Understanding the Solar Market

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Summarizes work done on capstone. Explains basics of solar market and dominant technologies. Examines cost competitiveness of PV and CPV technology with respect to grid electricity prices, solar irradiation levels, and module efficiency. Looks at various case studies to see how technologies will perform in specific locales.

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Introduction

Energy is the basis of modern human civilization. As mankind develops the world, he uses more of it. While the 21st century rolls inexorably onward, solar energy in particular is a viable option to solve civilization's energy needs. All energy originates from the sun, so directly harnessing solar radiation- free and abundant in most all of the globe- is a straightforward idea. And after a solar panel has generated enough electricity to cover its own manufacturing costs, it is essentially producing energy for free. Moreover, solar energy is cheaper by the year, and thus pays for itself- and starts generating "free" electricity- all the more quickly (Tracking the Sun, 2012). It is clear beyond a doubt that the Earth's fossil fuel reserves will not us forever, especially not with rapidly developing countries such as China and India burning more fossil fuels each year. The problem then becomes finding "a prosperous way down" (to quote the famous ecologist Howard T. Odum) from the problems of decreasing petroleum supply and increasing energy demand.

Renewable energies such as wind, solar, and geothermal have long been hailed as the solution. Solar has typically been seen as a very cost ineffective answer, however. This is rapidly changing. In many parts of the globe, solar energy is at parity with or cheaper than traditional grid electricity, as we will see below. It is quickly becoming an important component of humanity's energy supply. While not an on-demand source, as solar panels only generate electricity while the sun shines, when paired with other forms of renewable electricity generation and storage they can meet large parts of society's energy needs. This is especially true in areas of high solar resources, where energy use peaks in the summertime afternoons, often overloading the capacity of traditional grid electricities (Popular Mechanics 2012). During the middle of the summertime day is obviously when solar panels are at peak capacity. They thus contribute the most electricity when demand is greatest.

Kaldellis et al. (2012) provide a good example of such an integrated solar system. They discuss the viability of a combined solar-wind system for the tiny Greek island of Agathonisi, with a population of less than 500 people. They expensively import both petroleum for small scale diesel generators and potable water. The advantages of the Kaldellis et al.'s system, as they point out, is that excess energy can be used to drive water desalinators; and that the solar component operates at peak conditions during summer time, which is when demand is greatest on the island. Diesel would be used only as a backup. Once the system generates enough electricity to pay for itself it would be generating zero cost energy and potable water. This frees up the island community's limited financial resources for other uses.

Technologies

Solar energy is dominated by crystal silicon photovoltaics. Competing cadmium-telluride technology was viable due to its low cost, but a glut of cheap Chinese crystal silicon photovoltaics as well as abundant silicon production have largely undercut the market of cadmium-telluride. Concentrated photovoltaics, on the other hand, hopes to carve out its own niche in large, utility scale operations. Both technologies are fighting a drawn-out battle to achieve economic parity with typical forms of electricity, or "grid" electricity- utility scale coal, natural gas, and nuclear energy, for example (Swanson 2000). The aim of this paper to understand quantitatively under what conditions the two technologies will be at grid parity. It will also examine the conditions under which concentrating photovoltaics (CPV) will be at parity with crystal silicon photovoltaics (SiPV). Finally, it will examine various case studies of areas where PV technology makes the most sense. The goal is to provide context for Dr. Sellers' research focus of more efficient multijunction solar cells to be used in CPV applications. Specifically, they are researching the use of GaInNAs in multijunction cells, and 3rd generation processes in single band-gap solar cells, which will be important as we discuss the direction of the CPV industry in general.

SiPV creates electricity by absorbing certain wavelengths of electromagnetic radiation, exciting electrons in the semiconductor material (in this case, silicon). These excited electrons create an electric current. SiPV technology was developed in the 50s and 60s. Over 50 years of development and technological iteration have resulted in a mature technology whose price and performance have begun to stabilize. Current SiPV systems have module efficiencies of around 16% in field conditions. Experts believe that maximum (and consistent) efficiencies of about 20% are possible (Green et al. 2013). Module prices free-fell in recent years due to overproduction of modules, particularly by Chinese manufacturers, and undersupply of raw silicon for manufacturing. This caused financial ruin for many U.S. solar companies, but will ultimately prove beneficial for the industry as a whole, as price is the primary impediment to large-scale solar adoption (Lacey 2013). This competition has also caused a large amount of industry wide innovation in order to compete and stay in business. As can be seen in Figure 1, however, the price of SiPV is beginning to stabilize. Experts believe that manufacturers may shave some further cents off the module cost of SiPV, but that the bulk of further price drops will be from the balance of systems (BOS) and more solar-friendly policies. The rapidly increasing level of installed PV is also important to note.

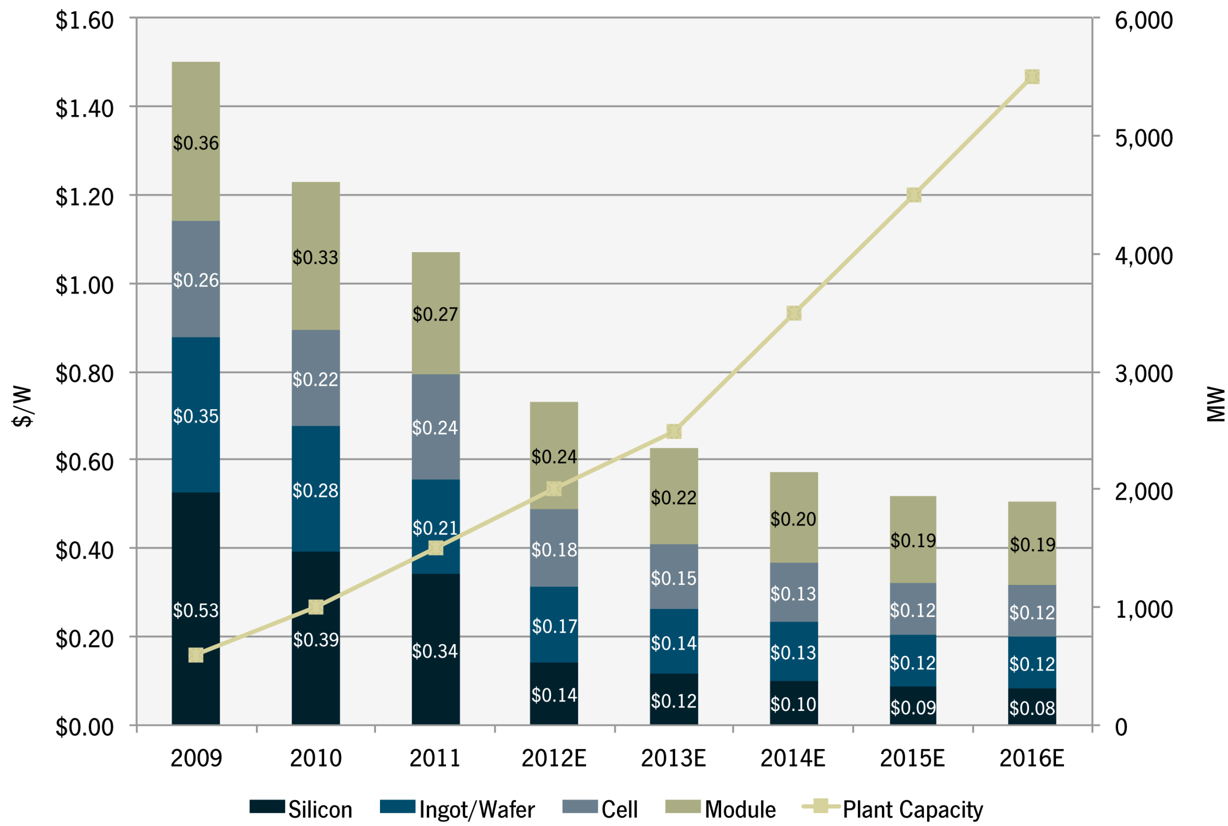


Figure 1. From Greentech Media. As installations increase, price falls rapidly but levels off as we reach 2016.

CPV is a much less mature technology. Concentrated development only began in the early 90s. CPV uses multijunction cells to absorb a much higher range of electromagnetic wavelengths. The manufacturing process is expensive, so instead of covering the surface of an entire solar module with the semiconductor material (as with SiPV), small amounts of multijunction semiconductor material are used instead. To achieve power outputs comparable to that of SiPV, concentrating optics are used to focus the light directly on the small areas of multijunction (MJ) semiconductor material (Swanson 2000). Unlike SiPV, the MJ material performs highly at such intense concentrations- often 500 to 1000 suns. Accordingly, CPV is able to perform at efficiencies higher than that of SiPV despite having a comparatively tiny area of semiconductor material. Current industry standard module efficiencies are about 30% (HCPV Siemens 2013). The technology is more expensive than SiPV, however. MJ semiconductors are still very expensive to manufacture, and there is the additional cost of the concentrating optics as well as additional hardware for the module to track the sun. In the same way a telescope must be pointed directly at a target to see it, CPV modules must point directly at the sun as they magnify it. This requires precise mechanical systems in each module, which is costly (Kurtz 2012). This cost can be seen in Figure 2, which compares average CPV, SiPV, and grid energy costs.

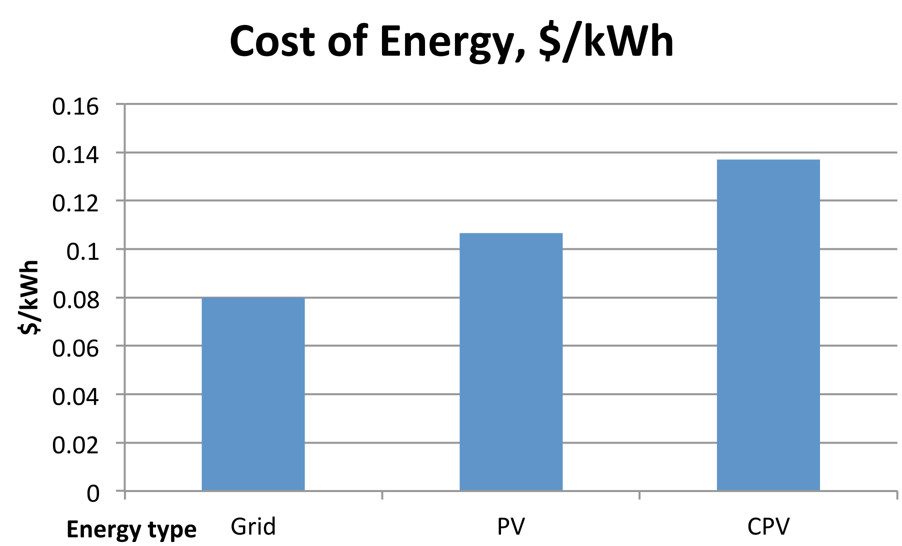


Figure 2: average US energy costs. Data: Barbose 2012, Kurtz 2012, US EIA.

CPV does have interesting advantages over SiPV, particularly on the utility scale in very sunny areas. Economy of scale means that BOS costs are a smaller percentage of the total installed cost, and the expensive supporting hardware of CPV matters less (Goodrich et al. 2012). To put it another way, there is already so much overhead associated with a utility installation, that the extra solar tracking hardware associated with CPV installations are not as expensive an investment, compared with the rest of the BOS and module costs. Furthermore, in very sunny areas, the concentrating optics of CPV allows for longer periods of peak energy generation compared to SiPV. This is seen in Figure 3 (HCPV Siemen 2013).

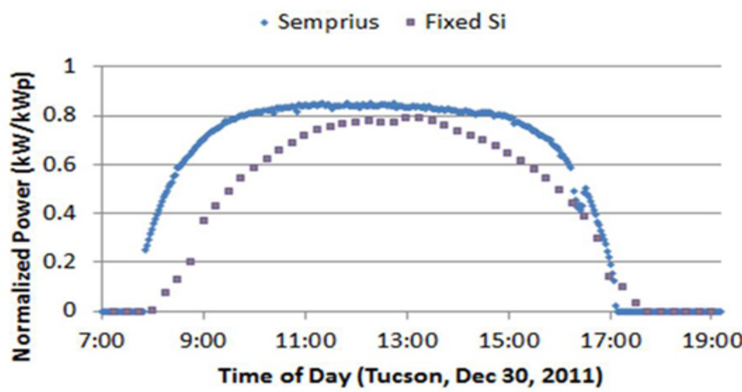


Figure 3: The Semprius CPV panel achieves peak capacity more quickly and for more hours than typical Silicon panels.

Ultimately, both SiPV and CPV are still too expensive in most places to compete, unsubsidized, with traditional energies. However, in areas of high cost energy and/or countries with heavy government support of solar energy, SiPV in particular has reached grid parity. Germany is widely regarded as the global leader in PV adoption because of concerted government efforts to encourage adoption. The average installed cost of solar in Germany is $2.24 per watt, which translates to a cost of less than $.10/kWh (Tracking the Sun, 2012). The cost of grid energy in Germany is $.31/kWh (US EIA).

Many critics of solar energy say it is time for solar to stand on its own feet and compete, unsubsidized, with oil and gas. This is an unfair statement, however. All energy is subsidized to a certain extent. Oil and gas companies have, for the past hundred years, been receiving tax breaks totaling billions of dollars. Conservative estimates put the number at $10 billion a year (Fossil Fuel Subsidies…, 2013). These include a 15% deduction of gross income, and the ability to deduct 100% of the cost of a new operation over 5 years. If the electricity market were truly level, solar power companies and other sources of renewable energy would be able to take advantage of the same tax structure. While the savings would be much smaller than the $10 billion the oil companies save- the solar industry itself is much smaller, after all- the tax breaks would be an important incentive to encourage investment in new, renewable energy infrastructure. Assuming a fairly standard 2% tax rate on utilities (Olin 2009), a $4/W system would be $3.90/W. While not a large price drop on its own, it could help make solar technology more competitive when combined with feed-in tariffs and declining costs.

Subsidies and tax breaks should not be seen as a magic bullet to implementing solar technology, however. Mangelsdorf and Shah at GreenTech Media (2013) point out that solar technology in Hawaii is already at grid parity with traditional energy, and the state's continuing solar subsidies are only impeding innovation. They point out examples like Germany, India, and the UK where subsidies were ended after the financial crisis. Rather than shrinking, the market expanded as companies innovated to bring costs down. What this means for the industry at large is that, while subsidies may be useful to get investment in solar started, they are not by any means necessary for solar to succeed and reach grid parity levels. Governments can still support solar technology through feed-in tariffs, for example, both encouraging growth and tapping into distributed generation to solve a modern society's energy needs.

Geographically isolated regions are likely to pay a premium for electricity. Islands in particular generally have expensive energy, as they import diesel for use in small, inefficient generators. Among U.S. islands, prices range from $.25/kWh in Hawaii to $.49/kWh in American Samoa (US EIA). Of course, the 1.5 billion people currently without access to electricity are another prime market (worldbank.org, 2012). The majority of these people are located in areas with high solar resources, making PV technology a viable solution to their future energy needs (See Figure 4).

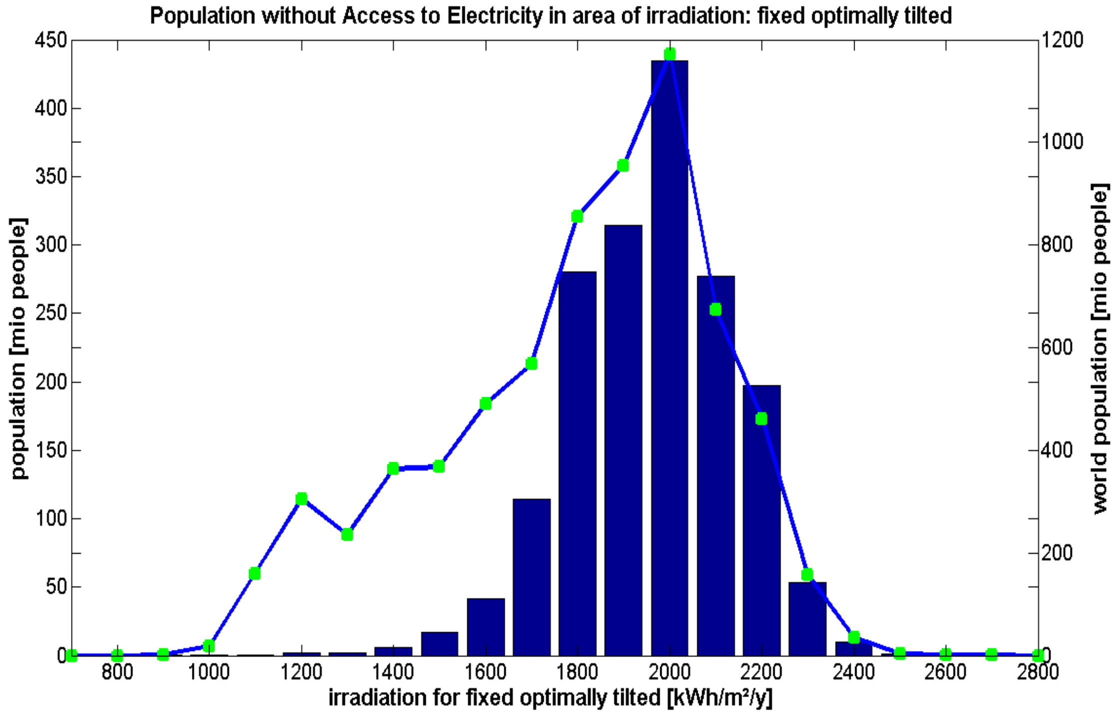


Figure 4: Most of those without electricity access live in areas of irradiation

Analyses

Whether the various solar technologies are at grid parity depends on several factors: the cost of local grid electricity, the cost of the PV module and its BOS, the solar irradiation the modules receive, as well as the efficiency the solar panels are operating at. The structure of government policy, especially subsidies, also has huge impacts on grid parity of solar, but is beyond the scope of this project. In Figure 5 below, the years to pay off various scales of SiPV systems are plotted against the local cost of traditional, grid energy. This is assuming an efficiency of 16%.

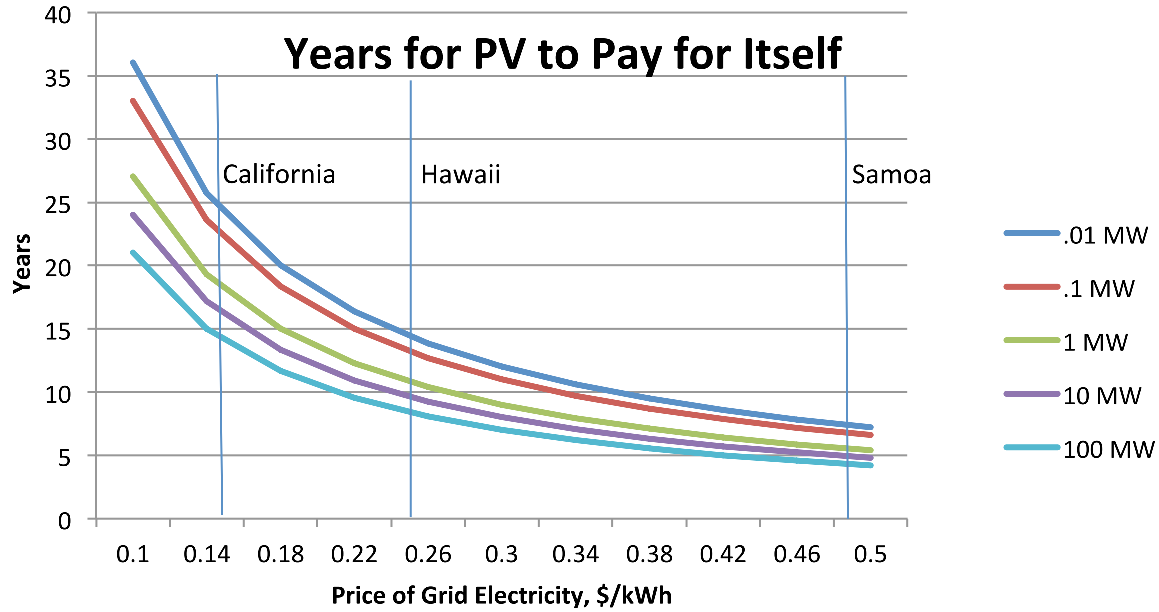


Figure 5: Samoa is a good place to install solar panels. Most of the US still is not.

As the cost of grid electricity increases, solar systems pay for themselves more quickly. In very energy expensive areas, any size solar system will pay for itself in a matter of years. In areas of inexpensive energy (such as Oklahoma, ~$.08/kWh) any solar system will take longer than 20 years to pay for itself. $.145/kWh is the break-even point where even small scale systems are at grid parity. That is to say that the system will pay for itself within its 25 year minimum life span. As seen in the figure, this is the current average price of electricity in California, and one of the contributing factors to the boom in solar installation on the west coast (California Solar Statistics, 2010).

Unfortunately, finding costs of CPV- whether module or installed prices- proved unfeasibly difficult. From very rough estimations, it was assumed that CPV installed costs run about $.60/watt more than a comparable SiPV system. It can be said, however, that the U.S. lags behind other countries in its adoption and encouragement of new solar installations (Figure 6).

Figure 6: Average SiPV Installation Prices around the World

If one is looking to make PV technology more competitive, then lowering the cost of the module and its installation is the most direct way. Module costs are fairly standard worldwide. Where costs wildly differ are in the BOS and lack of government support for solar initiatives. Due to lack of experience of contractors and inefficient legislation, the U.S. BOS is a much higher percentage of the total installed cost compared to a country such as Germany, which has actively encouraged investment in solar infrastructure (Tracking the Sun 2012). Figure 7, from Greentech Media, compares the BOS between regions (Smith 2012), and Figure 8 breaks down the expenses for a typical U.S. utility scale SiPV installation (Tracking the Sun, 2012).

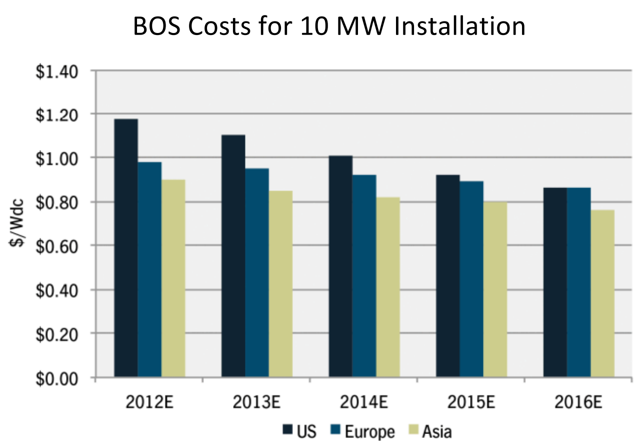


Figure 7

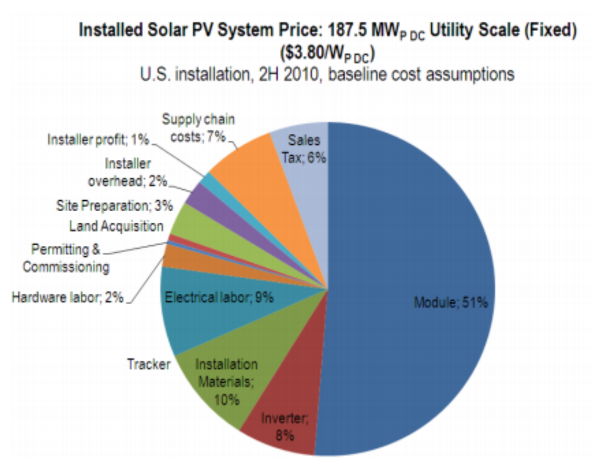
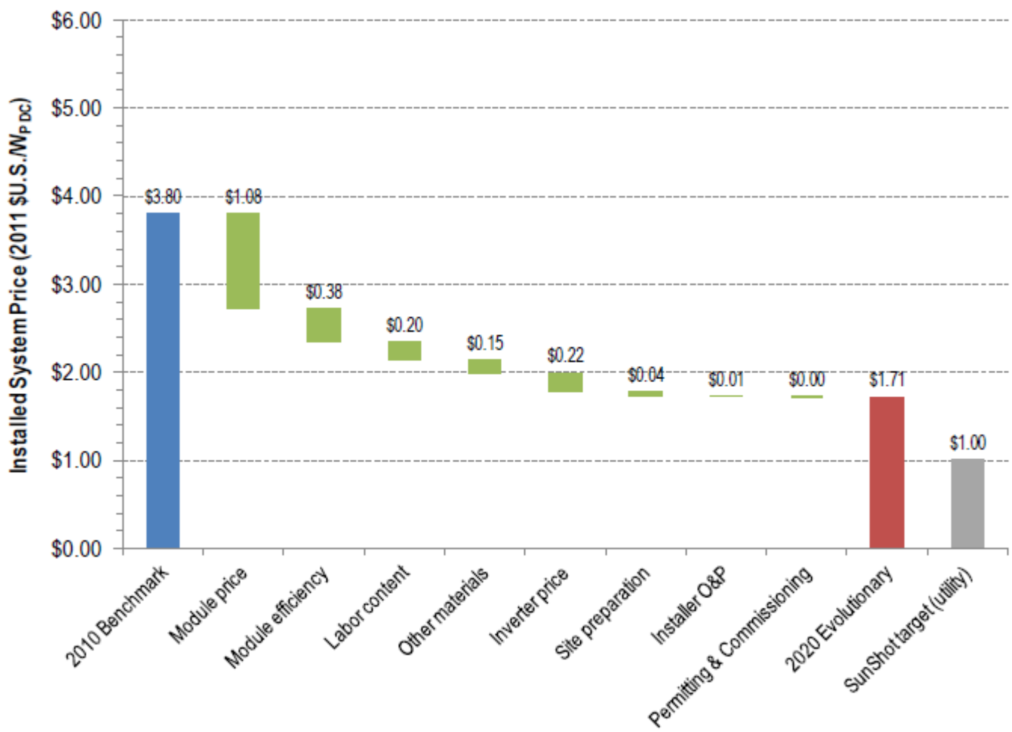


Figure 8

Figure 9 from the National Renewable Energy Laboratory (NREL) corroborates the Greentech Media estimates, though are slightly more conservative. It also includes estimates of where exactly the savings will come from in the BOS, as well as a projected drop in module price of over a dollar per watt. Their module price also includes small scale residential or commercial systems, which do not benefit from the economies of scale that utility level systems do. The NREL figure predicts a large drop in module price as the cost of modules for the smaller scale systems nears the true cost of the unit (Goodrich 2012). The main takeaways from Figures 7, 8, and 9 is that the US PV market still has plenty of price drops to come in the next several years, though the cost will stabilize soon after 2016 as it catches up to international markets.

Figure 9: NREL Projected Decreases in SiPV Installed Cost by 2020



Ultimately, much of the vagaries of installed cost lies beyond what consumers, researchers, or solar technology manufacturers can influence. This is why good siting and improved module efficiency is so important, as they are controllable factors. Beyond the local cost of grid electricity, the siting of a PV system will determine the level of solar irradiation it receives. The more irradiation, the more energy is produced. This is often expressed as a capacity factor, which is the fraction of its peak capacity a given solar system will produce with a given level of average solar irradiation.

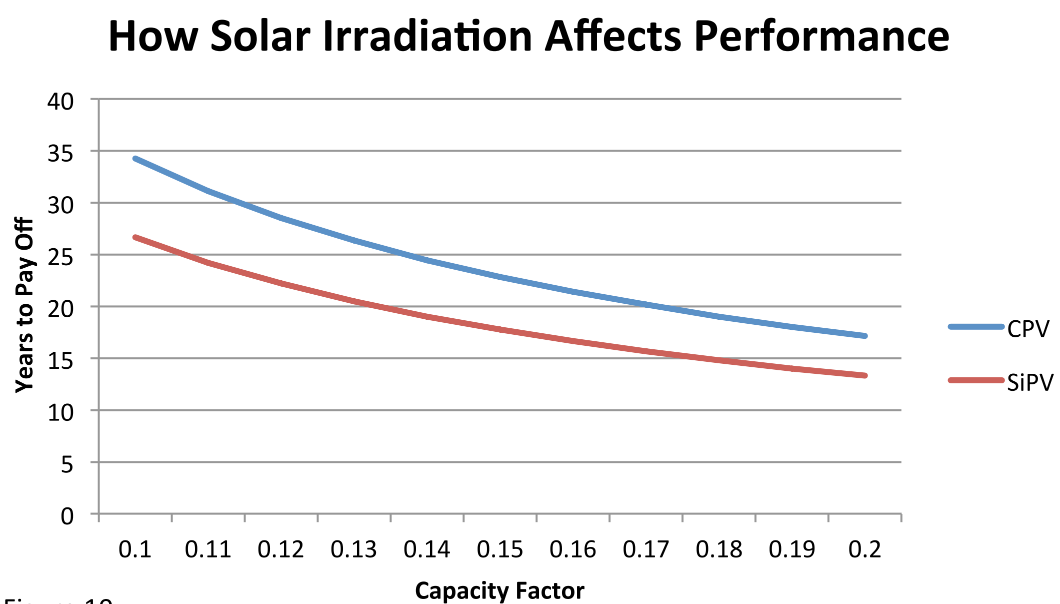


Figure 10

As Figure 10 shows, installing a system in an area of high solar irradiation (capacity factor .19) as opposed to one of mediocre solar irradiation (capacity factor .14) cuts 4 to 5 years off the payback time. Obviously, where the PV system goes is critical (HCPV Siemens 2013).

Efficiency, or how much of that solar irradiation is converted to electricity, is the final major component that determines how cost competitive solar energy is. As discussed previously, there is some, but not much, room for efficiency improvements in SiPV. NREL estimates a further $.40/watt price reduction as a result of increasing module efficiency (Goodrich 2012). Increasing efficiency will have a huge impact on the competitiveness of CPV, however. This is both due to its higher manufacturing cost and the simple fact that it is a less mature technology (Swanson 2000), and researchers are still far from nearing peak efficiency levels with MJ semiconductor materials (Green 2013). And as Figure 11 below shows, improving CPV module efficiency by even 5% can reduce the number of modules needed by a significant amount. By moving the average CPV efficiency from 30% to 35%, a 1 MW installation needs 714 modules (of 4 meters squared each) compared with 833 modules. Approximately one-eighth of the costs were just saved. Indeed, an efficiency of 35% is needed to reach parity with SiPV as is.

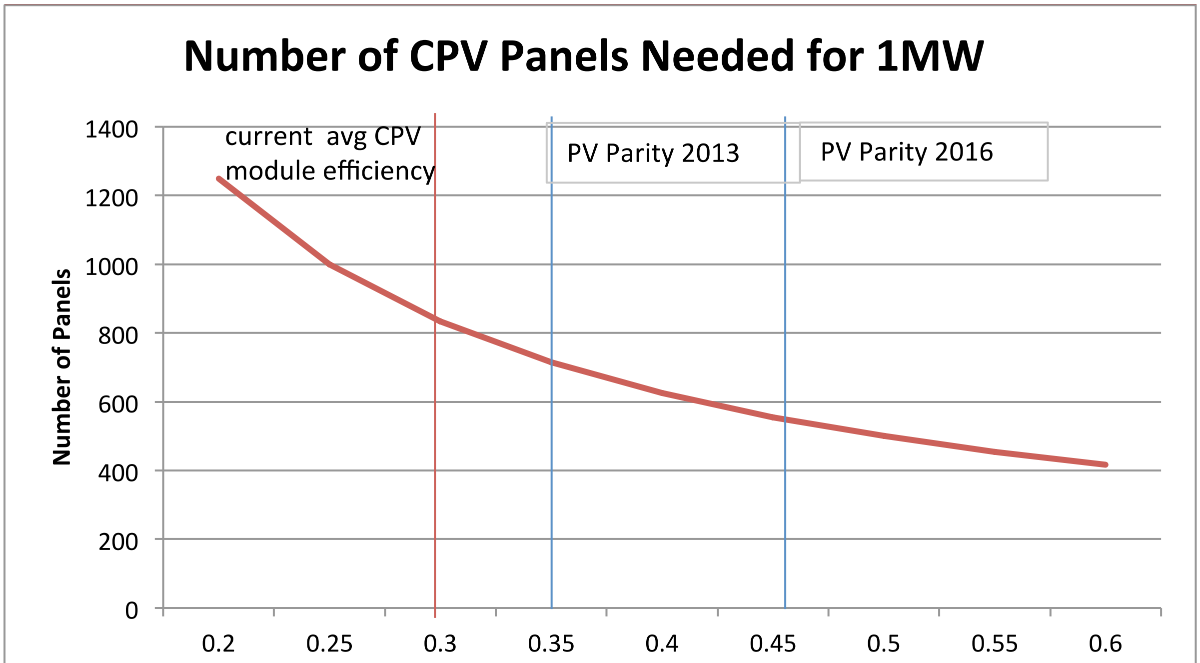


Figure 11: CPV efficiency

Unfortunately, this is a moving target, as SiPV prices are expected to drop from $3.80/W on average to $1.80/W by 2016 (Goodrich 2012). A CPV module efficiency of about 46% is needed to reach parity with SiPV in 2016. The current record for CPV cell efficiency is 44%, in a GaInNAs triple junction cell built by Solar Junction (Green 2013). This is impressive, but module efficiencies are typically lower than cell efficiencies by a significant percent. The amount of semiconductor coverage, actual sunshine conditions in the field, and losses in the AC-DC converter all contribute to make module efficiencies often 10% less than their corresponding cell efficiencies (Kurtz 2012). Good design, siting, and maintenance can reduce these losses. For CPV to compete effectively with SiPV, priority must be given to fully developing more efficient CPV cells. This is why Dr. Sellers' research focus is important, as his group is using low-dimensional structures (quantum-dots and quantum-wells) in single-gap semiconductors such as InAs, InSb, and InN to increase the efficiency of single gap solar cells. This has the potential to increase efficiency to upwards of 50%, while reducing the production costs and improving the unit's lifetime. In addition, GaInNAs cells are also being investigated in the group, specifically to boost the efficiency in more conventional multi junction systems. These would form part of a multi junction cell to be used in a CPV system. If research groups such as his can help achieve cell efficiencies of ~50%, CPV modules as a whole will easily be able to compete with SiPV in the years to come.

Discussion

Ultimately, a variety of things will need to happen for CPV to reach both SiPV parity and grid parity. Many of these will also aid SiPV in achieving grid parity across the globe. CPV efficiency needs to continue to rise, and intelligence used in determining where to construct them. Public policy needs to support and encourage investment in these technologies, particularly in grid-parity areas bogged down with unwieldy legislation and regulation. Finally, more initial investments need to be made in CPV. It has a real chance at being more cost effective for consumers than SiPV in large-scale applications. As a less mature technology, it lacks investment. Regardless, SiPV is quickly becoming an attractive, cost-effective energy choice in many parts of the globe. Any location with high solar irradiation and electricity costs greater than about $.15/kWh could potentially be using solar technology. Especially ideal locations for new deployments, due to a lack of existing grid infrastructure, include tropical islands that import diesel fuel and drinking water, rural desert locations such as the Australian Outback or the American Southwest, and developing countries with a large number of people living without electricity. In the latter circumstances, solar electrification as a component of a well-executed development scheme has the possibility to greatly improve quality of life while avoiding the West's overdependence on fossil fuels.

Figure 12: Paperwork needed to connect PV to grid in California

Case studies

To be considered a good fit for solar energy generation, and therefore for the case studies, a location has to fulfill two criteria:

1. Have good solar resources.
2. Currently have expensive energy.

Beyond that, this paper examines three distinct types of locations.

1. An island
2. An isolated community in a developed nation
3. A community in a poor nation

This will allow for the unique conditions of each to be examined and discussed in relation to solar energy installations.

Case study 1: American Samoa

For the first case study, we will examine two islands of the American Samoa: Tau, and Ofu-olosega. Insolation there is a fairly respectable ~5 kWh/m^{2}day (NASA). American Samoa imports all of its electricity in the form of diesel fuel. This is expensive, and Samoans pay accordingly: $0.49/kWh (US EIA). Because of these two factors, it seems to be a good candidate for solar energy. There are some problems specific to the islands that may impede adoption of solar technology, however.

Specifically, there are three problems. First, there is a lack of funding. American Samoa's only large scale solar operation- 1.75 MW near the main island's airport- was completed only with support from the US Department of energy. Second, usable land is at a premium on small islands such as these, particularly with the National Park on Tau. Finally, the ocean breezes quickly corrode many of the components of a solar module. SunWize, the company that installed the 1.75 MW project mentioned above, dealt with the corroding breezes with specially engineered components (Sunwize Completes the Largest…, 2012). In the analyses below, these extra costs are factored into the installed $/W price. These costs were determined by comparing typical solar installation costs per watt to the cost of the 1.75 MW SunWize project on the island.

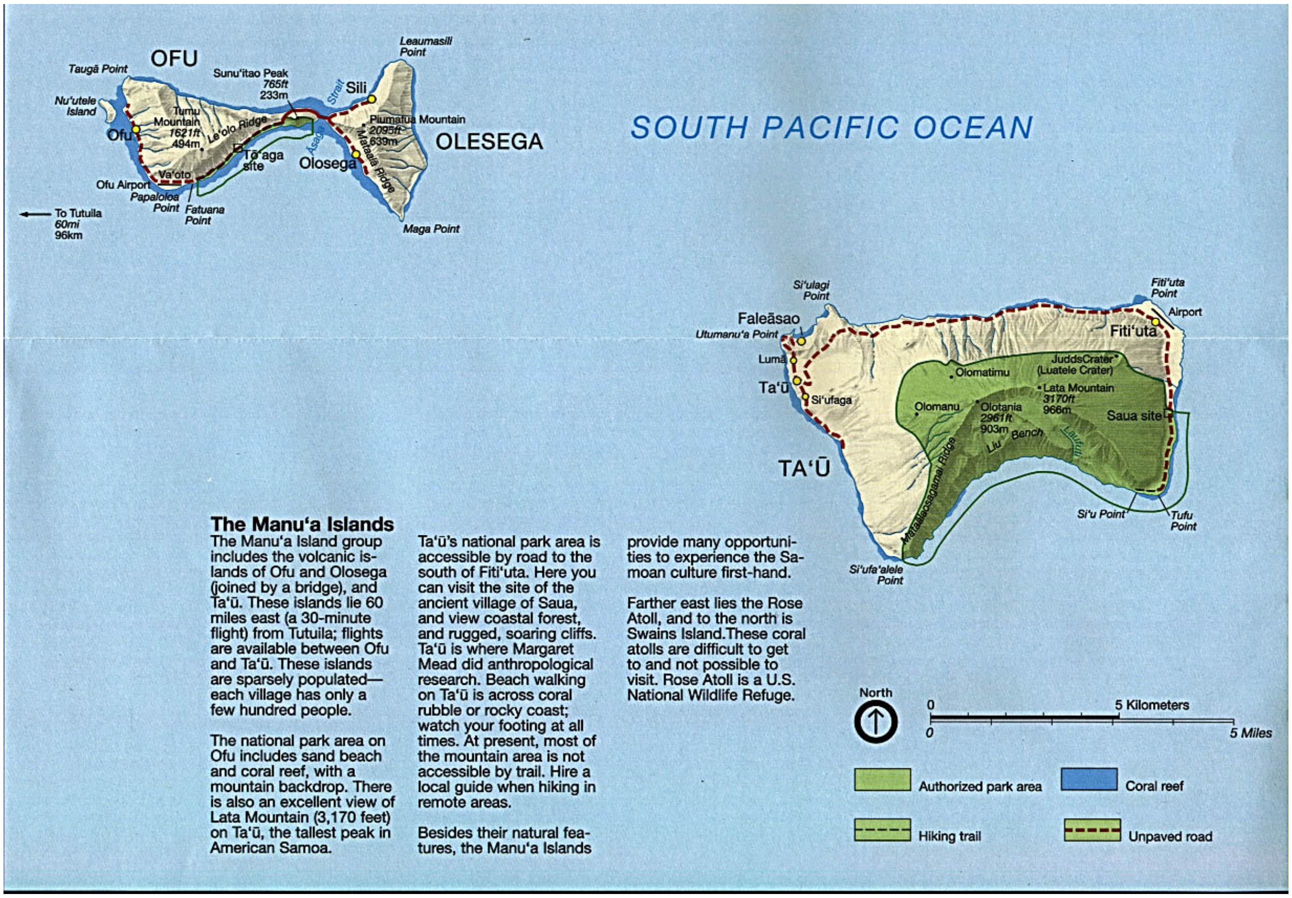


Figure 1: From AquiMapas.com.

A US EPA report proposes a series of wind turbines on Ofu-Olosega and Tau. These could easily be combined with solar panels and battery banks to make the islands almost completely energy independent, allowing the diesel generators to be used only in emergencies. Table 1 summarizes how easily the islands energy needs could be satisfied. A 1MW plant would supply 10% of the annual energy of the Tau and Ofu-Olosega (Manu'a) Islands. This would require 1.24 acres of 20% efficient solar panels. To completely supply the islands with energy, 12 acres are needed. The islands of Ofu-Olosega by themselves are over 3000 acres. Even more important, this system would pay for itself in less than 6 years. If the political will and capital were available, a comprehensive solar generation scheme would be very possible.

Manu'a Islands	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost	Annual solar kWh	Years to repay	LCoE $/kWh
1 MW plant	1378	13780000	1	0,49	5	5000000	1401600	7	0,14
all needs 10 MW	1378	13780000	10	0,49	4	40000000	14016000	6	0,11

Table 1, SiPV

Concentrating photovoltaics pose a bit more of a technical challenge, as they must be secure against often violent gusts of tropical storm winds. We will assume that by the time such a system were installed, the industry standard panel efficiency would be 40%. This is a reasonable assumption as top of the line CPV panels currently have achieved ~34%.

Manu'a Islands	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost	Annual solar kWh	Years to repay	LCoE $/kWh
1 MW plant	1378	13780000	1	0,49	5,5	5500000	1401600	8	0,16
all needs 10 MW	1378	13780000	10	0,49	4,3	43000000	14016000	6	0,12

Table 2, CPV

A concentrating PV system in Samoa pays for itself nearly as quickly as a crystal silicon PV system. Islands such as Samoa, where inhabitants pay a premium for electricity, are therefore unique opportunities to test CPV systems. They cost more to install due to the technical challenges present on the islands, but still pay for themselves in less than 10 years. They may even be more useful than SiPV in land scarce scenarios such as that of American Samoa, despite their slightly higher cost. Because they need to be able to rotate with 2 degrees of freedom to track the sun, they are built on top of sturdy poles that anchor them to the ground. Thus the terrain they are situated on matters less than the amount of sunlight they receive, the strength of the wind in the area, etc. They can be more readily built on steep, rocky slopes than SiPV modules, which are designed to be installed close to the ground (Irena 2012). As a general note, PV technology continues to be a smart investment on sunny islands that import expensive diesel fuel.

Case study 2: Birdsville, Australia

The next case study we will examine is that of a rural community in a developed nation. Australia is a good choice for this, as they are highly developed in general yet large parts of the country remain undeveloped. Although any rural Australian community works for our purposes, we will specifically consider the interior of Queensland. Birdsville, for example, has a population of 283. Due to a well developed electricity grid, electricity coverage is essentially 100% (australia.gov.au). The government subsidizes rural electricity so that rural customers pay the same as urban customers. Costs are still relatively high, about 0.30$/kWh (Rolfe 2012). This, combined with Australia's ample solar resources (6 kWh/m^2 day at peak conditions) and good government support of solar technology, make solar a good candidate for adoption (Solar Streetscapes).

Figure 2: Birdsville is located in the sparsely populated interior. Google Maps

This is all the more true considering Australia's mid-day, summertime peak loads stressing cash-strapped utility companies. Space is not an issue in Australia as it was the in the example of American Samoa, though we can assume areal requirements to be slightly smaller as

Australia receives more insolation. Table 3 and 4 detail the analyses performed on solar systems for the region. The SiPV systems- 1 and 1.7 MW, pay for themselves in 6 years. A relatively low install cost/W combined with the expensive of grid energy means a quick turnaround time on the investment, and a low levelized cost of energy. CPV, as previously, requires a higher up front cost. The levelized cost of energy, and required years to repay, are only slightly higher for the CPV system than SiPV. Costs were calculated based on country averages (Brakels 2013).

Birdsville	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost $	Annual solar kWh	Years to repay	LCoE $/kWh
1 MW plant	283	2830000	1	0,3	3	3000000	1664400	6	0,07
all needs (1.7MW)	283	2830000	1,7	0,3	3	5100000	2829480	6	0,07

Table 3: Analysis of SiPV in Birdsville, Australia

Birdsville	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost	Annual solar kWh	Years to repay	LCoE $/kWh
1 MW plant	283	2830000	1	0,3	3,5	3500000	1664400	7	0,08
all needs (1.7MW)	283	2830000	1,7	0,3	3,5	5950000	2829480	7	0,08

Table 4: Analysis of CPV in Birdsville, Australia

Australia is ideal for solar energy generation, and Tables 3 and 4 demonstrate. PV is at grid parity in the entire country, since utility prices are fairly standard throughout thanks to government subsidization. Solar can then be seen as a way to bring electricity to rural parts of the country without burdening taxpayers with a rural electricity subsidy, as new systems pay for themselves in 6-8 years. To this end, the country is installing more solar capacity each year, and the Australian government seems dedicated to supporting it. Additionally, some of the world's leading photovoltaics research occurs in Australia. This is important for the solar industry at large, but particularly for CPV. Australia is an excellent testing ground for CPV technology. Besides the government and popular support for solar technology, the high cost of grid energy makes solar, and CPV, attractive. These primary differences between Australia and, for example, the United States, could mean the difference between the technology succeeding and failing. CPV must find markets such as that of Australia where CPV is competitive in order to "iterate" the technology up to the level of SiPV.

Case study 3: Usuk, Uganda

As a final case study we will examine a community in the developing world. Specifically, we will look at Usuk, Uganda. Both the village (which has a population of about 1,500) and the county of Usuk are unelectrified. The nearest grid connection is in nearby Soroti, of population 66,000. The average cost of energy in Uganda is $0.14/kWh (afdb.org). In the case of Usuk, the cost would be substantially higher. First, a connection to the grid would need to be made. Each kilometer of new electric line costs about $10,000 (NRECA). Then there is the cost of connecting each household individually, for which power companies charge consumers anywhere from $50-$200. Current energy generation in the area may not be enough to reliably supply power to additional consumers, especially as Uganda is already plagued by constant blackouts (Green 2012). Usuk lies 66 kilometers, along the local roads, from Soroti. Total connection costs would then be upwards of $80,000 for the community (assuming 5 people per household) just to gain access to the unreliable grid. Due to relatively low consumption rates, low population density, and therefore little opportunity for profit, utility companies are unlikely to invest in villages such as Usuk.

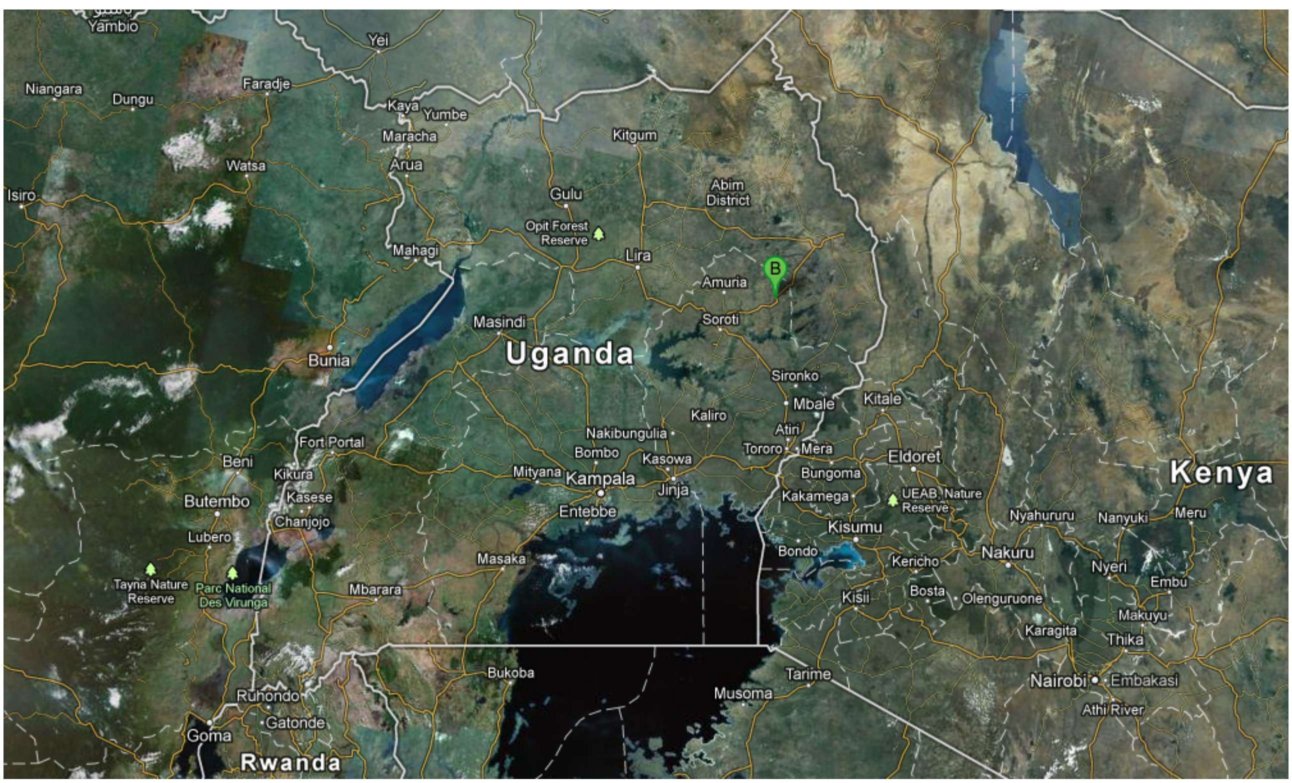


Figure 3: Usuk, Uganda. Google Maps.

Renewable energies such as solar can provide a reliable, sustainable, and cheaper (in the long run) solution to the development potential of communities such as Usuk. The biggest obstacle to solar energy in the area is cost. Due to the area's relative remoteness and lack of development, solar power will cost more per watt in Usuk than in the developed world. Module costs are atleast $2/W (Kulabako 2013). Factoring in the BOS, an installed price of $4/W is reasonable. Because there is no grid connection in Usuk, battery banks are needed for storage, adding $0.20/W to the system cost. Average per capita per annum energy consumption 200 kWh, though this is very conservative due to the large numbers of people without electricity. For a more reasonable consumption, the average of more developed African states is used, or 600 kWh (afdb.org).

Usuk	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost $	Annual solar kWh	Years to repay	LCoE $/kWh
500 kW plant	1500	900000	0,5	0,14	4,2	2100000	832000	18	0,10

Table 5: SiPV in Usuk, Uganda

As can be seen from table 5, a $2 million investment is needed, which would take 18 years to repay. This investment could easily be secured, given enough support on the ground in Uganda, thanks to a large amount of low interest, long term development loans provided by organizations such as the World Bank. Over its 25 year lifespan, the 500 kW solar system has an LCoE $0.04 lower than that of the grid.

Usuk	Population	Needs kWh/yr	Size MW	Grid $/kWh	Install $/W	Total cost	Annual solar kWh	Years to repay	LCoE $/kWh
1 MW plant	1500	900000	0,5	0,14	5	2500000	832200	21,5	0,12

Table 6: CPV in Usuk, Uganda

CPV poses a greater logistical challenge to install, due to the greater complexity and maintenance of the parts. For this reason the disparity in cost/W with SiPV is greater compared to the other case studies. Regardless, the LCoE is still cheaper than the Ugandan utility average. But, convincing an underdeveloped community to invest extra in the system may not be feasible.

Conclusion

The case studies have illustrated the trends and principles discussed in the analysis. We have seen how grid electricity pricing, solar resources, and government policy all affect the viability of solar energy. Regardless, in each location solar panels, whether concentrating or crystal silicon, were cost effective investments. In general, PV is at grid parity anywhere with adequate solar resources (~4 $kWh/m^2/day$) and electric utility prices greater than \$0.15/kWh. Concentrating photovoltaics lag behind silicon technology, but not by much. Investments in CPV in locations such as Australia and American Samoa could be the push the industry needs to get the technology iteratively on par with SiPV. In fact, for many places, cost is no longer an issue but rather government policy that encourages adoption of solar technology.

Appendix 1: ABET Engineering Considerations

Economic

This paper aims to understand where solar technology can succeed economically.

Environmental

Solar technology is a “prosperous way down” from fossil fuel dependence.

Sustainability

Solar tech rated to last 25 years, uses renewable resources (the sun) to make power

Manufacturability

Solar technology already very iterated. Paper provides clear efficiency goals for Sellers’ research team to aim for.

Political

Paper examines the importance of political support for solar initiatives to succeed.

Health and Safety

Solar technology is quite safe, and removes many of the health risks associated with burning carbon fuels.

Social

Renewable energy initiatives, particularly distributed renewable energy iniatives, are one of the keys to expanding global consciousness and increase empathy (and thus knit a stronger social fabric).

Ethical

Solar technology can be considered more “ethical” than traditional fossil fuels as they have comparatively low environmental impact.

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