Competing Solar Technologies for Compliance with the California Solar Initiative

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This paper explores the emerging role of remote-site solar power for providing electricity in California, with a primary emphasis on the technology options and their respective costs.

This paper is part of a series intended to explore the cost-effectiveness of remote site solar power for electricity generation in California.

California Renewable Power Mandates:

California has passed a number of key pieces of legislation to ensure swift in-state development and adoption of renewable energy. First and foremost here is California's Renewable Portfolio Standard (RPS), originally established in 2002, and frequently modified thereafter.[1] Currently, the RPS mandates that all retail sellers of electricity supply at least 20% of their load using renewable energy by 2013, and 33% by 2020.[1] For utilities to reach such a goal, they must invest in a considerable renewable energy portfolio, which involves paying for the premium prices often inherent in renewable energy generation. This will result in higher electricity costs for consumers; a study prepared by the California Public Utilities Commission (CPUC) estimates that average electricity costs for consumers could reach 16.9¢/kWh in 2020 as a result of the 33% RPS, compared to 12.49¢/kWh averaged from March 2008 to March 2009 (a 35.3% increase).[2, 3] This legislation supports renewable energy development not only by mandating

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[1] "RPS Program Overview." California Public Utilities Commission. http://www.cpuc.ca.gov/PUC/energy/Renewables/overview.htm (accessed July 4, 2009).
[2] Douglas, Paul, Elizabeth Stoltzfus, Anne Gillette, and Jaclyn Marks. "33% Renewables Portfolio Standard Implementation Analysis Preliminary Results." *California Public Utilities Commission*, June 2009.
[3] "Electric Power Monthly - Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State." Energy Information Administration. http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html (accessed July 5, 2009).

large-scale adoption in a short time frame, but the increase in electricity costs directly helps certain forms of renewable energy (such as solar) become more cost effective.

Although not a California-exclusive program, the federal investment tax credit for solar energy projects is another crucial incentive to financing solar power. The Emergency Economic Stabilization Act of 2008 provides for a 30% investment tax credit for solar energy and some other renewable energy projects, and this applies to residential buyers, businesses, and utilities.[4] This legislation extended the life of the investment tax credit out to December 31, 2016, which gives solar buyers plenty of time to take advantage of it before it nears its expiration date.[4]

Another California program, the California Solar Initiative (CSI) incentivizes the purchasing of solar installations by paying the customer based on the size/performance of the system. There are two incentive systems, one that only applies to systems under 50 kW in capacity (the Expected Performance-Based Buy-down, or EPBB), and another for systems of all sizes (the Performance Based Incentive, or PBI); a given solar system can only apply for one of the two incentives. For the purposes of this paper, we will only be examining the PBI, since it applies to usefully sized systems for a utility. The PBI makes 60 monthly payments over five years to the installation's purchaser based on the monthly energy production of the solar system. Table 1 details the payments made by the PBI, which change according to how many MW of solar capacity have already been installed under the CSI.[5] Currently, for the commercial PBI payment, Southern California Edition (SCE) is on step 5, and Pacific Gas & Electric (PG&E) is on step 6, meaning new solar systems installed under SCE's jurisdiction will receive $0.22/kWh payments under

[4] "Federal Tax Credits." Go Solar California!. http://www.gosolarcalifornia.org/csi/tax_credit.html (accessed July 28, 2009).
[5] "CSI Incentive Levels By Step." California Public Utilities Commission. http://www.cpuc.ca.gov/PUC/energy/Solar/incentives.htm (accessed July 5, 2009).

the PBI, and those installed under PG&E's jurisdiction will receive $0.15/kWh payments.[6] People can track how many MW of solar capacity remain before each IOU moves to the next step at http://www.csi-trigger.com/.

Step/Statewide MW in Step	1/50	2/70	3/100	4/130	5/160	6/190	7/215	8/250	9/285	10/250
PBI Payments for Commercial Installations (per kWh)	NA	\$0.39	\$0.34	\$0.26	\$0.22	\$0.15	\$0.09	\$0.05	\$0.03	\$0.03

Table 1: PBI Payment Structure

[6] "Statewide Trigger Point Tracker." California Solar Initiative. http://www.csi-trigger.com/ (accessed July 5, 2009).

Description of Relevant Technologies

In order to make an accurate assessment of the cost of solar power to utilities, this paper will consider some of the competing technologies that use solar energy to generate electricity. These include crystalline photovoltaics (crystalline PV), thin film PV, and solar thermal (also known as concentrating solar power). The following section will describe the important features of these technologies so that we may have a deeper understanding of their advantages and disadvantages.

A typical PV module, pictured in Figure 1, uses a junction between boron-doped (p-type) and phosphorous-doped (n-type) silicon to create an electric field (and subsequently, voltage); photons excite electrons across this junction, creating current.[7] This current is carried by electrical contacts, which sandwich the two silicon layers, and a glass cover protects the module from the elements. Additionally, various forms of antireflective coatings on the top of the module and reflective surfaces in the bottom of the module increase efficiency by directing more photons to the silicon layers for absorption. Crystalline PV modules have a 93% market share, compared to thin film's 7% market share.[8]

Figure 1: Crystalline PV module

Advantages to crystalline PV modules include higher efficiencies than thin film PV modules, high durability, and use of familiar silicon-based technology. Many crystalline PV modules can convert sunlight to electricity with ~15% efficiency, and the most efficient production-grade

[7] Image from http://www.solarconduit.com/shop/index.php/solarworld-sw175-mono-24v-nominal-w-mc4-con.html

[8] "Solar Cell Technologies." Solarbuzz. 6 July 2009 <http://www.solarbuzz.com/Technologies.htm>.

crystalline modules have efficiencies of 22-23%.[9, 10] Additionally, the robust glass covering and metal frame prevent crystalline modules from degrading very quickly. In fact, studies by the Institute of Electrical and Electronics Engineers (IEEE) show that "current module design would guarantee 90% power after 20 years of life and moreover there is no visible evidence that this degradation rate is increasing with time. […] This would indicate that the estimated life time is indeed well beyond the 20 year assumption which is commonly made today."[11] This has significant ramifications for the levelized cost of electricity (LCOE) of solar power, which would drop significantly if the time of life changed from 20 years to 30 or 40 years. A final advantage to crystalline PV technology is that using silicon as a semiconductor allows PV manufacturers to use "process technology developed from the huge knowledge base of the microelectronics industry."[8] Indeed, silicon's familiarity as a semiconductor gives crystalline PV a considerable advantage over thin films, since thin film PV often makes use of more foreign semiconductors, the properties of which are not as well-understood as silicon's.

While these advantages help explain the huge market share of crystalline PV (compared to thin film), it is worthwhile to note this technology's weaknesses, starting with cost. Crystalline silicon wafers "make up 40-50% of the cost of a finished module," due to the face that silicon is a "relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material."[8] Because silicon is such a poor absorber of light, it must be refined to almost 100% purity, and this refining process is mostly responsible for silicon's costliness.

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[9] "NREL: Learning - Photovoltaics." National Renewable Energy Laboratory (NREL). http://www.nrel.gov/learning/re_photovoltaics.html (accessed July 7, 2009).
[10] "SunPower Reaches 23.4% Cell Efficiency." Renewable Energy World. http://www.renewableenergyworld.com/rea/news/article/2008/05/sunpower-reaches-23-4-cell-efficiency-52470 (accessed July 7, 2009).
[11] Dunlop, Ewan, David Halton, and Heinz Ossenbrink. "20 Years of Life and More: Where Is the End of Life of a PV Module?." *Photovoltaic Specialists Conference, 2005. Conference Record of the Thirty-first IEEE*, January 3, 2005.

Thin film photovoltaics (pictured in Figure 2) offer an alternative to crystalline photovoltaics, being cheaper, lighter, and (mostly) utilizing much stronger light-absorbing semiconductors than silicon.[12] Semiconductors used in thin film PV include amorphous silicon (still silicon, but in a different molecular configuration than crystalline silicon), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). All of these semiconductors are deposited on a substrate (i.e. glass, stainless steel, tin) in quantities under 1 micron thick. Thin film photovoltaics work on the same principles as crystalline PV, with a p-type semiconductor, an n-type semiconductor, electrodes on either side, and often a glass covering. Panels with a conductive substrate, such as foil, do not need electrical contacts on the back, and panels that do not use glass are bendable.

The semiconductors used in thin film PV are much more efficient light-absorbers than crystalline silicon, and as mentioned above, need only be used sparingly. This helps contribute to thin film's cost advantage over crystalline photovoltaics. As an example, companies such as First Solar and Nanosolar are already shipping thin film modules costing less than $1/watt, or more than one-fourth the cost of crystalline PV modules.[13, 14] This lower cost is the main draw of thin film technology. Additionally, thin film semiconductors are easy to deposit onto their substrate, which eases large scale manufacturing.[8] Another small advantage is that thin film PV can be made flexible, which increases its range of applications significantly.

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[12] Image from http://www.greentechnolog.com/state/california/
[13] "First Solar Passes $1 Per Watt Industry Milestone." First Solar. http://investor.firstsolar.com/phoenix.zhtml?c=201491&p=irol-newsArticle&ID=1259614 (accessed July 8, 2009).
[14] Hunt, Jessica. "Nanosolar's Breakthrough - Solar Now Cheaper than Coal." Celcias. http://www.celsias.com/article/nanosolars-breakthrough-technology-solar-now-cheap/ (accessed July 8, 2009).

Figure 2: Thin film PV modules being installed

However, thin film PV has been slow to gain noticeable market share for a number of reasons. Primarily, employing the efficient CdTe and CIGS semiconductors has proven very difficult compared to silicon, since the microprocessor industry has made silicon a relatively simpler and more familiar semiconductor.[8] So, while these technologies were developing, thin film PV panels had far lower efficiencies than crystalline PV panels, a significant detractor, especially when space is a concern (First Solar's $1/watt panel is just over 10% efficient, compared to SunPower's 22% efficient crystalline PV panel, which is in production).[15, 16] To overcome these deficiencies, thin film manufacturers have created double and triple layer panels (two or three layers of semiconductors stacked on one another) for increased light capture, but this increases panel cost and manufacturing complexity.

A third alternative to using solar energy to create electricity is solar thermal energy, which comes in three forms: Stirling Dish, power tower, and trough/linear concentrator. All of these technologies, on the most basic level, use mirrors to direct the sun's energy at a fluid of some kind (i.e. a heat transfer fluid or water), and then this heated fluid either drives a turbine or a generator, depending on the technology. Like photovoltaics, these technologies make clean, efficient use of the sun's abundant energy.

The Stirling Dish (known as the SunCatcher™), manufactured by Stirling Energy Systems (SES), uses a parabolic arrangement of mirrors to direct sunlight at a Stirling engine (on the

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[15] "First Solar FS Series 2 PV Module." *First Solar*, January 2009.
[16] "Best Technology." SunPower. http://us.sunpowercorp.com/utility/why-sunpower/best-technology/ (accessed July 13, 2009).

end of the large arm shown in Figure 3), and this engine drives a generator, creating electricity.[17] The concentrated sunlight heats up part of the Stirling engine, which creates a heat differential with the surrounding air, which drives the engine. The dish uses a dual axis tracker so that it is always positioned at the most efficient angle relative to the sun; each dish creates 25 kW of electricity at 31.25% efficiency.[18]


Figure 3: A Stirling Energy Systems SunCatcher™

Power towers, such as that pictured in Figure 4, use heliostats (sun-tracking mirrors) to concentrate sunlight onto a boiler on top of a tower.[19] This heats a fluid, oftentimes water, and the high-temperature steam drives a turbine, creating electricity. Although less modular than photovoltaics or Stirling Dishes these systems do create a large amount of electricity: BrightSource Energy has recently made a 1.31 GW contract with PG&E and a 1.3 GW contract with SCE.[20]


Figure 4: A Luz Power Tower 550, made by BrightSource Energy

The third and final form of solar thermal energy can be divided into two categories: parabolic troughs (Figure 5) and fresnel reflectors.[21] Parabolic troughs feature a long, curved, sun-tracking mirror which directs sunlight at a fluid-filled tube. This fluid, if it is water, turns direct-

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[17] Image from http://www.sandia.gov/news/resources/releases/2009/stirling.html
[18] "Technology: Advantages." Stirling Energy Systems, Inc.. http://www.stirlingenergy.com/advantages.htm (accessed July 14, 2009).
[19] Image from http://www.economist.com/sciencetechnology/tq/displayStory.cfm?story_id=13725855
[20] "BrightSource Energy." Projects. http://www.brightsourceenergy.com/projects (accessed July 14, 2009).
[21] Image from http://www.reflectechsolar.com/references.html

ly to steam and turns a turbine, much like in power towers; if the fluid is a heat transfer fluid, a heat exchanger transfers the thermal energy to water to create steam, which drives a turbine. Fresnel reflectors work on exactly the same principle, except they use skinnier, long, flat mirrors which track the sun and reflect sunlight at a fluid-filled tube. From there, the fresnel reflectors work exactly like parabolic troughs, using steam to drive a turbine. It is worth noting that in all of theses forms of solar thermal energy, the heat transfer fluids are recycled by the system, and never need to be replaced (barring any malfunctions).


Figure 5: Parabolic trough

Solar Cost Study

The Center for the Study of Energy Markets (CSEM) prepared a paper analyzing what the author, Severin Borenstein, calls "the actual value of power from solar PVs."[22] The paper, entitled *The Market Value and Cost of Solar Photovoltaic Electricity Production*, conducts a cost-analysis of distributed PV power (panels located at the energy demand site), considering the "enhanced value [of PV power] within an electrical grid."[22] The paper uses a 10kW PV array in California as its hypothetical example, and applies both empirical data and theoretical estimates to develop the levelized cost of generating energy for this system. After his analysis, the author found this enhanced value to be fairly insignificant relative to the cost of solar PV power.

Borenstein identifies two characteristics of distributed PV that raise the value of solar PV energy: the timing and location of energy generation. The timing factor increases the energy value of photovoltaics because the prime energy generating time period coincides with peak energy demand in California. This has several benefits to not only consumers, who can benefit

[22] Borenstein, Severin. *The Market Value and Cost of Solar Electricity Production*. January 2008.

from increased generating revenues at this time, but also to the electricity grid. Theoretically, reducing peak load could help mitigate transmission line losses, since the amount of energy that dissipates into heat is proportional to the square of the flow in transmission lines; this effect could possibly result in substantially easing transmission line losses, which would increase the value of distributed PV. The locational advantage could have a similar impact on the transmission system. Because distributed PV is located at the site of energy use, there are savings in not having to transmit energy to the customer, which would result in line losses. So, the author carries out an analysis of these factors to determine how much they increase the energy value of distributed PV.

The timing analysis concluded that depending on location and orientation, time-related effects could increase the value of PV energy by 0%-20% (the theoretical installation in Los Angeles had a higher increase in value that the installations in northern California). The author came to these results when using wholesale energy price data from the CAISO, but when using simulated prices, he found the increase in value to be 30%-50%. However, he determined that the simulated model used too many assumptions that would not be compatible with the California energy market, so he concluded that time-related benefits could only result in a 0%-20% increase in energy value.[22]

While the above analysis does contain some positive results for the value of PV energy, the location-related analysis did not indicate any significant change in PV energy's value. There are certain locations in California that would benefit more than others from distributed PV (because of local transmission constraints and variations in line losses), as indicated by analysis done by the author, but PV capacity has not been distributed effectively in the areas that would benefit the most from the distributed generation.[22] The author attributes this phenomenon to the fact that there is no incentive to purchase PV energy in areas with congested transmission lines.

These findings lead the author to conclude that "the cost of solar PV remains many times higher than the market valuation of the power it produces."[22] It is important to note that the paper does not take into account any state or federal incentives in its analysis, which may be one of the major factors that brings the cost of solar PV closer in line with other forms of electricity generation.