea-level rise and endangerment of biodiversity; environmental degradation from pollutants including sulfur dioxide, oxides of nitrogen, and particulate matter; and negative effects on the economy due to high energy prices, the need to import fuel, and inability to meet peak energy demands. Each of these specific problems is addressed by use of solar energy rather than fossil fuel-based energy.

Signs of global climate change are clear.   The accuracy of the predictions that climate scientists have been making for years is becoming more and more obvious, even to the causal observer. Worldwide, average temperatures are 1° F higher than they were

100 years ago.[1]   Visitors to glaciers and ice fields find that they are receding at unprecedented rates.

Carbon dioxide (CO_2) is the most prevalent greenhouse gas (GHG), the driving forces behind climate change. The bonds in CO_2 and other GHGs let sunlight pass through them, and when that sunlight hits the earth, some is reradiated at lower energy. GHGs absorb that lower-energy radiation, preventing it from leaving the atmosphere. CO_2 concentrations are currently the highest on record; while the current level is 377 parts per million by volume (ppmv), the level had not risen above 300 ppmv in the last 650,000 years.[2]   Other GHG concentrations are also higher than any time on record.

Climate change, also commonly referred to as global warming, is much more than just warming. It is a widespread shift in climate patterns. Climate change may have a variety of negative consequences. First, it may cause more severe weather, including storms and droughts, that will disrupt primary production of agricultural products and other renewable natural resources. As shown by hurricanes Katrina and Rita in 2005, storms can also disrupt the production of other sectors of the economy, such as petroleum refining. Second, an increase in global temperature will most likely cause sea level to rise. As far back as 1997, President Clinton, in supporting a national program to increase use of solar energy, cited the possibility of a two-foot rise in sea level: "In America, that means 9,000 square miles of Florida, Louisiana and other coastal areas will be flooded," as well as many other places internationally.[3]   Third, as temperatures rise and weather

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[1] Moore, Lisa and Karen Douglas, "Global Warming and the Golden State: A Call to Action." Environmental Defense, 2006.
[2] Siegenthaler, Urs et al., "Stable Carbon Cycle-Climate Relationship During the Late Pleistocene." *Science*, vol. 310, pp. 1313-1317. November 25, 2005.
[3] Clinton, William Jefferson. Speech before U.N. Session on Environment and Development. 6/26/97.

patterns change, many plants and animals have to change with the changing environment. Some cannot adapt fast enough, such as the highly temperature-sensitive coral reefs that are now dying.

Presently, California's electrical mix is highly biased towards the fossil fuels that contribute to climate change (see Figure 1). [4] In 2005, 57.8% of California's power came from non-renewable fossil fuels (20.1% coal and 38.7% natural gas). This portion has been rising, especially regarding coal. While inexpensive and abundant, coal is the worst offender in the realm of climate change. The remainder of California's power supply comes from large hydro plants (17%, defined as dams producing over 30 MW and by law not considered a renewable power source), nuclear (14.5%) and renewables (10.7%).

Figure 1. [5]

California Gross System Power

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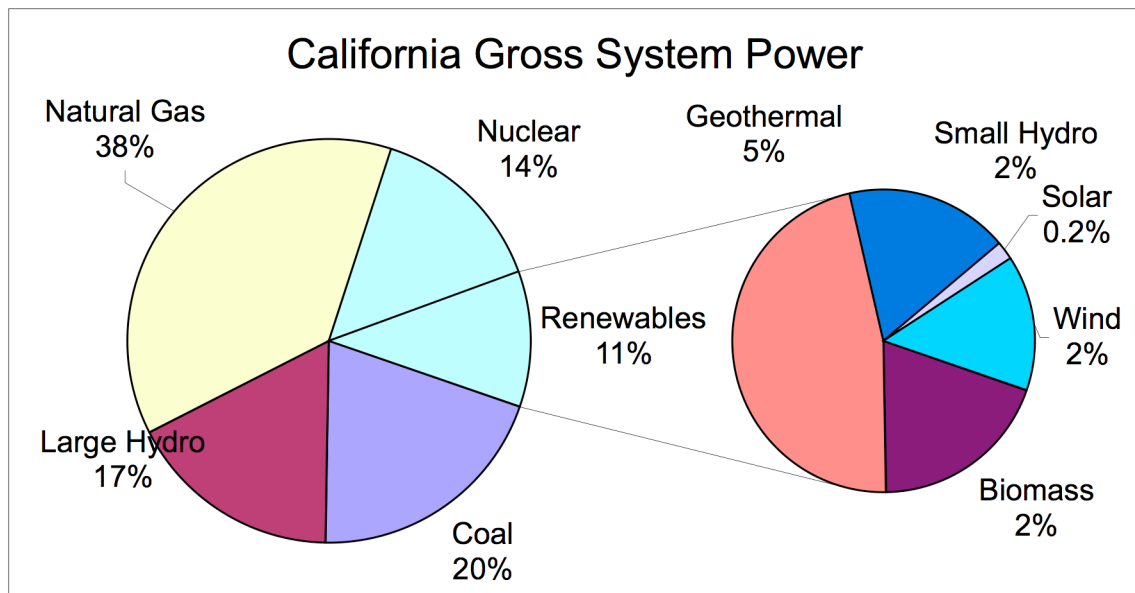
[4] California Energy Commission. "Net System Power: A Small Share of Califronia's Power Mix in 2005." Document CEC-300-2006-009-F. April 2006.
[5] California Energy Commission. "Net System Power: A Small Share of Califronia's Power Mix in 2005." Document CEC-300-2006-009-F. April 2006.

In addition to CO_2, fossil fuel combustion for electrical generation produces many other pollutants. Coal plants produce large amounts of sulfur dioxide (SO2), one of the major sources of acid rain. The high temperatures involved in any large combustion reaction create oxides of nitrogen (NOx), which contribute to smog. In addition, the high temperatures associated with climate change exacerbate the problems of smog. Asthma and other respiratory diseases have been linked to the particulate matter (PM) that is emitted by coal power plants.

At this point, California has some of the highest electricity prices in the nation.[6] The California Energy Commission projects that the price of electricity will remain roughly steady over the next seven years, never falling to pre-2001 price levels.[7] Although the future price trend is unclear, the price is unlikely ever to reach the low levels consumers enjoyed previously. California average electrical prices from 1991 to 2005 are shown in Figure 2. Electricity prices jumped after the deregulation attempt ended investor owned utilities' monopoly of electricity retail. This policy was enacted as a continuation of federal policies that were trying to bring more competition into regulated utility markets. In order to increase competition, Energy Service Providers (ESPs) were allowed to sell retail electricity so that consumers could decide between regulated utilities, which had traditionally held retail monopoly within distinct geographic regions. In order to ensure energy access to the ESPs, the investor-owned utilities were forced to divest all of their gas power plants to independent companies. A

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[6] Energy Information Administration. http://www.eia.doe.gov/cneaf/electricity/epa/epat7p4.html. Accessed 4/15/07.
[7] California Energy Commission. "Electricity in California." http://www.energy.ca.gov/electricity/#rates. Accessed 11/18/06.

number of other related events led to electricity prices rising precipitously and to shortages of energy.

Figure 2.[8]
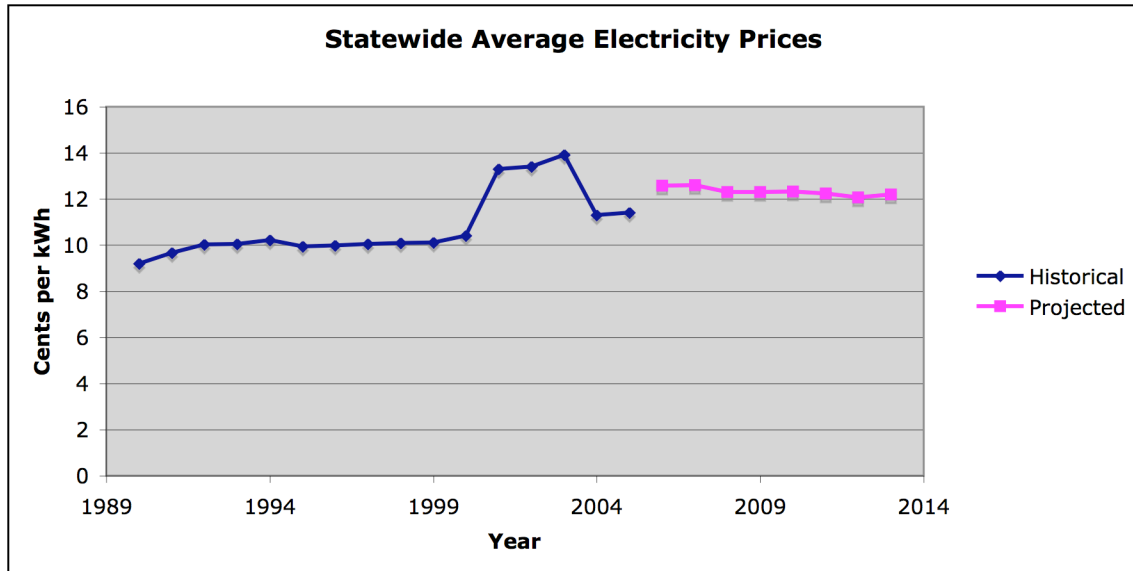
Given the United States' huge economic and societal reliance on energy, energy security is a key element in protecting California and the United States. In the past, increases in the price of energy have led to economic recessions. The effects of energy prices on inflation are well documented; according to the U.S. Department of Energy, "The pressure of energy prices on aggregate prices in the economy created adjustment problems for the economy as a whole,"[9] and according to the Congressional Budget Office, "The recent increases in energy prices have dampened economic growth in the United States."[10] Electricity is used by all households and businesses, meaning high

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[8] California Energy Commission. "Electricity in California." http://www.energy.ca.gov/electricity/#rates. Accessed 11/18/06.
[9] Energy Information Administration. "Energy Price Impacts on the US Economy." http://www.eia.doe.gov/oiaf/economy/energy_price.html, accessed 12/6/06.
[10] Congressional Budget Office. " The Economic Effects of Recent Increases in Energy Prices." July 2006.

electricity costs affect disposable incomes and thus disproportionately affect people with smaller incomes.

The United States imports a great deal of its energy from abroad. Most of this comes in the form of oil, but we also import natural gas. With declining domestic production and increasing demand, imports of natural gas are expected to increase.[11] California in particular brings in much of its energy from outside, which contributes to the state's trade deficit as money flows out of the state for energy, dampening economic growth.

California also has a shortage of energy transmission capacity. According to Paul Wuebben, the Clean Fuels Officer at the South Coast Air Quality Management District, the blackouts in the summer of 2006 were due to a problem of transmission capacity, not of generation capacity.[12] Transmission capacity is a major additional expense and incurs stiff opposition from those whose property would have to support the power lines, which are a major aesthetic blight on the landscape.

Part of the Solution

Solar energy, both solar photovoltaic and solar thermal, could be a major part of the solution to the problems laid out above. Solar energy production emits vastly less GHGs, SO_2, NO_x and PM, and has the potential to be a low cost, reliable distributed energy source. Each of these issues will be addressed in turn.

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[11] Energy Information Administration. "Energy Outlook 2006." February 2006.
[12] Personal contact.

Solar energy has no emissions during the process of generation. Over the entire life of a solar panel, CO_2 emissions come to about 0.22-0.37 lbs/kWh.[13] This was estimated by a life-cycle analysis (LCA) that looks at every step involved in creation and use of a good or service. Coal power produces over two pounds of CO_2 per kWh and natural gas produces about 1.3 pounds.[14] LCA is an important concept for alternative energy and other environmental issues because it better summarizes the total effect of the production method and puts emphasis on a holistic view of the economy, which is necessary for analyzing the real costs and benefits of any product. LCA also illuminates an important caveat for solar photovoltaics – while relatively small amounts of SO_2, NO_x and PM are created during production of photovoltaic cells, other noxious chemicals, generally not released into the atmosphere, are involved.[15]

One of the main benefits of solar energy is that there is no fuel cost. With fuel costs expected to rise into the future as supply tightens, this will likely make the attractiveness of solar energy only increase with time. However, solar energy does have a greatly increased capital cost that constitutes a possibly prohibitive barrier. A shift from operating costs to capital costs when paying for energy is a major paradigm shift that is necessary for a transition to solar and other renewable energies.

As a benefit of solar photovoltaic power, more of the total cost is likely to remain in the community. With fossil fuel power, the money for fuel is likely to leave the community, if not the country. While the United States has major coal reserves, most are

[13] International Energy Agency, "Benign Energy?: The Environmental Implications of Renewables." 1998.
[14] EERE, "Geothermal Technology Program: Geothermal Power Plants." http://www1.eere.energy.gov/geothermal/geopower_cleanair.html. Accessed 10/10/06.
[15] International Energy Agency, "Benign Energy?: The Environmental Implications of Renewables." 1998.

in the eastern part of the country, and while we have major natural gas reserves, we still import natural gas from Canada. California could be an important producer of solar energy products that would keep revenue in the state. The combination of subsidies to support the purchase of solar energy technologies as well as support for research and development are likely to increase the incentive for production within the state. Also, design, installation and maintenance costs are likely to stay in the community. Keeping money in the community benefits the local economy as a whole through the multiplier effect. The benefit holds as long as the levelized (average over an appropriate time period) cost of energy is equivalent to that of non-local fossil energy, meaning that there is no comparative advantage to be gained from trading. Solar energy companies can also provide major job growth. According to Jaeger-Waldau:

> The [German] Photovoltaic industry accounted for approximately 30,000 jobs in 2005. According to an industry survey, amongst renewable energy companies, every second company plans to increase the number of employees by 30 to 100% with the next 5 years. Photovoltaic companies are amongst the most optimistic ones and in total expect doubling of employment by 2010. In 2005 Photovoltaics accounted for a turnover in Germany of € 3 billion and 70% of the added value remained inside Germany.[16]

Clearly, photovoltaics could produce economic benefits beyond potential future cost reduction.

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[16] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Commission DG Joint Research Centre: Ispra, Italy, August 2006.

Photovoltaic power also has the potential, though not the necessity, to be a distributed energy technology. Distributed energy generation is any power source that is close to where the energy is used (the load), unlike the central generation model of power plants that tend to be far from the load with power lines to bring the electricity to the load. Although photovoltaic power can be used in a centralized power plant application, it is most commonly used in small amounts in distributed applications. Distributed generation reduces the electrical losses associated with transmission, as power is dissipated by the electrical resistance of power lines. Distributed generation also precludes the necessity of building new transmission capacity and relieves transmission congestion.

Solar photovoltaic power is ideally suited to distributed generation because generation capacity is modular; that is, it can be installed in relatively small discrete amounts, one panel at a time. This is in contrast to a coal or natural gas power plant that must be very large to be cost effective. And unlike wind power, which is also modular, though not traditionally in the same small units, solar resources in California are close to load, since sun shines on the buildings that need power. Wind resource is greatest in rural areas that do not have buildings blocking the wind. The solar resource of California is immense. California used 254.2 TWh (254.2×10^9 kWh) of electricity in 2005, and could meet its average electrical needs (real time needs are more complicated) with just 447 square miles of solar sites, or 0.3% of the state's area.[17] This is an area slightly smaller that the City of Los Angeles, not including other cities within the Los Angeles metropolitan area.

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[17] Wuebben, Paul. Presentation to the Valley Industry and Commerce Association Forum on Climate Change. October, 2005.

A Caveat

Although solar has a great deal of potential benefits, there are still problems that need to be worked out. At this point, solar energy is very capital intensive, and is not always available. Solar photovoltaic cells' efficiencies are well below the theoretical limits and solar thermal power is not well known. All of these problems can be addressed by research, development and demonstration.

As mentioned above, solar energy requires no fuel, but it is not free. A great deal of money is needed to pay for the initial capital cost of building solar panels or power plants. With uncertainty in future fuel prices, heavy capital investment to avoid fuel costs is risky.

Because the sun does not shine all the time, the intermittency of solar energy must be overcome. Intermittency is problematic for utility operators who must continually balance the amount of energy put onto the power grid and the load being used. Thermal storage is a way to deal with this problem in solar thermal power plants by maintaining a heat source even when there is no incident sunlight.

The efficiencies of solar cells have increased over the past thirty years, but there is still more room for improvement. Low energy efficiencies and high costs make solar panels less attractive to potential consumers. Solar thermal generation is projected to be cost effective, but is not yet common. As it becomes better understood by utilities and power companies, it will become a less risky prospect and is likely to become more common.

Research, development and demonstration in solar energy have the potential to address these shortcomings. Improvements in the technology and processing brought about by research and development (R&D) could significantly decrease the cost of material production. Improvement in thermal storage technology could continue to make solar thermal more reliable, and R&D will bring about overall increased solar efficiency. Demonstration projects will increase the visibility of solar thermal projects in the utility community. Thus, research, development and demonstration are an important part of harnessing solar energy as a valuable resource.

Variables

This paper seeks to answer the question, "What should the state of California do regarding research, development and demonstration to increase the amount of solar energy generated effectively and in a fiscally responsible manner?" I will use a variation of the policy analytic framework that looks at an independent variable influencing a dependent variable in the presence of intervening variables, which are the processes that occur between the dependent and independent variables. Instead I will consider an independent variable that affects the dependent variable, which will in turn effect subsequent processes toward reaching an ultimate goal. The reason for this is to specifically target R&D as means for increasing solar generation, while understanding how R&D could lead to increased solar generation.

The independent variable will be state action because that defines the set of tools that the state of California can use. The dependent variable will be technological activity in solar energy. The subsequent processes, equivalent to intervening variables but no

longer intervening between the independent and dependent variables, will be technological learning and knowledge diffusion. Each of these will be explained briefly in this section and fleshed out in greater detail in Chapter 1.

Generally, there are four main policy tools available to policy makers: rules, incentives, disincentives and direct action. Each of these policy tools can be used to achieve the same policy end, but each has different benefits, drawbacks, and side effects.[18] Rules involve any mandate that requires a certain type of behavior. For example, the state could mandate a certain percentage of profit be spent on R&D. Incentives encourage desired behavior, such as a tax credit for spending on R&D. This reduces the total tax burden, making the spending more desirable. Disincentives try to prevent or decrease undesired behavior, and thus indirectly increasing desired behavior. An example would be a carbon tax that increases the cost of fossil fuel generated energy, thus favoring non-carbon generating technologies, such as solar energy. Direct action, such as research and development carried out in a government lab, involves the state actually carrying out the action to achieve a desired result. Each of the policy tools can also be used in conjunction with the others. Generally, a rule must be combined with some disincentive, such as a fee for non-compliance, to be effective. Each of these policy tools can also be used in different ways. For example, there could be an incentive to use solar power, or an incentive on researching solar power. Both are ultimately likely to increase the total use of solar energy.

The dependent variable has two parts, the first of which is technological activity. A different possible measure of this would be the total amount of solar energy generated.

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[18] Jaffe, A. B., R. G. Newell, and R. N. Stavins. "Environmental Policy and Technological Change." *Environmental & Resource Economics* 22.1-2 (2002): 41-69.

The problem with this is that it gives no indication of whether the state action has made solar energy more market ready, or simply artificially forced it onto the market. Instead, this must be the ultimate goal of the policy. The price of solar energy products, such as solar panels and solar power plants, would be another choice. It shows how market ready solar energy would be even if state support ended. Unfortunately, we would be unable to determine what the effects of a RD&D policy would be because of existing policy that is aimed at reducing the price. Thus, patenting and R&D spending are the best choice. These are the standard measures of technological activity.

The second dependent variable is technological learning. Technological learning is the process by which firms improve their ability to produce a good or service, thereby decreasing the cost, and ultimately the price. The cost is the amount of money required by the firm to produce the good and the price is what is charged to the consumer. The most basic and simplified model of technological learning deals solely with "learning by doing." Learning by doing is the process of producing the good and improving with practice. For example, as more of a good is produced, businesses refine the production process so that it can proceed faster and with less wasted resources. The cost of a good tends to follow a power law as a function of the cumulative capacity, the total amount of the good that has been produced.[19] This means that the cost tends to fall by a certain fraction for every doubling of the cumulative capacity. This fraction tends to be constant over many doublings of the cumulative capacity.[20] Technological activity corresponds to

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[19] Kobos, P. H., J. D. Erickson, and T. E. Drennen. "Technological Learning and Renewable Energy Costs: Implications for US Renewable Energy Policy." *Energy Policy* 34.13 (2006): 1645-58.

[20] Algoso, Dave, Mary Braun and Bernadette Del Chiaro. *Bringing Solar to Scale: California's Opportunity to Create a Thriving, Self-Sustaining Residential Solar Market*. Environment California, Los Angeles: April 2005.

research, and technological learning, in its more complex manifestation explained in the next chapter, corresponds to development.

Knowledge diffusion will be the first subsequent process. It takes time for technology to diffuse into an industry. There are various different models to describe this process. The most popular theory describes knowledge diffusion in a similar fashion to population growth with a carrying capacity. That is, it starts slowly and as the technology diffuses further, the rate of diffusion increases, much as growth increases with population.[21] But there is also a total technological capacity, equivalent to the potential for the technology to be used within the industry. As the technological diffusion approaches this point, the rate of diffusion decreases, and the total level of diffusion approaches the technological capacity asymptotically.

As mentioned above, the ultimate goal of the policy is increased production of solar energy. I have created **Error! Reference source not found.** below as a schematic of the flow of the policy analytic model.

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[21] Lund, P. D. "Analysis of Energy Technology Changes and Associated Costs." *International Journal of Energy Research* 30.12 (2006): 967-84.

Figure 3. Policy Analytic Model

Independent Variable Policy tools: Rule Incentive Disincentive Direct action Inaction	→	Dependent Variable Knowledge Creation Research	→	Dependent Variable Technological Learning Development	→	Subsequent Process Technological Diffusion	→	Ultimate Goal Increased production of solar energy
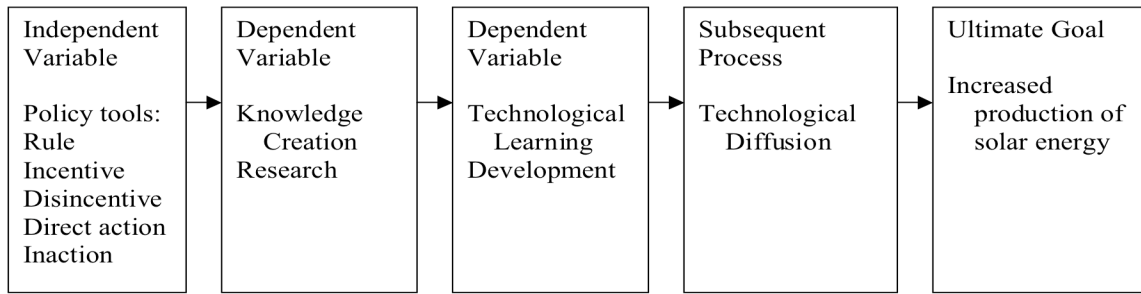
Methodology and Analysis

This study is primarily meant to create an applied theory for considering solar energy RD&D policy, rather than test a hypothesis. The data at this point in time are too scarce for testing and the constraints of this study too great to successfully test a hypothesis. The research and analysis will thus revolve around understand the market realities and all the economic and physical processes involved.

The methodology for the study will have two main components, literature review and data collection. The literature review will have two parts. Chapter 1 focuses on understanding the nature of each of the variables outlined above. Chapter 2 will also look at the process of harnessing solar energy. Understanding that process is necessary for understanding where research has the greatest capacity to improve the cost-effectiveness of the process.

The data collection will be both quantitative and qualitative. Information is available from the Energy Information Administration (EIA), the statistics division of the U.S. Department of Energy (DOE); from the many companies that have information on their websites; and from researchers like Arnulf Jäger-Waldau. These sources provide information on price, cost, and efficiency and the nature of the industry and policy.

Google Patents is a searchable database of all U.S. patents. This will be used to better understand the current state of the research.

Chapter 3 will lay out information about the state of the market. This will include the producers, the state of technology in use, the relevant existing policies and research and development and patenting activity.

In Chapter 4, I will consider policy recommendations. I will consider the reasons for creating a policy, as well as the reasons for maintaining the status quo. Policies will have to take into account the political landscape. Only policy changes that will have a possibility of gaining public support will be recommended. These include policies that are fiscally responsible, likely to produce positive results and unlikely to draw major opposition from industry, or environmental or consumer advocacy groups. My recommendations will be targeted to the California Public Utilities Commission, the California Energy Commission and the California Office of the Governor.

Chapter 1: Theory on Technological Learning and Diffusion

This chapter will discuss policy and economic literature about technology change. I will begin by giving an overview of the technology change process. Then I will explain in greater detail how research, development and technological learning take place, followed by an explanation of how technological activity is measured. Finally I will discuss theories of technology diffusion and the policy implications of the research.

The Process of Technology Change

Technological change is important to understand because it is fundamentally what we are trying to affect with a potential policy. The formative work on technological change was done by Joseph Schumpeter in the early 1940s.[22] He described the process as three steps, invention, innovation and diffusion. The first two stages of this process are in essence the dependent variable in the policy analytic model I am using. Invention is the creation of new knowledge that leads to a new product or production process. Innovation is the improvement of the new product or production process for commercialization. Diffusion is the process whereby the product or process reaches the buyers in the market. Although this is appears as a linear process by the above description, in reality it is far

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[22] Jaffe, A. B., Newell, R. G. and Stavins, R. N. Environmental policy and technological change. *Environmental and Resource Economics*. June 2002, 22, 1-2, p. 41.

from linear. Many inventions never reach the innovation stage and many innovations never completely diffuse throughout the market. Also, each process feeds back on the previous ones as greater understanding of the product or process leads to more research.

The invention stage of the process is largely enacted through research. Research is defined as "systematic study directed toward fuller scientific knowledge or understanding of the subject studied." [23] Research is generally considered to have two components, basic research and applied research. Basic research aims to "gain fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind." Applied research attempts to gain knowledge or understanding that will allow a specific need to be met. In essence, basic research is commonly thought of as science, and applied research is commonly thought of as technology. According to Stoneman, science produces public goods, technology produces private goods.[24]

Innovation happens primarily through development. Development is "the systematic application of knowledge or understanding directed toward the production of materials, devices, and systems or methods, including design, development, and improvement of prototypes and new processes to meet specific requirements."[25] Research and development are often combined and occur primarily in private firms.[26] R&D is not the only source of technological improvement. It can also come from learning, design,

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[23] Eisman, Elisa, Kei Koizumi and Donna Fossum. "Federal Investment in R&D." RAND Corporation, MR1639.0-OSTP: September 2002.

[24] Stoneman, Paul. "Introduction." Handbook of the Economics of Innovation and Technological Change. Paul Stoneman, ed.

[25] Eisman, Elisa, Kei Koizumi and Donna Fossum. "Federal Investment in R&D." RAND Corporation, MR1639.0-OSTP: September 2002.

[26] Jaffe, A. B., Newell, R. G. and Stavins, R. N. "Environmental policy and technological change." *Environmental and Resource Economics*. June 2002, 22, 1-2, p. 41.

reverse engineering and imitation, and it can spill over from one area to another.[27] These two processes just described constitute the technological activity that is the dependent variable of this study.

Technological learning is a blanket term for the process by which products and processes improve. The two parts of technological learning are referred to as "learning by doing" and "learning by searching." Learning by searching is essentially R&D. Learning by doing is the process by which simply producing more product streamlines production, and if applicable installation, driving down the price.

Theories of Research and Development

There are two main theories of firms' decisions to undertake R&D, induced innovation and the evolutionary approach.[28] There are also problematic policy issues with R&D. These include the issue of trends in funding, and the public good attributes of R&D.

According to induced innovation, technological change happens as firms engage in R&D as a form of investment to maximize their profits. The evolutionary approaches holds that because of the uncertainty of R&D returns, firms engage in "satisficing" rather than optimizing behavior, using arbitrary guides or rules of thumb to make research funding decisions.

Despite the important role of research and development, funding for R&D has

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[27] Stoneman, Paul. "Introduction." *Handbook of the Economics of Innovation and Technological Change*. Paul Stoneman, ed.

[28] Jaffe, A. B., Newell, R. G. and Stavins, R. N. "Environmental policy and technological change." *Environmental and Resource Economics*. June 2002, 22, 1-2, p. 41.

lagged. Although funding for general R&D has continued to grow over the years in nominal terms, it has been outpaced by economic growth. Particularly in energy R&D, total funding has declined steeply over the past 30 years in terms of both private and public funding.[29]

Additionally, research and development has many of the attributes of a public good, which leads the market to produce less than the socially optimum amount.[30] A public good is one that is non-rival in consumption and non-excludable so that the consumption by one additional person does not diminish the enjoyment of other consumers and it is difficult to stop others from consuming it. Of course, the patent system can serve to counteract the non-excludability, but reverse engineering and other forms of technology spill-over, as well as the limited life-span of the patent, mean that the firm that pays for the R&D may not be able to recoup all the benefit. There is also a great deal of uncertainty when using R&D as a form of investment. The cost are sunk, and the benefits can be specialized and intangible, and so cannot be leveraged or mortgaged.[31] Any investment decision must then consider the potential benefits of R&D against the opportunity to invest in new equipment or some other desirable investment with a higher certainty of returns in a short-term timeline.

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[29] Kobos, P. H., Erickson, J. D. and Drennen, T. E. "Technological learning and renewable energy costs: implications for US renewable energy policy." *Energy Policy* 34, pp. 1645-1658, 2006.
[30] Hall, Bronwyn and John Van Reenen. "How effective are fiscal incentives for R&D? A review of the evidence." *Research Policy* 29, pp. 449-469: 2000.
[31] Jaffe, A. B., Newell, R. G. and Stavins, R. N. "Environmental policy and technological change." *Environmental and Resource Economics*. June 2002, 22, 1-2, p. 41.

"Learning by Doing"

The adage "practice makes perfect" has a certain amount of applicability in production. Practice does not necessarily make perfect, but it does make cheaper. Empirical evidence from a wide array of industries shows that increasing the total amount of a good produced decreases the price.

This makes sense when one considers what is happening. As the total amount of a good that has been produced, the cumulative capacity, increases that means that factories have had more experience producing it. Short cuts are learned that allow for decreased labor or materials costs. As long as there is competition in the market, firms have an incentive to pass those savings on to consumers to try to increase their market share. The price of a good as a function of the cumulative capacity tends to follow a power law. Thus, every doubling of the cumulative capacity decreases the price by a certain percentage, called the learning ratio (1 minus the learning ratio, the percentage of the original price that remains after the doubling, is called the progress ratio). This learning ratio is related to the exponent of the relationship and tends to be constant over multiple doublings of the cumulative capacity.[32]

Kobos et al have extended this theory of learning by doing to incorporate learning by searching, that is R&D. The theory becomes more complicated because of the time dependent effect of R&D, which is in essence technology diffusion, discussed below. Additionally, the knowledge stock (R&D) loses its value over time as newer technological advances succeed older ones. The Kobos study suggests that the learning rate for photovoltaics is about 18%, which is consistent with other studies. The value of

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[32] Kobos, P. H., Erickson, J. D. and Drennen, T. E. "Technological learning and renewable energy costs: implications for US renewable energy policy." *Energy Policy* 34, pp. 1645-1658, 2006..

R&D depreciates at 10% per year and there is a 5-year time lag between new discoveries and their penetration into the market.[33]

Measuring Technology Change

Measurement of technological change is the way a policy's implementation could be evaluated. There are multiple ways to measure technology change in the invention and innovation stages. The two most typical ways are by measuring R&D and by counting patents.[34] This is the main measure of activity in science-based technology. It measures how much firms are putting into R&D units. It tends to underestimate technological activity related to production because activity in that area does not tend to be counted in a way that relates it to R&D of the firm. Also, small firms do not tend to report them separately, and so R&D is not counted officially. Furthermore, measuring the success of R&D induced technology change by measuring the quantity of R&D would be circular.

The number of patents literally measures the number of new products or processes developed and protected as proprietary. There are many drawbacks to the use of patents as a measure of technology change.[35] Patenting activity tends to be very different depending on the sector in which research occurs (both geographically and topically). There is great variability between economic sectors regarding the usefulness of patenting,

[33] Kobos, P. H., Erickson, J. D. and Drennen, T. E. "Technological learning and renewable energy costs: implications for US renewable energy policy." *Energy Policy* 34, pp. 1645-1658, 2006..

[34] Patel, Pari and Keith Pavitt. "Patterns of Technological Activity: their Measurement and Interpretation." *Handbook of the Economics of Innovation and Technological Change*. Paul Stoneman, ed.

[35] Patel, Pari and Keith Pavitt. "Patterns of Technological Activity: their Measurement and Interpretation." *Handbook of the Economics of Innovation and Technological Change*. Paul Stoneman, ed.

and there are different patenting procedures in different countries. Also, patents vary greatly in their economic value; patents do not fit nicely into technology categories (neither of these is truly deemed a drawback by the Patel and Pavitt). Different firms patent at different stages of the innovation and invention processes and with different frequencies. For example, small firms tend to patent only major breakthroughs due to the high cost of patent lawyers, while large firms, who employ patent teams full time, patent everything they can.[36]

Patel and Pavitt describe a number of other measures of technological activity, all with serious drawbacks. Researchers try to quantify payments made for technology across national borders. Unfortunately, this is very inaccurate, results are difficult to interpret, and the channels monitored are not the main ones utilized in technology transfer (imitation, and reverse engineering). The direct measurement of innovation and their diffusion tries to measure not just R&D, but design, testing, production engineering, start-up investment and marketing. While this measure is very helpful, it is also costly and labor intensive. Technometrics attempts to measure and compare the various technical dimensions of a product or process. It is very difficult to generalize. Patent citations tend to be indicative of high quality patents. But patent activity tends to be highly-geographically localized. Bibliometrics, counting scientific papers and citations has proven to be a very difficult activity and does not account for language issues.

These alternative measures, while useful, do not seem to add enough to a study to forsake the standard measures. Thus, spending on R&D and patenting activity will be used as measures of technological activity.

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[36] Tanenbaum, David. Personal communication. 1/24/07.

Technological Diffusion

Technological diffusion, the third step of the Schumpeterian model, is the process whereby innovations are used by an increasing number of firms in a market. This process is very important because one of the fundamental assumptions of this study is that improved products and processes created as a result of a policy would actually diffuse out into the market. Without this process technological innovation will not allow consumers to have better products to buy and power companies to have better plants to build, increasing the market share of solar energy. Additionally, understanding this process has implications for policy.

There are many different theories about how this process takes places and what factors affect it. The epidemic model treats technology as infectious, spreading as more people come into contact with it. The probit model focuses on how an improving technology spreads through a non-uniform population of adopters. Legitimation and competition models consider strategic action under resource constraints. Information cascades help explain which technologies take hold in the market. The epidemic model of technology change has long been the most widely used.

Empirical data on technology diffusion demonstrates that the time path of cumulative adoption of a new technology initially has an increasing speed, and then changes to a decreasing speed. That is, a graph of total users of a technology with respect to time is initially concave up, then goes through an inflection point to become concave down. This produces an S-shaped curve. Most empirical data shows an asymmetric S-curve. Most theories assume that diffusion happens too slowly and seek to study the process in order to increase the rate of diffusion.

Diffusion happens slowly and at vastly different rates for different innovations in different places. Two important questions arise: Why is adoption spread over time? And, why does adoption proceed in time, rather than stopping after some n-th iteration?[37] It is hard to judge the speed of diffusion because it is hard to judge the total scope of application as the number of "potential adopters" changes over time. As time goes on there are changes in an innovation that increase its benefits and scope of application.

According to Dosi, there are two primary dichotomies that differentiate theories into four groups: optimizing vs. institutionalized decision making; and equilibrium vs. disequilibrium dynamics.[38] Optimizing decisions follow tradition neoclassical economic theories about maximization of profit using rational decisions with perfect information, or a close approximation thereof. Institutional decision-making tends to follow rules of thumb, or use other, non-rational or non-optimizing processes to choose among competing options. Equilibrium dynamics involve path independent trajectories, where disequilibrium dynamics are path dependent with more complicated feedback loops and non-linearities in the growth process.

Institutional decision-making equilibrium models focus on the factors that affect the rate of change of adoption, assuming that the actual process of deciding to adopt or

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[37] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.
[38] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.

not is not particularly important. They are primarily descriptive of the process and focused on economic and social factors. There is no deeper explanation of the process.[39]

Epidemic models fit into this category. They assume that if there is some new technology that will improve a profit margin, then all firms that know about the technology will adopt it. The decision of whether or not to adopt is not part of the models. Thus, they are actually models of information diffusion.[40]

Consider a population of potential adopters of the technology. Then, assume that there is a central source of information that reaches a portion of the population in every time period. The percentage of the population that has not received the information, and thus has adopted the technology, will fall exponentially. Thus, the percentage of adopters will rise quickly and then asymptotically approach 100%. Of course, technological diffusion takes longer than information diffusion. And the decision to adopt a new technology requires more than mere knowledge of the technology. As more members of the population adopt the technology, they can communicate the benefits to more other members of the population, each of which adopts or not depending on how enticing (contagious) the technology is.[41] Geroski describes this as awareness of the difference between the hardware and the software of the technology. The hardware would be the physical object or the process which embodies the technology. The software is the understanding of how it works, how well it works and how beneficial it can be. This

[39] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.
[40] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[41] Jaffe, Adam B., Richard G. Newell and Robert N. Stavins. "Environmental Policy and Technological Change." *Environmental and Resource Economics*. June 2002, 22, 1-2, p41.

cannot be realistically conveyed by the central source, which we can assume to be the producer of the new technology who is advertising it.[42]

Knowledge of the software comes from a "word of mouth" diffusion of information. Assume that everyone who has adopted a new technology communicates with a certain portion of the potential adopters who have not yet adopted. The number of contacts will thus depend both on the number of people who have adopted at any given time, and the members of the population who have not yet adopted.

This model of course has the problem of how the initial users find out about the technology. This cannot be endogenous within the model, and so it must be imposed through some other sort of communication, namely the central source of our first model. Thus the models can be coupled, changing the total size of the population to the size of the population that has received the initial information, and factoring in the relative speed of the two information diffusion processes.[43]

Theoretically, the contagiousness of the technology should be determined by factors such as the proximity of the members of the population, the degree to which they communicate, the complexity of the technology, the format of the technology (e.g. software, a manufacturing process or a circuitry component), and the quality of the technology relative to previous technology. Most economists consider these factors to be reducible to expected profits, learning and risk.[44] Unfortunately, these qualities are hard to quantify or measure.

One of the major advantages of this model is that it can be applied to multiple populations, for which the parameters may not be the same. This is done by breaking

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[42] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[43] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[44] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

down the populations into distinct groups, each with different rates of communication between the groups. One of the major problems of the epidemic model is that it tends to treat the number of potential adopters and the contagiousness of the technology as constant. The multiple populations modification can help deal with this problem by adding new populations to increase the total population size and varying the contagiousness in the different populations.

The epidemic model looks at information diffusion as the driving force behind technology diffusion.

> "There is an important distinction to be drawn between understanding something and being persuaded, between hearing and acting on what you have heard…. However, the important point is that once one begins to think seriously about diffusion as a process of persuasion rather than simply as a process of spreading news, the analogy with epidemics begins to break down." [45]

The epidemic model makes assumptions that simplify the process of technology diffusion.   But these are simplifications that may not be desirable, given the circumstances of technological adoption.   Individual firms make their own decisions about adoption, often in the presence of strategic considerations.   This suggests that characteristics of individual firms are important for understanding technology diffusion.

Probit models deal with these salient characteristics, albeit abstractly. Consider a characteristic, x_i, that varies between firms, affects the profitability of adopting a new technology and is in principle quantifiable. A firm will adopt the technology if x_i for the firm is greater than some threshold value x*. We can consider that the distribution of firms in terms of their x-value is some normal or single peaked function and x* decreases

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[45] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

at a constant rate. Alternatively, we can assume that the distribution is flat and x*
decreases at an accelerating and then decelerating rate. In either case the diffusion will
follow an S-curve.

Figure 4. Probit Models
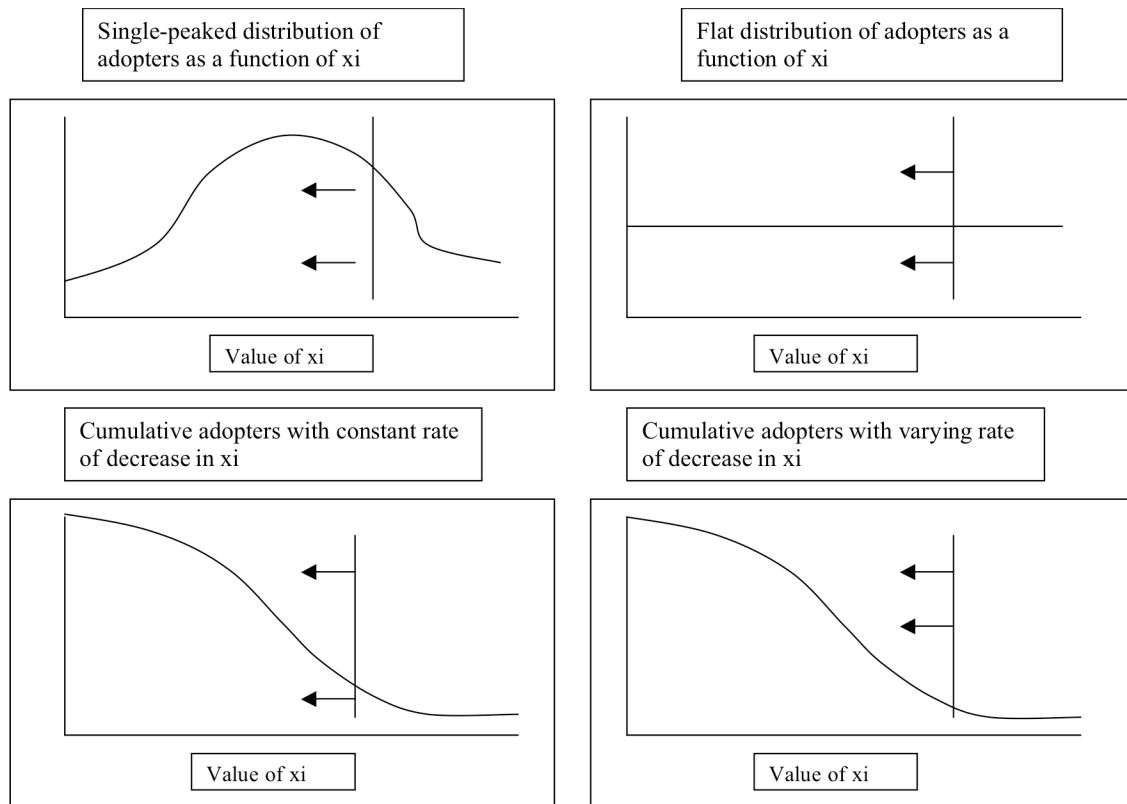
The characteristic x_i is often taken as firm size. This is partly because firm size
works relatively well with the data, and partly because it is an easily measured value.
Firm size is used as a proxy for many characteristics of firms. In the case of firm size, a
firm will adopt either when its size changes such that it is profitable to adopt the
technology, or when x* has changed sufficiently. Research suggests that large firms are

in general much quicker adopters of new technologies. [46]   Firm size is not the only possible attribute for x_i. Some other typical characteristics are vintage-distribution of capital (firms are less likely to switch to a new technology if they have just bought new equipment using old technology), uncertainty, and risk-aversion distribution of firms. [47]

Fundamentally, x_i is benefit of adopting a technology (Geroski calls it the net benefit, but it is not benefit minus cost) and x^* is the cost, and so if the cost is greater than the benefit, a firm will not adopt a technology. If a firm has high searching costs, costs associated with finding information, they will be less likely to adopt, because they will be less likely to find the information about the new technology, or even the necessary information about the risk level of the technology.

Switching costs are also important. This encompasses not only the cost of equipment or information rights to a new technology, but also the learning process and other disruptions in the production process. Adoption involves not just the new innovation itself, but learning how to use it, changing all related processes, and organization (and products). "Diffusion involves innovation for the user."[48] Having the technological capability to adopt is a major determinant of adoption, so "technological asymmetries" between firms are important determinants of adoption. A PV manufacturer that starts using a new technology will have to make changes in their production process, so will incur costs as well as the benefits associated with the new technology. Similarly for a power company that builds a new solar thermal plant: engineers and operators will

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[46] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[47] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.
[48] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.

need to learn different techniques and principles to work with the new technology. The greater the shift between old and new technologies, the greater the switching cost. The opportunity cost of the new technology includes the vintage issue addressed above and the specialization of the equipment. Highly specialized equipment is unlikely to have a second-hand market, increasing the opportunity cost of adopting a new technology, compared with retaining an old technology that has a relatively new vintage of equipment.[49]

Technological adoption is part of the process of technological diffusion. But while technological diffusion tends to focus on the net benefit a technology, there are other issues involved. Often there are cultural barriers to adoption. For example, although building integrated photovoltaics (BIPV) tend to me more cost-effective than roof mounted units, they are under-utilized in Japan. Jaeger-Waldau explains this: "People investing in PV systems want to exhibit them in order to show their environmental consciousness and lifestyle."[50] Similarly, some people are wary of using photovoltaics, regardless of the nominal benefit, because of a perceived negative aesthetic effect.

The probit model has the advantage of explicitly dealing with decision making processes, and identifying the factors that will affect decisions. It looks at individuals, rather than market aggregates (as in the epidemic model). Unfortunately, it does not explain interactions between firms as well as the epidemic model does.

The legitimation and competition model comes from population biology and is analogous to population growth with a carrying capacity. Assume there are a density-

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[49] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[50] Jaeger-Waldau, Arnulf. *World PV Progress Report 2006*. European Joint Research Council: October 2006.

dependent rate of birth and a density-dependent rate of death. This is because as population increases, there are increasing resource constraints on a population. This will lead to population growth with a mathematical form identical to that of the epidemic model, with a carrying capacity of the environmental niche and the natural growth rate of the population. In technology diffusion, the two forces are legitimation and competition rather than birth and death.

Legitimation occurs as more firms successfully adopt a technology. As these firms demonstrate the benefits of the technology by earning profit, more firms adopt and the technology becomes well established. As more firms adopt, competition sets in and returns to the early adopters decreases, decreasing the expected returns to potential adopters and decreasing the rate of adoption.[51]

Of course, firms often act strategically and have some degree of foresight not built into this model. Two important factors of strategic action are the pre-emptive effect and rent displacement.[52] The first occurs for firms that will have some other function improved by a new technology, which will give them an advantage and makes them more likely to adopt. The second occurs for firms for whom some function will be impeded by a new technology, and are thus less likely to adopt.

Information cascades deal with choice between variants of a new technology (A and B) that are entering the market simultaneously. Suppose for one reason or another, early adopters decide to utilize A rather than, not knowing if A is better than B or even than the existing technology. As these firms gain more experience with the technology, other firms are likely to adopt A because they can free-ride on some of the learning that

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[51] Jaeger-Waldau, Arnulf. *World PV Progress Report 2006*. European Joint Research Council: October 2006.
[52] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

the early adopters have done, decreasing the search cost associated with A. There is not an incentive to adopt B when A is understood to work well and B is still a risky unknown. This snow balling effect for variant A is called an information cascade. The more information is passed throughout the market, the greater this effect will be and as the information cascade proceeds, the information advantage will only increase, as the number of potential adopters of B decreases. Thus information cascades are an example of the optimizing disequilibrium models described by Dosi.[53] Movement of information can also impede the progress of diffusion if the initial adopters have problems, even problems unrelated to the adopted technology or failure to realize the potential benefits of the technology, that disincline other firms from adopting the technology.

Note that this process can occur regardless of whether A is actually a better choice for individual firms than B. Early adopters may have chosen A simply because it was better advertised, came on the market earlier or had a lower price. This model may explain the predominance of silicon-based photovoltaic technology, as discussed below.

This explanation brings up an important issue. Although an S-curve is one outcome of this process, it is not the only possible outcome. Although the case literature shows that S-curves map the time progression of new technologies, they only tend to focus on technologies that successfully diffuse, so there is a selection bias in the data. It is important also to realize how crucial the early adopters of a technology are.[54]

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[53] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.
[54] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

Policy Implications of Technology Diffusion

Different theories have different implications for policy. The preeminence of the epidemic theory of technology diffusion has led thinking by policy makers to become routine.[55] The other theories here suggest that other tools might be useful. The epidemic model suggests that aiding information flow and giving subsidies are the ways to increase the rate of diffusion, which is implicitly assumed to be too slow.

Probit models suggest a different set of policy tools. As they focus on individual firms, probit models suggest that policies that help firms gain new skills and human capital, in addition to increasing technology diffusion. Probit models also limit the possible policy tools because firms operate independent of policy makers.[56] The exogenous drivers of diffusion can be targeted as a way to increase the speed at which technologies are adopted.

The alternative theories do not necessarily assume that diffusion occurs too slowly. Indeed, information cascades imply that rash decisions made without clear forethought can lock the market into a less effective technology. They also suggest that the window of policy effectiveness is small, mainly confined to the initial choice processes that take place early in the diffusion process. Although the window is small, early influences can be very powerful. According to Geroski, policy tools should be selective to be effective.[57] Dosi disagrees, recommending support of technological

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[55] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[56] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.
[57] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

pluralism, rather than state directed technological trajectories.[58] Given that many firms operate far from best practices, it may be more effective to move those firms closer to best practices than to improve the best practices.[59]

Any policy regarding solar energy research and development should be made keeping the theories of technological change in mind. These theories suggest that the assumption that knowledge created will diffuse into the market is valid, as long as this technology is seen as beneficial to producers. They also suggests that, while subsidies to increase the prevalence of solar energy technologies are beneficial to the market, there is an important place for research and development to make improvements to the technologies. Thus, it is important to consider the technology of solar energy.

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[58] Dosi, Giovanni. "The Research on Innovation Diffusion: An Assessment." *Diffusion of Technologies and Social Behavior*. Nebojsa Nakicenovic and Arnulf Grübler, eds. Springer-Verlag, New York: 1991.
[59] Geroski, Paul. "Models of technology diffusion." *Research Policy* 29, pp. 603-625, 2000.

Chapter 2: Physics theory section

We will now turn from economic and political theories about technology, research and development to look at the physical theories of how solar energy works. There are two general methods of solar energy for electricity, photovoltaic and thermal. Photovoltaic systems convert the energy of photons directly into electrical energy. Solar thermal systems come from using sunlight as the fuel in thermodynamic cycles similar to those used in fossil fuel power generation.

The importance of the information in this section is for understanding the complexity of solar power. The technology, especially photovoltaic technology has many variables that are not yet well understood and must be optimized in concert, a task for research and development. Furthermore, understanding the technical aspects informs one's understanding of the strength of solar energy as a power source.

We will look at the two broad categories of solar energy, but will not consider other types of solar energy, such as passive solar energy used for heating, ventilation and lighting. First, the physical processes will be laid out, along with important considerations about cost and efficiency. Then, we will consider the different types of technology available.

Photovoltaics

First, we consider photovoltaic (PV) cells. Photovoltaic cells are modular units that can be connected in series or parallel to provide a wide range of power and current combinations. Thus, they are will suited to distributed generation application, such as

providing power directly to an individual house or business, although they can also be used in central generation like traditional power plants. The can be used in remote applications that have no connection to a grid, but are becoming more common in "grid-tied" application in which they supplement (or replace) power delivered by the grid.

The photovoltaic process

The most basic structure of a silicon-based photovoltaic cell is to have a junction of p-type and n-type doped silicon. This means that there are regions doped with a substance that has more than four valence electrons such as phosphorus (n-type) next to a region doped with a substance that has fewer than four valence electrons such as boron (p-type), as shown in Figure 5.[60]

Figure 5

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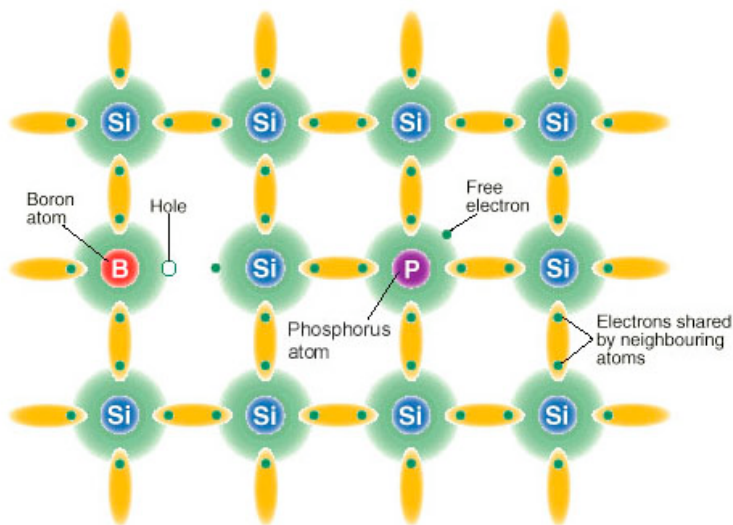
[60] "Energy and the Environment."www.esru.strath.ac.uk/ Courseware/Class-16110/. Accessed 4/16/07.

Around this junction, electrons diffuse from the n-type area to the p-type area because it is energetically favorable to be in the low energy state of the fourth valence electron. This creates an electric field as the negative electrons have become separated from the positive protons in the n-type region. This field eventually stops the net migration of electrons (when there is no illumination of the cell).

At low temperatures and in the absence of some other stimulus, silicon only has electrons in the valence band (unlike metals that have electrons in the valence and conduction bands), but the band gap between the valence band and the conduction band is small enough (1.1 eV for c-Si) that the electrons can be excited into the conduction band. This is what defines silicon as a semiconductor. When light hits the cell connected to a circuit, some photons are absorbed by the electrons of the silicon and excited into the conduction band. This is an exciton, an excited electron bound to the hole where it used to be by electrostatic attraction. The electronegativity of silicon is low enough that the electron can easily escape the hole and the electric field in the cell (described above) causes the electron to move, attracted by the net positive charge in the n-type region. The excited electron will then combine with a hole closer to the anode.

This process occurs repeatedly as photons excite electrons, which then fill holes. Thus, the holes effectively move toward the p-type region and the electrons move toward the n-type region, creating a current. As long as the cell is connected to a circuit and receives incident light of an appropriate energy, the process continues, with the electrons and holes leaving the cell and entering the circuit, providing power to the load.

The description just given describes the photovoltaic process in a single crystal silicon (c-Si) cell. It also describes polycrystalline (p-Si) solar cells and other types such

as amorphous silicon, cadmium telluride, copper indium diselenide and organic solar cells fairly well. But the production costs of these materials is much lower, as will be discussed below.

Many non-crystalline or non-silicon cells, such as those of α-Si, cadmium telluride (CdTe) and copper indium diselenide (CIS) have a more complex architecture than the simple structure described above. Often, multiple junctions will be created by stacking multiple layers of doped bulk. At each of these junctions an electric field is created, as described above. Multiple junctions extend the field into a large volume, increasing the active area of the cell. Often, a layer of undoped material, known as an intrinsic layer, is placed between the doped layers. This again creates more junctions and more volume, extending the electric field.

Because of the production processes used, these types of cells tend to be much thinner than c-Si and p-Si, giving rise to the name, thin-film photovoltaic cells. Thus, they require less material to produce. Most of the bulk silicon in c-Si and p-Si is outside the active area and is effectively wasted.

Photovoltaic cells with organic semiconductors work under the same principle as inorganic ones, but there are important differences. Organic semiconductors do not tend to be crystalline. Instead, they tend to be polymers. Also, existing organic semiconductors tend to have a higher band gap than silicon.

Again, incident photons excite electrons into the conduction band, creating excitons. But the excitons are too closely bound together to separate under the conditions in the bulk of the semiconductor. The excitons must diffuse to some interface (electrode-semiconductor, or a semiconductor heterojunction), much as in α-Si cells. Unfortunately,

there is not a significant internal electric field in the semiconductor, as there is with silicon, so diffusion relies on the natural drift of electrons within the material. At the interface, the change in the energy level allows the charges to separate. The exciton has a limited life span before the electron and hole recombine, so only regions within the diffusion length of an interface contribute to the current.

As in thin films, this problem has been partly addressed by the use of bilayer heterojunction devices. These devices have two different types of organic semiconductors sandwiched together to create additional interfaces. This concept has been extended to a bulk interpenetration or bulk heterojunction device in which the two types of semiconductors are mixed so that the interface is as large as possible to make the region within the diffusion length of the interface larger.

Cost and Efficiency Considerations

Photovoltaic devices are non-ohmic, making the relationship between current, voltage, and power complicated. In ohmic devices, an increase in the voltage leads to a proportional increase in the current. In photovoltaic cells, an increase in the current leads to a decrease in the voltage. Thus, the highest voltage is the open circuit voltage, when no current is flowing. Similarly, the highest current is the short circuit current when there is no voltage. The curve between the open circuit voltage and short circuit current is bowed out as shown in Figure 6.

Figure 6
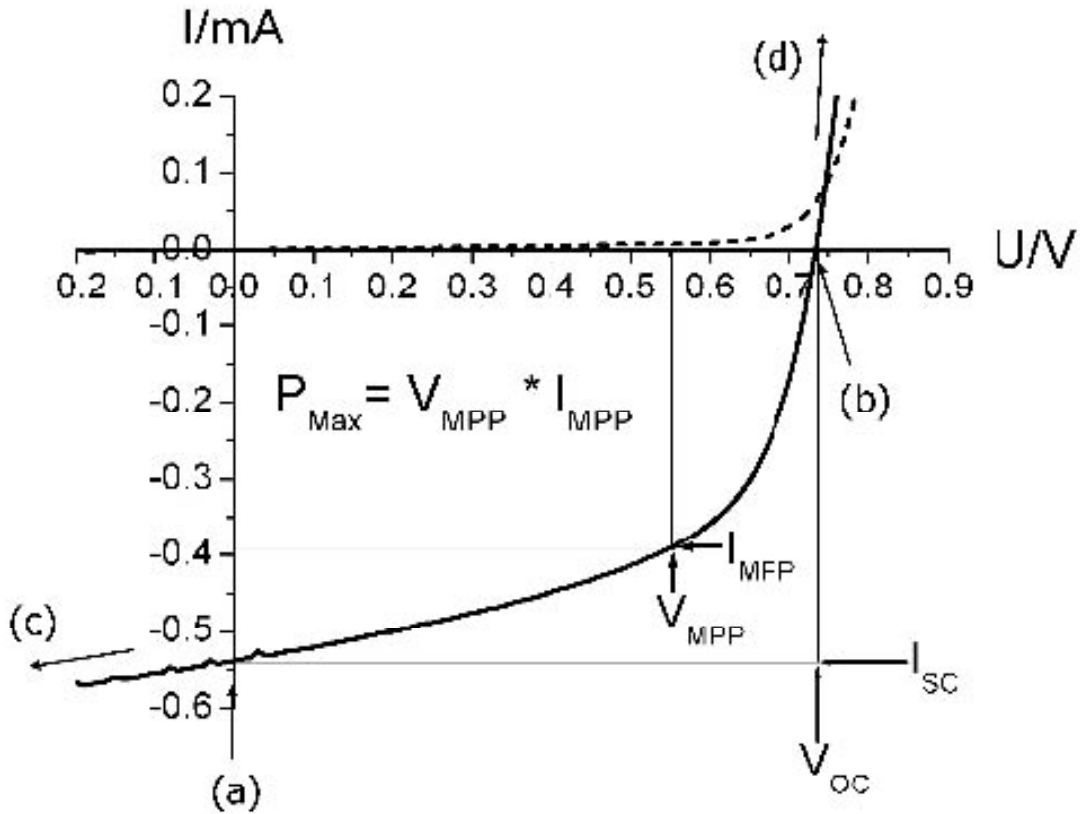
An IV curve for a photovoltaic cell. The solid light is under illumination, the dashed line is without illumination. (a) is the short-circuit current, (b) is the open-circuit voltage.[61]

The maximum possible power for a cell would be the largest voltage times the largest current. But this never occurs because of the offset between the two. The maximum power is out at the elbow of the curve. This gives us a characteristic called the "fill-factor," defined as the maximum power divided by the product of the open circuit voltage multiplied and the short circuit current. To maximize efficiency, the fill-factor for a cell should be as high as possible.

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[61] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.

As described in the previous section there are three very important processes in the photovoltaic process: excitation, separation and transport. Each of these processes must be maximized to maximize the efficiency. Enhancing separation, as explained above, largely relies on the existence of interfaces.

Excitation relies on a good match between the band gap of the semiconductor and the energy of the incident light. Picking a good semiconductor is an important step, but any single semiconductor can only absorb certain energy levels. One way to deal with this is with multiple layers. In addition to increasing the number of interfaces at which separation occurs, multiple layers with different band gaps increases the portion of the solar spectrum that is able to be harvested. As the solar spectrum is well known, band gaps can be chosen to match the incoming sunlight.

Successful charge transport relies on clear paths along which charges can travel to an interface without getting trapped. For example, in pure α-Si, dangling bonds will trap charges and prevent them from reaching the interface. Excitons have a short life-span and so these paths must be direct enough for the charges to travel along them without recombining.

Cost, as well as efficiency, is a major concern. A cell with 40% efficiency is actually less economically viable than one with 10% efficiency if it the cost differential is more than four to one. Of course space is also a resource constraint. A less expensive lower efficiency cell will not be useful in an application in which area for solar panels is scarce. Two of the major factors in the cost of the cells are the materials and the production.

Materials for photovoltaic cells have vastly differing costs. Silicon is one of the most abundant substances in the earth's crust (sand is primarily silicon), but single crystal silicon must be heavily refined and produced under specific conditions, making it very expensive. There is also an issue of competition for resources. When demand for photovoltaics was small, the silicon could be obtained primarily from waste from computer semiconductor processing. As demand and production increase, the quantity of silicon required has surpassed this quantity, and must be obtained from other sources. Additionally, indium for CIS cells is also used for flat-panel televisions. Gallium arsenide cells provide the highest efficiency, but gallium is very rare and thus the cells are very expensive.

Production costs are also very important. Processes differ in their energy intensity and complexity. Many thin film technologies rely on chemical vapor deposition (CVD) that requires a clean room atmosphere. Creation of c-Si cells is much more simple, and less expensive, as long as one already has crystalline silicon from another source. Producing the c-Si from which to make solar cells is very expensive.

Thus, the optimization of the benefit of photovoltaic cells requires a complex juggling of multiple issues. Materials costs must be balanced with production costs and with efficiency, which itself relies on multiple processes. When economic and financial considerations are added, such as subsidies, loan interests rates and tax rebates, the issue becomes even more complex.

Inorganic Photovoltaic Cells

Single crystalline silicon has a perfect crystal structure that gives it good electrical properties. With a band gap of 1.1 eV, c-Si also is well suited to the solar spectrum. Polycrystalline silicon consists of many domains of perfect crystals that do not line up perfectly. That is, there are shifts in the crystal lattice. At this interface charges tend to recombine, decreasing the efficiency of the cell.[62] Because c-Si is so much more expensive to produce than p-Si, p-Si is much more common because the cost benefits outweigh efficiency drawbacks. Poly-crystalline are 2-3% less efficient, but cost less.[63] Both of these technologies use silicon either cut as a wafer from an ingot or drawn out of molten silicon as a ribbon.

Amorphous silicon lacks a crystalline lattice. This allows dangling bonds to inhibit complete charge escape because the excitons get trapped.[64] By adding hydrogen to the silicon during production, the hydrogen fills the dangling bonds, making α-Si useable for photovoltaics. As a benefit, α-Si has better absorptivity than p-Si and c-Si (by a factor of 40).[65] This means that only a very small amount of α-Si is needed to create a working cell, meaning that α-Si can be made into a thin-film cell. Additionally, as mentioned above, cell can be made by chemical vapor deposition (CVD) at a much lower cost than crystalline silicon cells.

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[62] Cook, Gary, Lynn Billman and Rick Adcock. "Photovoltaic Fundamentals." Solar Energy Research Institute: 1990.

[63] Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options*. MIT Press, Cambridge, Massachusetts: 2005.

[64] Cook, Gary, Lynn Billman and Rick Adcock. "Photovoltaic Fundamentals." Solar Energy Research Institute: 1990.

[65] Cook, Gary, Lynn Billman and Rick Adcock. "Photovoltaic Fundamentals." Solar Energy Research Institute: 1990.

Non-silicon photovoltaic cells tend to be comprised of different types of semiconductors sandwiched together in a heterojunction (as opposed to the homojunction in a cell with both sides made up of the same substance).[66] One type of thin-film cell is copper indium diselenide ($CuInSe_2$), known as CIS. CIS, much like α-Si, has a high absorptivity, allowing it to be used in thin layers. Cells can be produced by CVD, decreasing productions costs. Efficiencies higher than those of amorphous silicon are found and production costs are roughly the same. The challenge is that the production process must occur in a clean room environment, but still be low cost. Also, some of the substances involved are toxic.[67] Another common substance for thin films is cadmium telluride (CdTe), which has a band gap of 1.5 eV, making it very well suited to the solar spectrum. Similar substances include silica (SiO_2), cadmium zinc sulfide (CdZnS), zinc telluride (ZnTe) and cadmium sulfide (CdS).

The sunlight incident on a solar panel can also be concentrated to increase the yield. This process in effect trades lower-cost mirrors for the more expensive solar cell allowing for a much smaller cell. Gallium arsenide (GaAs) is often used in this type of set up. GaAs is very high efficiency, up to 22% in the field, but it is also very high cost due to the rarity of gallium.

Traditional uses of crystalline silicon for solar cells waste a great deal of the silicon. There is material wasted in the cutting process, and there is excess material in the cell that has no photovoltaic function. Ribbon and sliver cells both help to address this problem.

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[66] Cook, Gary, Lynn Billman and Rick Adcock. "Photovoltaic Fundamentals." Solar Energy Research Institute: 1990.

[67] Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options*. MIT Press, Cambridge, Massachusetts: 2005.

Sliver cells are made using a process that vastly reduces the amount of silicon used, and makes a crystalline silicon cell that is relatively thin. It starts with a 2 mm thick silicon wafer that is divided up into small connected strips, much like a grill. The wafer is doped and coated to create a photovoltaic cell and then the strips are cut perpendicular to the face of the wafer to be 2 mm by 50-100 mm long by 50-60 μm thick. This process is stylized in Figure 7.

Figure 7. Production Process for Sliver Cells

| Cut a wafer | Cut wafer perpendicular to its face | Resulting thin cells |
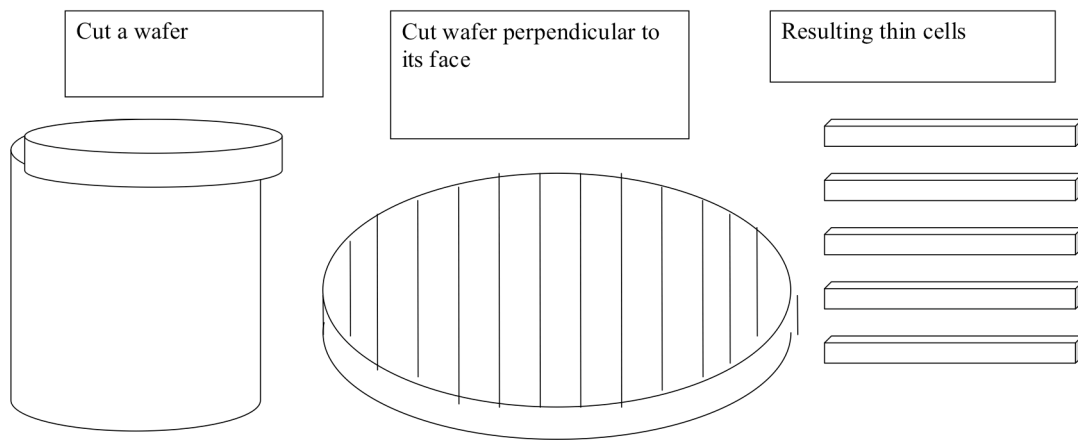
This results in a cell with efficiency of about 13-18% using only one quarter the silicon required for standard silicon cells. The real advantage is in being able cut along the short dimension, allowing for a much thinner slice than if the whole wafer must be cut. This is reported to reduce production costs from $4.50/W to $1/W.[68] The cells are flexible, light and bifacial, so they can be used in a whole host of applications. There is currently a pilot project and discussion about increasing production.

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[68] Normile, Dennis. "Andrew Blakers and Klaus Weber Profile: Eureka Moment Puts Sliced Solar Cells on Track." *Science* vol. 315, no. 5813, p. 785, 2/9/07.

Ribbon cells are another thin crystalline silicon technology. They are produced with a process that draws strings through molten silicon. As the strings come through, a film of molten silicon forms between them, which then hardens into in a thin silicon surface. This can then be used for a solar cell. It can make long ribbons of silicon that can be rolled into spools. The process is continuous and produces twice as many cells per pound of silicon as standard methods.[69]

Organic Cells

Research in organic PV material began with using pigments and grew into the use of organic semiconductor polymers after these were developed. The main benefit is the very high absorption, which is counteracted by extremely low charge-carrier mobility and short diffusion lengths for the first photon excitation. Furthermore, band gaps tend to be high.

The first organic cells were single layers with very low efficiency. With the development of conjugated polymers (carbon backbone has alternating single and double bonds, allowing them to conduct electricity), new single layers devices were developed. These initially had low efficiencies (.1%), but were greatly improved by doping one layer with C60 and creating a bi-layer heterojunction.[70] C60 is strongly electronegative and so receives the exciton from the polymer. Because C60 is more n-type, but receives the electron, nomenclature of donor (D) and acceptor (A) were developed to describe the materials. Various types of devices have been created that have up to 4% efficiency.

[69] Evergreen Solar. "String Ribbon." http://www.evergreensolar.com/technology/ index.html. Accessed 3/7/07.

[70] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.

Organic polymers are a fairly new kind of chemical that have been developed, and organic polymers with good photovoltaic properties are even newer. These properties are common in materials that have extended π-electron systems. Organic materials tend to have a band-gap around 2 eV, limiting the number of electrons in the conduction band due to thermal excitation. Also, they tend to have low charge transport because of disordered structure, like α-Si, and low Van der Waals attractions making them nearly insulators.[71] This can be partially mitigated by "doping" the organic material by exposing it to air or another oxidizing agent. This transfers an electron to the oxidizing agent, allowing the hole-conducting organic semiconductor more conductivity.[72] There are several common substances that can be used to dope.

Device architectures are important for all types of solar cells, but the characteristics of organic semiconductors have made device architecture particularly important for this category. Organic solar cells have higher binding energies for their excitons than silicon, so the internal fields, which are very weak, are not strong enough to dissociate the charges directly.[73] But the sharp drop in potential at the donor-acceptor interface and at the semiconductor-metal interface can dissociate the charges. This is why charge diffusion is necessary.

Single layer devices are the simplest but because diffusion lengths are so short and there are no internal interfaces (all dissociation must take place at the electrodes)

[71] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.
[72] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.
[73] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.

only the regions close to the electrodes (within ≈20 nm) contribute to the photocurrent.[74] This small active area greatly reduces efficiency. Also, because of high series resistance, these devices have low fill factor.

Bilayer heterojunction devices are similar to the silicon cells in that they have two doped layers, a donor (D) and an acceptor (A). Excitation occurs in the D area and charge dissociation occurs at the D-A interface.

Bulk heterojunction devices intermix the A and D substances to try to put all regions within the diffusion length of an interface. The main challenge is that each substance must constitute a continuous region to allow charge pathways to the electrodes. Otherwise, isolated regions trap charges that will then be unable to reach the contacts. Diffuse bilayer heterojunction devices try to replicate the large interface area of bulk heterjunction devices and the continuous pathways of the bilayer heterojunction devices.

Organic solar cells can be produced by evaporation or various wet chemistry techniques, such as spin coating, screen printing and inkjet printing.[75] Evaporation is better with smaller molecules because they tend to be thermally stable (will not break down), but may not be highly soluble. Solution is better for large polymers because they break down with heat, but are often soluble due to side-chain solubility. Wet-processing allows for the use of standard technologies like printing that are easier to engineer than CVD and other techniques.

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[74] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.

[75] Hoppe, Harold and Niyazi Serdar Sariciftci. "Organic solar cells: An overview". *Journal of Materials Research* 19, #7.

Photoelectrochemical Cells

A completely different type of cell is the photoelectrochemical cell, or Grätzel cell, named after its developer, Michael Grätzel. Photoelectrochemical cells use a non-solid state component in the junction, rather than two solid-state semiconductors. There are two types of cells, a regenerative cell that produces electricity and a photosynthetic cell that produces some chemical, such as hydrogen. In the regenerative cells, when the semiconductor is put in contact with the electrolyte, there is a flow of charges, much as in solid-state photovoltaic junctions, until the energy level of the electrons in the solid reaches the redox potential of the electrolyte.[76] Photons of sufficient energy then create excitons. The negative charge carrier moves through the bulk of the semiconductor to the circuit. The positive hole migrates to the interface, where it is picked up by the reduced form for the electrolyte and then moves to the electrode, where the electrolyte is once again reduced. This process provides electrical power without creating any net chemical change.[77] The photosynthetic process is similar except that there are two redox reactions, leading to the chemical change necessary for synthesis of a chemical.

The major problem with photoelectrochemical cells has been that semiconductors that are stable enough to produce the reactions tend to have a high band gap, and so do not harvest the majority of the incoming light, and semiconductors with a small enough band gap tend to break down.[78] In solid state devices the materials only have to be stable enough to resist photocorrosion, but in photoelectrochemical cells there is and actual chemical change occurring, and so the chemical corrosion must be avoided. This problem

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[76] Grätzel, Michael. "Photoelctrochemical cells." *Nature* 414, November 15, 2001, pp. 338-344.
[77] Grätzel, Michael. "Photoelctrochemical cells." *Nature* 414, November 15, 2001, pp. 338-344.
[78] Grätzel, Michael. "Photoelctrochemical cells." *Nature* 414, November 15, 2001, pp. 338-344.

has been addressed by separating the absorption from the charge separation using a sensitizer.

Dye-sensitized cells work by having a dye particle absorb the electron and create the charge separation, and then having a semiconductor execute the charge transport.[79] The cells are made by sintering together nanometer scale crystals of TiO_2 (anatase) that are then covered in a sensitized dye. Other oxides such as ZnO and Nb2O5 have also been used. The key is to use a semiconductor with a high band gap, and then let the dye act as the charge separator.[80] The dye is then returned to its previous state by an electrolyte in a redox reaction. The two most promising dyes are known as N3 and "black dye."[81] Further experimentation with organic dyes and quantum dots has provided promising results.[82]

In traditional silicon-based cells, the silicon has to act as the charge-separator, as well as the conductor, and so must be very pure. This means that production costs are very high. In addition, because dye-sensitized cells use TiO_2, an oxide, they do not require the energy input involved in making Si out of SiO_2. This greatly decreases the energy payback time and increases the benefit as a sustainable technology.

There are a number of promising results for testing of photoelectrochemical cells. As temperature decreases, efficiency does not decrease very much, unlike silicon cells.

[79] Bullis, Kevin. "Solar cells for cheap." *Technology Review*. MIT: September 12, 2006.
[80] Grätzel, Michael. "Dye-sensitized solar cells." *Journal of Photochemistry and Photobiology C: Photochemistry Reviews* 4 (2003) 145-153.
[81] *cis*-RuL2(NCS)2, where L is 2,2 -bipyridyl-4,4 -dicarboxylic acid and (tri(cyanato)-2,2 2 -terpyridyl-4,4 4 -tricarboxylate) Ru(II)), respectively.
[82] Grätzel, Michael. "Dye-sensitized solar cells." *Journal of Photochemistry and Photobiology C: Photochemistry Reviews* 4 (2003) 145-153.

Currently, efficiency is about 30-40% lower than silicon-based technology, but cost is projected to be lower by a factor of 4-5.[83]

Other Cost and Efficiency Factors

The cost of the photovoltaic cell tend to be approximately one-third of the total price of the whole solar energy generation unit. The other major costs are the other parts of the system that are required to integrate it into an electrical system, known as the balance of system (BOS), the installation and the operation and maintenance costs (O&M). BOS tends to comprise about a third of the cost, as does the combination of installation and O&M.[84] O&M costs tend to be very small, and as fuel costs are zero, the bulk of the cost of comes all at once at the time of purchase.

One of the most promising ways to decrease the effective cost of solar panels is to integrate them into the building they serve. Building integrated photovoltaics (BIPV) become part of the structure of the building and serve some function in addition to power generation. For example, a building built with solar roofing materials instead of standard roofing shingles saves the cost of the shingles, but gains the advantage of solar generation, so the solar generation is effectively less expensive.

In general, installing solar panels at the time a building is built is beneficial. The installation process can be streamlined into the whole construction process. In terms of financing, the cost of the solar panel is amortized with the cost of the entire cost of the process, simplifying payments.

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[83] Bullis, Kevin. "Solar cells for cheap." *Technology Review*. MIT: September 12, 2006.
[84] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Union Joint Research Centre.

Solar panels can be used in either grid-tied or off-grid applications. In the past, remote off-grid applications were the primary niche of photovoltaics because they offer a much lower cost than extending power lines longs distances or building other small scale generation capacity. As the price has declined, grid tied applications have surpassed remote applications.

Although photovoltaic solar power is most closely associated with distributed generation, it can also be used for a centralized power plant. In fact, in some ways photovoltaic power is well suited to a power plant because its modular nature allows planners to design a power plant to any specification and to change the size of the plant to meet changing demand much more easily that a traditional fossil fuel burning plant.

Solar Thermal

We now turn to solar thermal energy. Solar thermal energy tends to take the form of a centralized power plant, although this does not have to be the case. Solar thermal generation utilizes sunlight as a heat source to replace or augment fossil fuels. As such, it uses well-understood thermodynamic cycles to convert heat into mechanical energy and mechanical energy into electrical energy. Other than the use of sunlight as fuel, much of the technology is the same as that for tradition power plants.

Types of Solar Thermal Systems

There are three main types of solar thermal power systems: power towers, parabolic troughs and dish systems. An additional type of solar thermal power is hybrid solar power that uses solar as well as fossil fuel. Each of these will be discussed below.

Power towers use large arrays of tracking mirrors called heliostats to reflect sunlight onto a large central collector tower. This heats a prime mover fluid to run a turbine in a Rankine cycle. Basic models utilize single-use steam, but more advanced models use salts as the working fluid, allowing for a closed system with thermal storage. Current projections run at about $3000-$4000/kW coming to about $.08/kWh.[85] Of course, this is nearly all capital cost.

In parabolic trough systems, long arrays of parabolic trough mirrors create a linearly extended focus along the length of the mirror. A fluid, often water or oil is pumped in a pipe placed along the extended focus, absorbing the collected sunlight. The hot liquid is then used in a Rankine cycle to generate electricity. These units can be modular, and so can be added to as demand (or funding) increases. Units can be connected in series for a higher temperature or in parallel for a higher total flow. Large amounts of land are necessary for parabolic troughs, and so it is only practical in locations with very low property values. Heat capture and retention in the receiver are very important; currently available technology allows for absorptivities of up to 96% and emissivities of as little as 14%. Thermal storage and hybridization with other fuel sources increases the dispatchability of the technology. This form of hybridization, utilized at the Solar Electricity Generating Station (SEGS) near Barstow, CA, involves

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[85] Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options*. MIT Press, Cambridge, Massachusetts: 2005.

having two separate fuels that can be used, but does not actually use the two fuels in concert. SEGS's solar conversion averages 14%, with peak efficiencies of 21%.[86] Capital costs are projected at $3000/kW.[87]

Dish engine systems use a reflective dish to concentrate sunlight onto a receiver at the focus. The light is concentrated by a factor of 600-3000 yielding very high temperatures desirable for conversion of heat to power but presenting engineering challenges. Sometimes a transfer fluid is used to move the heat from the receiver to a generator elsewhere, but some models put the engine right at the receiver. Sterling cycle engines are commonly used in this application because they use air as the working fluid. Sterling dish systems have efficiency up to 30%.[88] Dish systems can be hybridized with gas systems to improve reliability and dispatchability, the ability to provide power exactly when it is needed. Unfortunately, capital costs are very high and system lifetimes are not long. Units are completely discrete, making them ideal for small, integrated and remote applications.

There are also hybrid solar systems that actually integrate solar energy with fossil fuel energy. In a combined-cycle natural gas, the lower cycle is reheated with concentrated sunlight to increase the input temperature. This increases the efficiency and the total output. These units have reached solar conversion efficiencies of 19% and would have a levelized electrical cost of as low as .07 $/kWh.[89] Of course, this type of

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[86] Philibert, Céderic. "The Present and Future Use of Solar Thermal Energy as a Primary Source of Energy." International Energy Agency, Paris, France: 2005.

[87] Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options.* MIT Press, Cambridge, Massachusetts: 2005.

[88] Tester, Jefferson W., et al. *Sustainable Energy: Choosing Among Options.* MIT Press, Cambridge, Massachusetts: 2005.

[89] Schwartzbözl, Peter, et al. "Solar gas turbine systems: Design, cost and perspectives." *Solar Energy* 80, Issue 10, October 2006, pp. 1231-1240.

system also has the drawback that it still relies on fossil fuels for the bulk of the generation, and only gains additional energy by adding on the capability to convert solar energy as well.

Summary

The science and technology involved with solar power are very complicated. Certainly much progress has been made in understanding and optimizing the processes, but there is still a great deal that is not well understood. These unresolved issues could be addressed by increased research and development in solar energy. Certainly, although much still can be improved, much of the technology is already mature.

Chapter 3: Current State of the Market

This chapter will give an overview of the solar energy market. First I will outline the industry in terms of the major producers and the technologies they employ. Next I will explain the current solar energy policy regimes for the federal government, California, Germany and Japan. Then I will discuss demand for solar energy. Finally I will consider current RD&D.

Solar energy production and technology

The photovoltaic market is a global market in terms of producers. Major producers from the U.S., Germany, Japan, the People's Republic of China (PRC) and Taiwan produce large volumes of solar panels and market them internationally. The international nature of the market does not mean that prices are the same in all countries. Indeed, they are not and are affected by production volume in each country, experience of producers and installer, transportation and exchange rates. Additionally, the market price of electricity influences the desirability of photovoltaic power.

The top ten producers of solar panels in 2005, their market share and country of production are shown in

Figure 8.[90] All others produced 23.5%.

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[90] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Union Joint Research Centre.

Figure 8. Major Photovoltaic Producers

Company	Country of Production	Percent Market Share
Sharp	Japan	24.3%
Q-Cells	Germany	9.4%
Kyocera	Japan	8.1%
Sanyo	Japan	7.1%
Mitsubishi Electric	Japan	5.7%
Schott Solar	Multiple countries	5.4%
BP Solar	Multiple countries	5.0%
Suntech	People's Republic of China	4.7%
Motech	Taiwan	3.4%
Shell Solar	Multiple countries	2.4%

Jäger-Waldau lists five producers in California. SunPower, based in Sunny Vale, CA has a plant in the Philippines with 100 MW of yearly production capacity, but they are adding 108 MW more and planning a second plant that will eventually have 300 MW of capacity. They produce the highest efficiency commercial solar cells available. DayStar Tech, although based in NY has some operations in CA.[91] They plan to build up to 1 GW of production capacity. NanoSolar in Palo Alto is building a facility to produce 430 MW of thin-film PV utilizing nanotechnology. Schott Solar of Germany has a facility in Rocklin, CA. SolarWorld AG of Germany has a production facility in Camarillo, CA. The California Solar Energy Industries Association (CalSEIA) includes a few more California PV producers among its members[92], including TCT, DC Power Systems and SunWize. Note that none of the top ten producers are in California.

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[91] http://www.daystartech.com/ accessed 12/5/06.
[92] http://calseia.org/component/option,com_directory/Itemid,70/ accessed 12/5/06.

Supporting R&D in the state could potentially incentivize production as well, depending on the exact form of the policy.

The solar photovoltaic market presently is dominated by silicon technologies. The other technologies outlined above are either not present on the market, or have not yet claimed a large market portion. But this is beginning to change, due in part to market growth in the U.S., as well as improvements in technology and price increases for crystalline silicon. In 2005, the U.S. had 8.75% of the world PV market, but 40% of the thin films market.[93]

All of the major producers thus far have focused on silicon technologies. The total reliance on silicon-based technology suggests that other technologies would benefit from improvement. According to the websites of the top ten world producers found above, none of them is currently marketing panels using anything but silicon. Sharp, the world leader, has 12 p-Si models and one c-Si model. Q-Cells, Kyocera, Schott, BP Solar, Suntech and Motech all focus on crystalline, semi-crystalline or multi-crystalline (m-Si) silicon. Mitsubishi Electric uses p-Si. Sanyo uses a heterojunction technology with c-Si and α-Si. The p-Si panels tend to have efficiencies of 12-13%, the c-Si and m-Si panels tend to have efficiencies of about 13-16%.

Thin-film technologies are beginning to come to market. Shell solar, one of the top ten producers, has divested all of its silicon PV interests to Solar World AG, a German company, and has started a joint venture, Avancis, with Saint-Gobain Glass Deutschland. Avancis is expected to begin production of thin-film CIS PV cells in 2008.

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[93] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Union Joint Research Centre.

Jäger-Waldau lists 4 other solar companies in the U.S. that produce solar panels based on other than silicon technology.[94]

In the past, c-Si was especially common because waste silicon from the computer industry could be used in production of photovoltaic cells. The increased presence of m-Si and p-Si, which are not suitable for computer chips, may be due to the fact that demand for photovoltaics has outgrown its position as a consumer of waste products.

Solar thermal power does not have a market in the same way that photovoltaics do. Individual consumers do not purchase solar thermal power plants, but rather utilities build them. Thus, the market is much more a matter of discreet production units, rather than many small units that are constantly being added to the grid.

There are a number of solar thermal power plants throughout the world. The Solar Energy Generation Station (SEGS) is in California produces about 350MW, and there are others in Arizona, Nevada and Spain that will come online soon. This method of power generation is not yet common, but may become so in the coming years.

Southern California Edison, an investor owned utility in Southern California, has signed a 20-year power purchasing agreement for 500-800 MW of Stirling dish solar thermal generation capacity from Sterling Energy Systems, which would be larger than all other U.S. solar power facilities combined.[95] San Diego Gas and Electric, another investor owned utility, has a power purchasing agreement with Sterling Energy Systems for between 300 and 900 MW of capacity. The two companies that produce the receivers for trough systems, Luz and Schott, are increasing their production to meet demand for

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[94] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Union Joint Research Centre.
[95] "Edison International: Pressroom Major New Solar Energy Project Announced By Southern California Edison and Stirling Energy Systms, Inc.
"http://www.edison.com/pressroom/pr.asp?id=5885. Accessed 4/1/07.

500 MW per year of capacity to meet future demand. SEGS is in the process of replacing all the receivers, regardless of age, because the new receiver technology is such a vast improvement over the previous technology.[96]

Solar energy policy

The section will describe the existing general solar energy policies of the federal government, California, Japan and Germany. The focus of the policies, with the exception of Japan, is on subsidies for purchasing solar panels, rather than research and development of photovoltaic and solar thermal technologies. Understanding the current policies not only demonstrates the prevalence of the epidemic model of technology diffusion, but also informs our understanding of how future policy should fit into a coherent policy scheme.

National policy

The federal government does not have a wide array of policies supporting solar energy throughout the country. The two primary policies are the Million Solar Roofs Initiative (MSR) and provisions of the Energy Policy Act of 2005. MSR is an attempt to have solar panels, either PV or solar water heating, on one million roofs by 2010. MSR is not a single policy, but a blanket designation for a set of separate positive inducements. It provides financial resources to help consumers buy solar products, provides funding for research and seeks to remove barriers in building code that make solar utilization more

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[96] Tanenbaum, David. Personal communication. 4/26/07.

difficult. It also seeks to set up relationships to facilitate the expansion of solar use in the U.S. Unfortunately, MSR does not have a full budget and is primarily limited to decreasing barriers, rather than providing any sort of real impetus to the market.[97]

The Energy Policy Act of 2005 contained many policy measures aimed at a whole host of types of energy and applications. The act, which was signed by President Bush in August 2005 and took effect in 2006, increased the business energy credit to 30% for two years, up from its permanent value of 10%. It also created a 30% residential credit for two years, which had not existed before.

California policy

California's current set of policies regarding solar energy are grouped together in what is known as the California Million Solar Roofs Plan. This plan started with an order by Gov. Schwarzenegger to the California Public Utilities Commission (CPUC) to create policies that would lead to solar panels on one million roofs primarily by providing incentives.[98] The plan, embodied in the Self-Generation Incentives Program at the CPUC and the Emerging Renewables Program at the California Energy Commission (CEC), offered subsidies per peak kilowatt to offset the cost of a solar panel. A plan to extend that program through the legislature died in 2005. The current policies are pursuant to California State Assembly SB1, signed into law August 21, 2006. The law sets the requirements for programs under the CPUC and the CEC and mandates that publicly owned utilities create their own policies, within specified boundaries.

[97] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Union Joint Research Centre.
[98] "Schwarzenegger Signs Legislation to Complete Million Solar Roofs Plan." Press release. State of California, Office of the Governor, 8/21/2006. http://gov.ca.gov/index.php/press-release/3588/. Accessed 11/14/06.

The exact details of the CPUC policy have not been determined as the most recent ruling came just days after the signature of SB1 and conflicted in certain specifics. But the form of the policy has been decided. The new California Solar Initiative (CSI), as it will be administered beginning January 1, 2008, uses a performance-based incentive (PBI). This means that, rather than pay a certain dollar amount based on the peak power rating of the system, the CPUC pays a monthly tariff for five years based on the amount of energy actually produced by the system. For systems under 100 kWp, though, the PBI may be substituted for an "Expected Performance Based Buydown" (EPBB). With an EPBB, the expected energy generation is calculated from the system characteristics (e.g. power rating), design characteristics (e.g. angle of inclination), and location characteristics (e.g. average solar exposure for the area and total shading). The new form for these incentives is meant to encourage the projects that are most efficient and thus will have the most impact. The CPUC policy has incentive reduction indexed to the cumulative installed capacity among a utility's customers, but SB1 mandates yearly reductions in the incentive. According to Shannon Eddy, an energy analyst at the CPUC, the form of the German EEG served as a partial model in creating this incentive scheme.[99] The CPUC policy covers all existing homes and all commercial, governmental and industrial buildings.[100]

The CEC has an incentive that is similar in form to that of the CPUC. The CEC policy only deals with "production homes". "Production home" is defined as "a single-

[99] Eddy, Shannon. Telephone interview. 11/09/06.
[100] Clinton, Jeanne. "California PUC's Program for the California Solar Initiative." Presentation to the Solar Power 2006 Conference, October 17, 2006.

family residence constructed as part of a development of at least 50 homes per project that is intended or offered for sale."[101]

SB1 also mandates that publicly owned utilities created their own solar policy by 2008. The policy must have an incentive of at least $2.80 per kWp or an equivalent amount indexed to energy production.[102] The exact form of the policy is at the discretion of the utility.

Eligibility for all of these policies is somewhat restricted. To be eligible, the building on which a solar panel is placed must have some "reasonable and cost-effective energy efficiency improvements."[103] The generating system must be on the same building that would otherwise be drawing from to grid for the equivalent energy and the system's energy must be primarily for consumption, not for resale using net-metering.

SB1 provides for a few other changes. Time of use metering (TOU) is mandated for program participants. The CPUC in its August 24 decision addressed TOU, but found that more deliberation was necessary before making a decision about requiring TOU for solar incentive program participants.[104] The cap on net-metering is raised from .5% to 2.5%. The CPUC can fund training for solar installers and can fund research, although the funding for the research has been specifically limited.[105]

The California Million Solar Roofs Plan and its California Solar Initiative are part of a broader set of policies in the state to combat climate change. Other notable policies

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[101] SB1, California State Assembly 2006. Section 2.
[102] SB1, California State Assembly 2006. Section 5.
[103] SB1, California State Assembly 2006. Section 4.
[104] California Public Utilities Commission. "OPINION ADOPTING PERFORMANCE-BASED INCENTIVES, AN ADMINISTRATIVE STRUCTURE, AND OTHER PHASE ONE PROGRAM ELEMENTS FOR THE CALIFORNIA SOLAR INITIATIVE." Agenda ID 5846, 8/24/06, pp. 82-83.
[105] SB1, California State Assembly 2006. Section 7.

include increased fuel efficiency standards, a plan to reduce state-wide greenhouse gas emissions and an aggressive renewable portfolio standard (RPS) that mandates that investor owned utilities procure 20% of their electricity from renewable sources by 2010 and 33% by 2020. Solar panels owned by individual customers, such as those purchased under the CSI, do not count toward this goal.

California's policies undoubtedly go a great distance toward making solar energy viable. It has never been the goal of this analysis to criticize the existing policies, but rather to examine the potential for their extension. The existing policies are primarily focused on photovoltaic technology, and as such do not provide incentive to solar thermal energy, with the exception being the RPS. Also, as noted above, the California Solar Initiative explicitly limits the funds that can be used for research and development in solar energy. These are two areas where potential for policy extension is particularly great.

Policy Results from Germany and Japan

Japan and Germany are the premier photovoltaic markets in the world. They are leaders in both production and utilization of PV technology, standing at number one and number two and constantly vying for the top spot. While this may be expected of two industrial giants, it must be pointed out that neither of these nations has considerable solar resources, at least not compared to the U.S. Nationally, the average solar radiation gives a yield of 950 kWh/kWp (kilowatt-hours per peak kilowatt) of installed capacity in Japan. Radiation in Germany ranges from about 800 kWh/kWp in the north to up to 1200 in the south. The lowest solar radiation levels in the contiguous 48 states of the

U.S. are around 1200 kWh/kWp in the Olympic peninsula of Washington state. Annual solar radiation reaches above 2100 in the region of southern Nevada, Southern California and Arizona, as shown in Figure 9.

Figure 9. Solar Resource in Germany and the United States
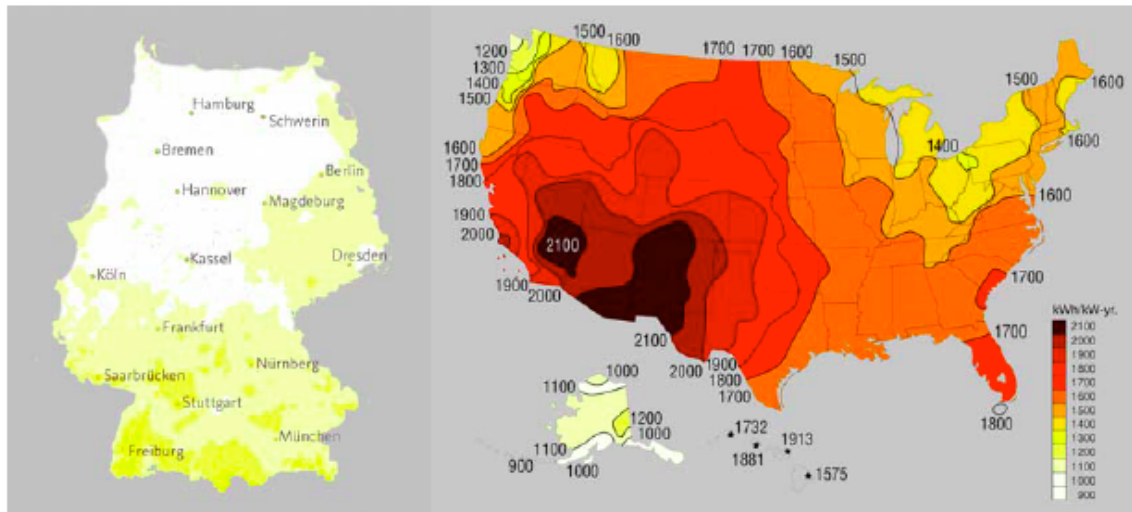
In 1993, Japan's New Energy and Industrial Technology Development Organization (NEDO) began implementing the "New Sunshine Program," a follow-up to the "Sunshine Program" of 1974. The Japanese subsidy was structured around a buy-down of PV systems. The subsidy was 50% of the cost of the system, including the PV module, the balance of system (BOS) equipment and the installation.[106] This percentage decreased over time and was set to end in 2002. Because of the popularity of the program, the Ministry of Economy, Trade and Industry (METI) extended the subsidy to 2005. In addition to subsidies provided by the national government, municipal governments could offer incentives.

NEDO also created a strong research and development program. The government offers matching grants for seed identification and offers full funding for PV research at

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[106] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.

selected Japanese universities and in industry.[107] This program has been expanded under Advanced Photovoltaic Generation (APVG), the successor to the New Sunshine Program. That is, Japanese solar energy policy is now completely focused on research and development. The policy contains specific targets for improvements in different technology regimes.

The price of photovoltaic electricity has come down significantly. Starting at an average price of 2 million yen per kW, the price was 670,000 yen in 2004 (at the time, one dollar was approximately 106 yen, that is about $19,000 to $6300).[108] Data from Jaeger-Waldau suggest that photovoltaics have a progress ratio of approximately .84, meaning that for every doubling of total installed capacity, the price decreases by 16%.[109]
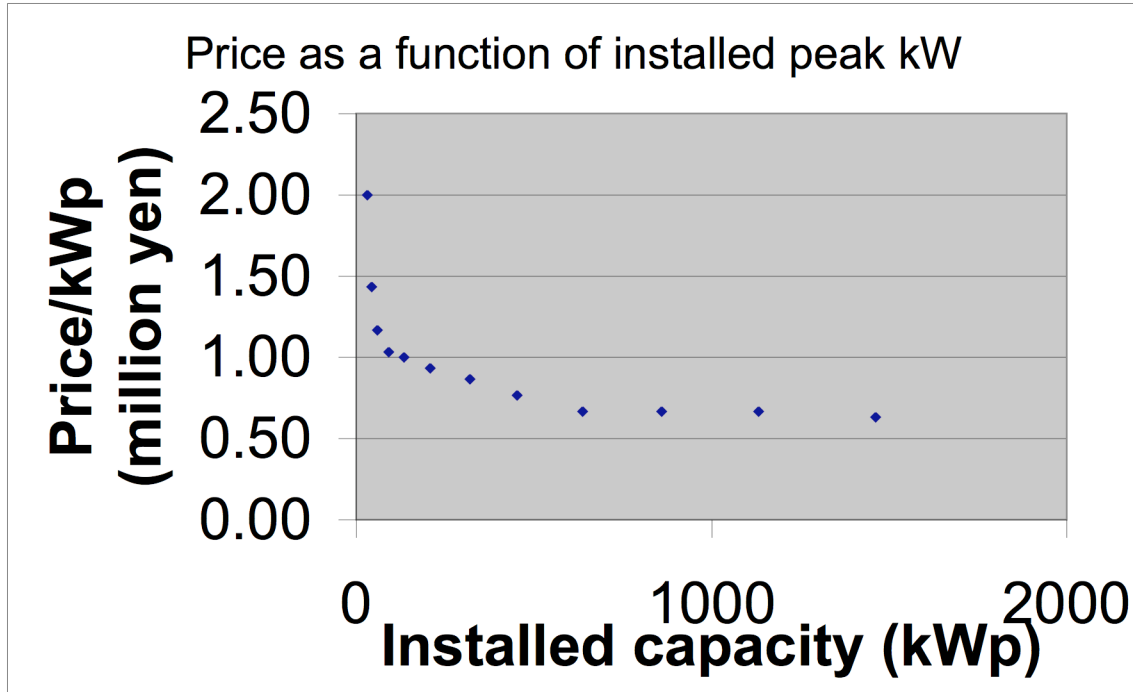
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[107] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.
[108] Bank of Canada. http://www.bankofcanada.ca/ en/rates/exchform.html, accessed 12/5/06.
[109] The line of best fit using a least-squares method was derived using Microsoft Excel. The equation of the line was (Price/kWp)=3.73*(Total installed kWp)^(-.255) and had an R-squared value of .91.

Figure 10

Because the New Sunshine Program ended in 2005, data on the PV market in Japan in the absence of subsidies is not yet available. The Japanese Photovoltaic Energy Association is confident that the growth will continue despite the end of national subsidies.[110] Jaeger-Waldau cites lending practices as evidence that the market is moving beyond reliance on government subsidy. Some Japanese financial institutions offer a reduction of 1-2% on the entire mortgage of new houses that use PV.

German's solar energy policies are structured much differently than Japan's. Instead of paying a percentage of the cost of the system, the German government has a "feed-in tariff" that pays energy producers per kilowatt-hours (kWh) they produce. The key to the effectiveness of the German program appears to be the direct linkage of the tariff subsidy to the aggregate amount of total energy actually produced in kWh, rather

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[110] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.

than simply the aggregate size of the system in kW. Unlike the Japanese subsidy, the German subsidy is structured to incentivize actual PV-generation, rather than simple deployment of the largest systems possible. There are multiple rates depending on the size and type of the system (BIPV, sound barrier, etc.) but the minimum rate in 2005 was .434 €/kWh (about $0.54).[111,112] The size of the tariff decreased 5% per year at the start of the program in 2004 and now decreases by 6.5% per year in 2006. Previous to the EEG, there was a feed-in tariff that offered the same incentive to wind power and PV. This caused massive growth in the wind market, but was too small to significantly spur the solar market.[113]

The German market has responded enthusiastically. In 2004, the year the EEG took effect, the German PV market saw a 235% increase, from 153 MW to 363 MW, in new installations.[114] This made Germany the world's largest market for photovoltaics. That year, German installations accounted for 88% of all installations in the EU. The huge growth also caused Europe to return to being a net importer of photovoltaics, after a few years as a net exporter, despite continued growth in production. According to Bettina Frenzel, the German solar industry saw 30-40% growth annually between 1999, when a first feed-in law was enacted, and 2004.[115]

Unlike Japan, which has transitioned to an emphasis on R&D rather than on subsidies, German policy is wholly focused on subsidies. Together, these two case

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[111] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.
[112] In 2005, $1 U.S. was worth € .74-.86, varying throughout the year. Bank of Canada. http://www.bankofcanada.ca/en/rates/exchform.html, accessed 12/5/06.
[113] Boling, Mark and Ryan Wiser. "Innovation, Renewable Energy, and State Investment: Case Studies of Leading Clean Energy Funds." Lawrence Berkeley Nation Laboratory.
[114] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.
[115] Frenzel, Bettina, "Acceptability in Germany for Wind Power, Solar Power and Fuel Cells as Energy Supply." Vattenfall Europe AG (Berlin, Germany). Presented at the 19th World Energy Congress, Sydney Australia, September 2004.

studies demonstrate the effectiveness of subsidies for spurring market growth and a decrease in cost. But more important for our purposes, the case of Japan shows that other governments have seen research and development as the important step that follows initial market growth.

Solar energy demand

According to the California Public Utilities Commission (CPUC), which oversees the California Solar Initiative, current levels of solar installation in California are about 40 MW per year. In order to meet the 3,000 MW goal of the CSI, this level needs to increase to about 300 MW installed per year. This is three time the current total in the whole United States and roughly equal to the amount installed in Japan in 2005. Total world installations in 2005 were about 1,800 MW.[116] I have been unable to find more detailed information than this.

Solar Energy Research, Development and Demonstration

Technological progress is notoriously difficult to quantify. The two most common ways of measuring technology change, R&D spending and patenting, do not actually correspond to technological change. Each has strengths and weaknesses.

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[116] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Commission DG Joint Research Centre: Ispra, Italy, August 2006.

R&D funding is the main measure of activity in science-based technology. It measures how much firms are putting into R&D units. It tends to underestimate technological activity related to production because activity in that area does not tend to be counted in a way that relates it to R&D of the firm. Also, small firms don't tend to report them separately, and so R&D is not counted officially.[117] The New York Stock Exchange requires all listed companies to publish R&D figures, and figures are published by *Business Week* and the *Independent*. But spending money on research and development and discovering new and better products and processes are not the same thing.

Patenting activity tends to be very different depending on the sector in which research occurs (both geographically and topically). This is due is part to the fact that patenting is related to R&D expenditure, which is not uniform. There is great variability between economic sectors regarding the usefulness of patenting. And there are different patenting procedures in different countries. Also, patents vary greatly in their economic value.[118] Patents protect intellectual property, but they also disclose technological progress. Thus, it is sometimes advantageous for companies not to patent unless they are worried that another company will soon discover the improvement. For example, if a solar cell manufacturer discovers a new process that decreases the cost of production, it is unlikely that other companies would be able to "reverse engineer" (discover by examining the product) this process, but it is likely that they would learn of the process

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[117] Patel, Pari and Keith Pavitt. "Patterns of Technological Activity: their Measurement and Interpretation." In *Handbook of the Economics of Innovation and Technological Change*, edited by Paul Stoneman.
[118] Patel, Pari and Keith Pavitt. "Patterns of Technological Activity: their Measurement and Interpretation." In *Handbook of the Economics of Innovation and Technological Change*, edited by Paul Stoneman.

by reading the patent. Thus, patenting will not capture this new process. Additionally, patents often contain multiple parts, such as a new design for a solar cell and the process for manufacturing it.

Spending on R&D for solar energy has declined steeply over the past 25 years, as it has for energy R&D in general. Both federal and private R&D funding have declined, but private funding has fallen even more precipitously. In the 1980s, the two sources were roughly equal, but now private R&D accounts for only 24% of the total. [119]

Patenting in solar energy has also declined. Nemet and Kamman have demonstrated the decline up until 2003.[120] Figure 11 shows the recent history of patenting and public spending on photovoltaic research and development.[121]
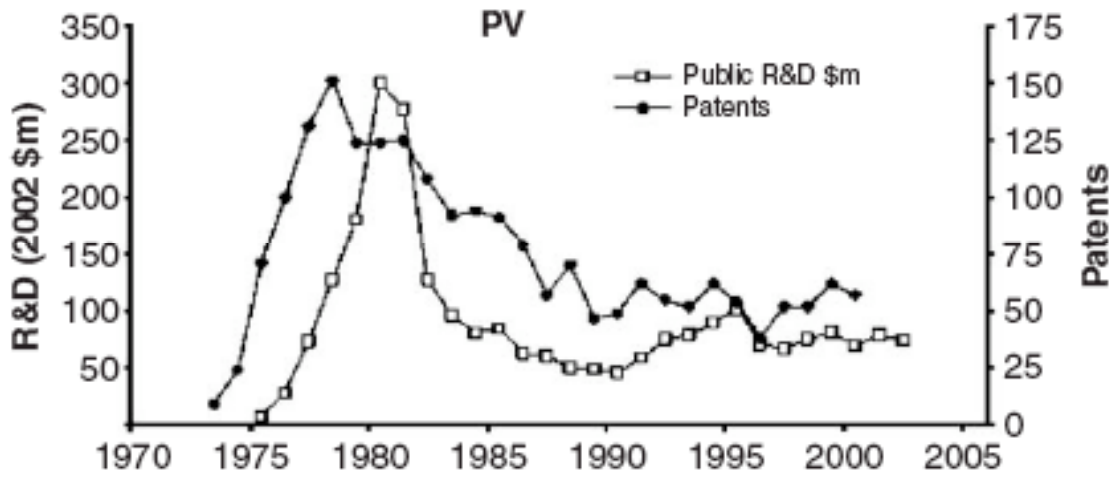
[119] Nemet, Gregory F., and Daniel M. Kammen. "U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35 (2007) 746-755.
[120] Nemet, Gregory F., and Daniel M. Kammen. "U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35 (2007) 746-755.
[121] Nemet, Gregory F., and Daniel M. Kammen. "U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35 (2007) 746-755.

Figure 11. Research and Development and Patenting Activity[122]

More recent data are available. I searched the patent database available on Google Patents for all patents that included the word "photovoltaic" for the period January 2001 through to the middle of 2006, the most recent date that the database contains. I eliminated patents that were not actual photovoltaic devices, such as solar powered battery chargers. The results, broken up by private, university and government patents, is shown in Figure 12.

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[122] Nemet, Gregory F., and Daniel M. Kammen. "U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35 (2007) 746-755.
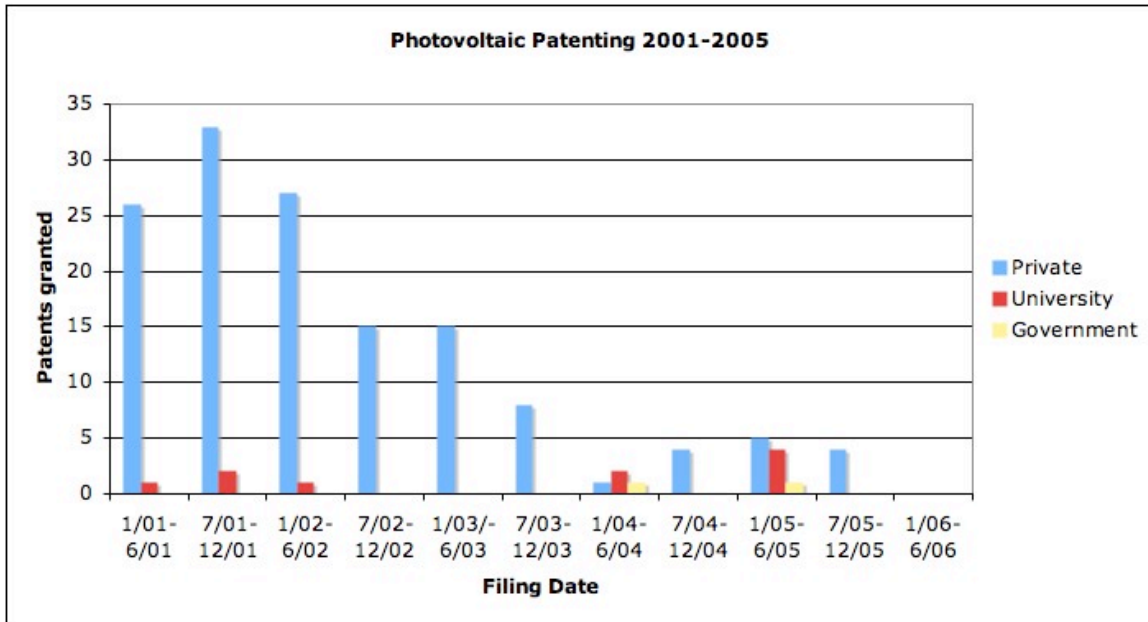
Figure 12. Recent Patenting Activity.

Clearly, the number of patents containing the word "photovoltaic" have greatly decreased. It is certainly possible that there are patents during this period that were meant for photovoltaic applications but did not contain that word or that there were other patents that will be applied to photovoltaics in the future. It is also clear from the above figure that the majority of patenting is from the private sector, rather than from universities or government labs.

Clearly the output of research and development has declined over recent years. The reason for this decline is unclear. Given that the trend has continued for a number of years it is unlikely that the data are anomalous outliers. This suggests that state support for research and development could have a major positive influence and is unlikely to replace R&D that companies were going to do anyway.

Chapter 4 Policy Recommendations

Given the information laid out in the previous chapter regarding the process of technology change, the science and costs of solar energy and the current state of the market, what policy response, if any, is most appropriate? This question really has two important antecedents that must first be addressed. First, would more research and development in solar energy be beneficial? Second, if so, should the State of California take an active role in supporting solar energy R&D? Each of these questions will be addressed in turn.

Would more R&D be beneficial?

It does appear that solar energy research and development is occurring at a less than socially optimum level because patenting is declining while demand is increasing, and there are few types of technology competing in the market. There are theoretical reasons for believing that R&D would be under-provided by the market, and we know that spending on R&D and solar patenting have each declined. Solar energy can help mitigate the problems and potential problems discussed in the Introduction, so increased technological progress seems desirable.

In their analysis, Nemet and Kamman have determined that spending on energy research and development should increase. Part of this increase would be in solar energy. They recommend a 5-10 fold increase in research and development as insurance against

climate change. Although this would be a major increase, they argue that is it not only possible, it in line with previous coordinated R&D campaigns, such as the space race.[123]

The Solar Energy Industries Association (SEIA), a solar energy trade group, has identified an increase in research and development as one of their primary goals as part of a "solar roadmap" because R&D is viewed as an important part of making the industry viable in the long term in the absence of subsidies. The SEIA recommends, among other things: [124]

- Increased R&D investment to $250 M per year by 2010;

- Supporting higher-risk, longer-term R&D;

- Enhanced funding for universities and national labs; and

- Increased partnerships between industry, universities and national laboratories.

Thus, the industry views R&D as important, regardless of the willingness of individual companies to take on the risk associate with it.

In order for current levels of R&D to be a shortage, increasing it must yield some improvement. The history of photovoltaic devices suggests that the efficiencies do increase with continued R&D, just as the price decreases. Figure 13 demonstrates this trend.

[123] Nemet, Gregory F., and Daniel M. Kammen. "U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35 (2007) 746-755.
[124] Jaeger-Waldau, Arnulf. "PV Status Report 2006." European Commission DG Joint Research Centre: Ispra, Italy, August 2006.

Figure 13.[125]
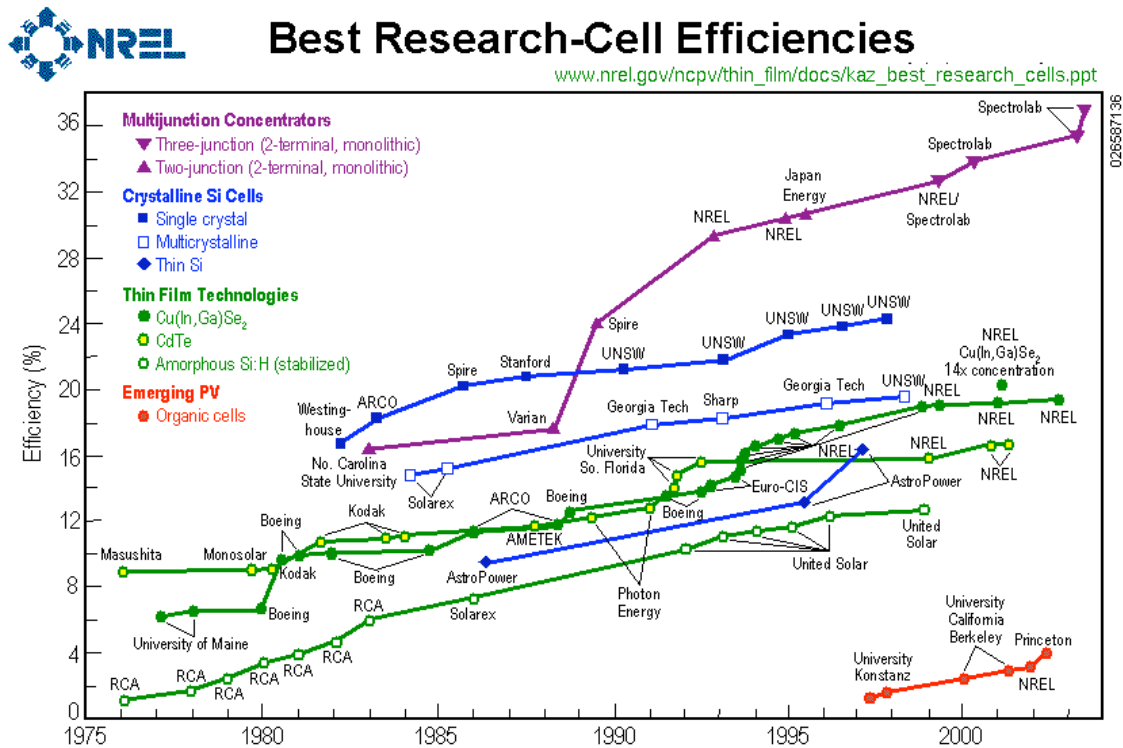
Clearly, significant improvements have been made in the past.

In addition to evidence of past improvements in photovoltaics, there are clear opportunities for future improvement. Many of the technologies are still not well understood and must be tested and experimented upon. For example, different cell architectures have potential to increase the absorption spectrum of different cells. Within the realm of organic semiconductor photovoltaics there is a need to develop and test new materials, as well as experiment with a whole host of parameters such as electrode composition, solvent, and preparation techniques. The technology of solar thermal power is well understood, but still needs to be developed to increase its market impact.

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[125] National Renewable Energy Laboratory. "Best Research-Cell Efficiencies." http://www.nrel.gov/pv/thin_film/docs/kaz_best_research_cells.ppt. Accessed 4/19/07.

Given that the market is dominated by silicon technologies, and yet other technologies exist, there is clear need for more research and development. These technologies need to be better understood in order to increase efficiency and decrease cost. And their risk associated with them must be decreased through continued development. Here, the caveat about information cascades should be remembered. It is possible that the dominance of silicon technologies in the market is a result of an information cascade that has thus far limited the market to a subset of its potential. This means that the decreased risk of using familiar technology may be limiting the market's ability to grow and technology's ability to improve. R&D has the potential to expand the possibilities for the market by increasing the number of technologies available so that they can be better tailored to specific needs.

It is important to consider if government support for R&D a worthwhile investment. That is, what is the benefit to society received from state support of R&D? The traditional view has been that tax incentives are an ineffective way of promoting R&D, but new studies contradict that notion, although tax incentives will encourage the least under-provided R&D first.[126] That is, research that is high-risk but also would provide great social benefit will not be provided as much as low-risk technologies because the low-risk R&D has a lower opportunity cost. Reliance on the government to do or directly fund R&D has two problems. First, government funding requires some level of government choice rather than market choice. This may be ineffective because the government does not have all the information that private actors do and is often less flexible. Many people are opposed to government control of private action for these and

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[126] Hall, Bronwyn and John Van Reenen. "How effective are fiscal incentives for R&D? A review of the evidence." *Research Policy* 29, pp. 449-469: 2000.

other reasons. Second, political timelines and technology timelines are not compatible. Elections cycles and accountability encourage policymakers to create short timelines that can return results within a few years. But as we saw in Chapter 3, technology change takes longer than two years. Companies that would consider investing in R&D are more likely to do so if they are guaranteed a longer timeline to allow them to continue earning return on the investment, even if that investment is subsidized.

There are two ways of measuring a subsidy for a public (or quasi-public) good, such as R&D. First, one measures the total social benefit and the total social cost. This is very difficult to do. Most studies instead measure the increased R&D spending versus the lost tax revenue. In other words, is the lost tax revenue being used on increased R&D, or is it simply replacing existing spending on R&D. This does not actually measure the social benefit because of the uncertainty in the benefit created by the R&D. But it is a good way to determine the relative effectiveness of a tax credit versus direct funding. If the increased spending on R&D is greater than the lost tax revenue, then a tax credit is better than direct funding, otherwise direct funding subsidy is better. This method will not tell us whether R&D funding is better than some other activity in terms of social benefit.

There has been a great variation among the studies. The tax price elasticity of R&D seems to be about 1.[127] Thus an additional dollar of foregone tax revenue for R&D yields an additional dollar of R&D. Newer studies put this value higher than old studies do. Differences between industries, markets and companies make the value uncertain for any specific case, so the effect for solar energy could be either bigger or smaller.

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[127] Hall, Bronwyn and John Van Reenen. "How effective are fiscal incentives for R&D? A review of the evidence." *Research Policy* 29, pp. 449-469: 2000.

Should California Support R&D?

Given that it is at least plausible that more research and development should be done and that government support can achieve that end, should the State of California actually be the one to do it? There are various arguments on either side.

Probably the most compelling argument against California supporting solar energy R&D involves the free-rider problem. The free-rider problem arises whenever there is a non-excludable resource, such as access to better and cheaper solar energy technology. Any program enacted by the State of California will be funded by California taxpayers. The benefits will accrue not only to California taxpayers, but also to anyone else who is affected by improved solar energy technology. These people will not have paid for the benefit, but will have received it nonetheless. This is not necessarily a problem because the benefits are non-rival in consumption, meaning that other people enjoying the benefit does not reduce the enjoyment of California taxpayers. The important additional point, though, is Japan is already supporting solar R&D, at least for photovoltaics. As explained in the previous chapter, Japan's incentive for purchasing solar panels has ended and now the focus of the national photovoltaic policy is on R&D. Therefore, Californians could free-ride on Japanese taxpayer dollars. Californians would enjoy less benefit, but would also not pay for it.

The Japanese policy provides an incentive to support R&D. If California were to support research and development in solar energy, it would not be the first to do so, and so would have a model to work on. The Japanese government has made a conscious decision to pursue research and development as the successor to subsidies. The Japanese

Photovoltaic Energy Association is confident that the growth will continue with the R&D program, despite the end of national subsidies.[128] This would allow policy makers to study the results of the policy and try to improve upon it.

There is also reason to believe that support of solar energy research would have benefits other than improved solar energy technology. The growth of the solar energy market in Germany has led to significant job creation. According to the German Energy Agency (DENA), there are 30,000 people working in production, sale, planning and installation of PV systems in 3,500 workshops and companies active in the field, including 50 manufacturers at the various levels of the value chain.[129] Jaeger-Waldau quotes 20,000 jobs, and says that half of German companies expect to increase their number of employees by 30-100% in the next 5 years.[130] The European Photovoltaic Industry Association (EPIA) forecasts 59,000 jobs in 2010 throughout Europe if its goal of 3.6 GWp is met. The EPIA estimates 50 jobs throughout the value chain for every MW of PV production capacity.[131] Currently, there is very little production of photovoltaics in California, but this could change. Increased R&D will encourage existing companies as well as new companies to operate in California.

Solar energy has the potential to be a growth industry in the future. If there is a significant improvement in the technology that brings the price per kWp down, it is likely that demand will continue to grow. If California can take this opportunity to play a major role in the market, then there will be money coming into the state with the purchase of

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[128] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.
[129] DENA, "The German Photovoltaic Industry." *Renewables Made in Germany*.
http://www.renewables-made-in-germany.com/en/photovoltaics. Accessed 10/5/06.
[130] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.
[131] Jaeger-Waldau, Arnulf. "PV Status Report 2005." European Union Joint Research Centre.

solar energy products and services, good jobs and tax revenue, in addition to greater energy security, reduced emissions and the other benefits laid out in the introduction.

There is no clear correct course of action. There are costs and there will be benefits. But there is a precedent for this situation. In 2004 California voters decided to fund stem-cell research. Although this is not the same situation, it does represent a willingness on the part of the voters to taxpayer dollars to produce socially beneficial outcomes through research and development that will not accrue solely to themselves.

Recommendations

The evidence thus far presented can be applied to policy recommendations. Unfortunately, I have been unable to collect enough data to make a firm policy recommendation. Instead, my recommendations take two forms. First, I will outline potential policies that could be pursued. Second, I will recommend further research that needs to be done to determine which policies are the most promising.

Potential Policies

There are multiple policy parameters that can affect the eventual form of a policy. The types of policy tools discussed in the introduction to this study each have multiple possible forms. There is the specific implementer, whether it is corporations, universities or government laboratories. There is the technology to be targeted, whether it is c-Si, CIS, parabolic troughs, or balance of systems equipment, for example. Each of these parameters will be discussed below.

The main policy tools available to policymakers for directly targeting solar energy research and development are rules, incentives and direct action. Each of these contains different possibilities of specific policy types, each with benefits and drawbacks. Two rules that would affect R&D would be a spending requirement and a technology forcing policy.

The state could mandate that companies in the state devote a certain amount of money to R&D. This would force companies to spend money on R&D, and could focus on different quantities to determine the amount required, for example total operating budget, total revenue or profits. In addition, companies that did not want to conduct the R&D themselves could pay someone else to do the work for them. Although this policy is fairly straightforward, there are multiple difficulties and drawbacks. First, it would only affect California companies, of which there are few, so the impact would not be great. An effort to target all companies operating in California could discourage companies from doing business here. Probably most significantly, the solar energy industry is likely to be opposed to this type of policy measure because it takes away their autonomy and forces them to spend there money in a certain way, regardless of whether the company perceives that as the best use of the money. This policy can also be inefficient because it treats all firms the same, regardless of whether they are well equipped to fund or carry out R&D.

A technology forcing policy is a policy that sets a future requirement that is beyond current technological capability. This gives companies an incentive to innovate in order to meet the future requirement and thus avoid fines. The Renewable Portfolio Standard is considered technology forcing. The green house gas limit in AB 1, discussed

previously, is considered to be technology forcing. These policies can be problematic due to uncertainty in future technological progress.[132]

An incentive would most likely take the form of government financial support for research and development. This could be a tax break for R&D funds, some type of matching grants, or direct funding. As discussed above, tax breaks do appear to be cost effective for supporting research and development.[133] Matching grants, in which the state matches some portion of spending by on R&D could have a similar effect and would give the state more control over what types of research are funded. State funding of research and development would be effective in increasing the amount of R&D, but would not be efficient in terms of using market forces.

The most obvious direct action related to solar energy research and development would be to conduct solar energy research at a government lab. California does not have any State Laboratories that work in solar energy research, but there are university laboratories in the public university system that could be used. Additionally, California could found a laboratory devoted to solar energy research, although it is unclear what utility this would have given the existence of university labs.

Policies can be targeted to companies, or universities. This comes down to an issue of private versus public R&D. Private R&D tends to be primarily profit driven. Public R&D can more easily provide socially beneficial knowledge that is less promising as a financial investment for a firm. "…Divergent trends for federal and industry R&D are important because of the very different character and missions of these two sources of U.S.

[132] Jaffe, Adam B., Richard G. Newell and Robert N. Stavins. "Environmental Policy and Technological Change." *Environmental and Resource Economics*. June 2002, 22, 1-2, p41.
[133] Hall, Bronwyn and John Van Reenen. "How effective are fiscal incentives for R&D? A review of the evidence." *Research Policy* 29, pp. 449-469: 2000.

R&D funds. They are not substitutes for one another."[134]   Thus, there is a reason to support both public and private R&D in order to help solar energy companies optimize profits and provide public benefit.

A policy could also target specific technologies, or treat all the same. By targeting specific technologies in specific ways, policy makers can try to provide assistance to the technologies that are deemed to be the most in need of support. For example, policymakers could provide specific funding for organic and thin film materials research or solar thermal production development. Unfortunately, this presents the classic policy trade-off of specificity and flexibility. This type of policy would be specific about what it intends to address, but flexible enough to meet surprising or changing circumstances. Needs identified by companies and universities might not be able to be addressed due to regulations within the policy. Additionally, there is a danger to allowing policymakers rather than practitioners set technology priorities.

Any policy that requires funds must be paid for. These funds could come from some tax on undesirable behavior, such as a carbon tax, or a tax on fossil fuel-based generation of electricity. The State of Oregon has a surcharge for all investor owned utility customers that is put into a fund to support renewable energy. A similar program could be used to fund a solar R&D policy in California. Policies also must have timelines. Policy intermittency has had a negative effect on the renewable energy market.

There is also room for more creative policy making. For example, the federal government could extend or shorten the patent protection period for photovoltaic patents.

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[134] Eisman, Elisa, Kei Koizumi and Donna Fossum. "Federal Investment in R&D." RAND Corporation, MR1639.0-OSTP: September 2002.

Extending the patent protection would increase the incentive for companies to develop useful patents, as they would be able to be sole beneficiaries for a longer period of time. Shortening the patent protection would decrease the time required for technologies to diffuse into the market, but would also decrease the incentive to develop useful patents. This option is not open to California as the state does not have control over patenting. Other innovative ideas such as design competitions could also be pursued. Perhaps a strategy to increase in-state production along with research and development could be developed.

The evidence available does seem to suggest some possible guidelines for policy. There should be elements that support both public and private R&D. Various technologies should be supported, perhaps with specific goals set for each technology regime, as with Japan's R&D policy. Any policy should have a timeline of at least 5 years, the time that Kobos et al. have determined as the time for technology to diffuse into the market, but should also be updated to meet changing circumstances.

The other important possibility, mentioned above, is that the state not create any policy. This would obviously not cost any money and might allow the state to pour more money into other beneficial policies, such as subsidies for solar thermal power. This would allow current market forces to influence the state of technology. This is a very important policy option that should be seriously considered.

The firm policy recommendation that I am able to make is that more data need to be collected. Some of this data exists and has not been made accessible. Other data exist and I was simply unable to locate them. But a great deal of important data has not yet been generated. The next section deals with future research on the topic.

Recommendations for Future Study

More information is needed before policy recommendations are possible. The information needed falls into two categories: Japanese policy results and California market data.

Given that Japan already has a policy to support solar energy research, it makes sense to examine the results of the policy. At this point, the policy is too new to see how the market has reacted. In the next year or two it should be possible to see what levels of continued consumer interest in photovoltaics has continued in the absence of subsidies. Japan's policy is based on sharing the cost of R&D through contracts that are publicly bid and sets specific benchmark goals for improvements in efficiency, cost and market penetration, it is important to determine whether these goals are being met, and if not what the barriers have been.

A better understanding of the California market is also important. The level of market demand as well as how that responds to the new subsidy should be considered when forming a policy. High demand in the market could justify a larger program, but at some level of demand, a policy may be unjustified because the market is already robust.

Table 1 below gives responses to future research regarding the success of Japanese policy. Table 2 gives responses to future research regarding the market in California. Because statute limits state funding for R&D to $50 million, that provides an upper, but not a lower limit on any policy. Policymakers have discretion to choose where the funds

are going and in what form. Note that the table assumes a research and development policy should be created.

Table 1. Policy Responses to Data from Japan

Result	Policy Conclusion
Japanese R&D levels	
Strong growth in R&D levels	Consider similar policy of bid contracts for matching grants
Small increase in R&D	Make bidding process less restrictive, increase incentives
Over subscribed bidding process (too much demand for the contracts)	Tie contracts to other desirable outcomes, such as production
Technology targets met	Create similar but complimentary targets, including solar thermal
Targets not met	Tailor contracts more directly to targets, reassess targets

Table 2. Policy Responses to Data from California

Steady market growth	Maintain subsidy level
Stagnant production	Tie contracts to production
Continued reliance on silicon technology	Favor other technologies
Low growth in solar thermal generation	Increase funding for solar thermal development and demonstration

Solar energy offers the promise of inexpensive carbon free, pollution free electrical generation. Despite the clear benefits of solar energy, the details of a policy to support solar energy research and development are not obvious. Gathering more information will allow policymakers to formulate a policy that supports solar energy research and development in a financially responsible manner.

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