PDHonline Course E200 (2 PDH)

Advances in Solar Electric Generation Technology

Instructor: Jeffrey Havelin, PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

Chapter 3

A Primer on Solar Generating Technologies

Whereas the public often associates flat panel photovoltaic (PV) with solar power, it is in fact thermal solar power plants, such as parabolic trough, power towers, and dish Stirling, that can provide economic large-scale power generation today. With PV, electric power is produced by light directly in a semiconductor, while in thermal solar generation the heat of the sun is used to power an engine or turbine.

The 354-MW parabolic trough solar thermal power plants in California's Mojave Desert (see "The 354-MW SEGS Power Plants") contribute more than 70% of the worldwide production of solar electric energy. The capacity of these plants is 140 times greater than the 2.5 MW of utility PV installed in the West as of October 2000. And, it is 2.5 times larger than the cumulative capacity of all PV cells—from calculators to the international space station—ever sold in the U.S. since the solar cell was first invented.

Thermal solar power plants, such as dish Stirling, power towers, and parabolic trough, are cost-effective means of generating electric power from solar energy. They are simple, well understood, and already achieve efficiencies currently out of the reach of commercial PV cells. Though both PV and thermal solar generating technologies have risks, the type of risk is different. Thermal solar power plants are simply new applications of technologies originally developed for fossil fuel power generation, the chemical industry, and the military. Solutions for most of the technical challenges they would expect to face have probably already been devised, whereas advances in PV will require advances in materials.

In the following sections we provide a primer on solar generating technologies from flat panel PV to solar towers.

Photovoltaic Electric Power

At the heart of any PV cell, commonly known as a "solar cell," is a semiconductor junction, which absorbs light within a certain frequency range and creates an electric potential. PV cells with only one such junction, the typical PV cell, can only utilize a portion of the light spectrum. This is one of the reasons that the efficiency of even the best single-junction cell does not exceed 16%. Inherent losses due to imperfections in the semiconductor and losses related to the semiconductor's operating temperature are other reasons.

Multi-junction PV cells are able to use a wider spectrum of light and thus achieve higher efficiencies. However, these devices are difficult to manufacture and so expensive that their use is limited to special applications, such as in space or for concentrating PV. Flat panel PV cells, typically made from silicon, are used for small solar power applications, from solar cells on rooftops to modules on traffic signals, and are easily recognized by their bluish panels.

In the last five years, the worldwide PV industry has seen growth of about 20% annually and the industry is bullish about the future, especially after the California energy crisis. Domestic shipments of PV cells increased 74% during the two-year period ending in 2000, reaching approximately 75 MW of peak power.[1] It is doubtful, though, that this kind of growth is sustainable, because the projected penetration levels of distributed generation, such as rooftop PV, appear too optimistic in the face of near-term forecast power prices. The crisis mentality of the California energy crisis is already subsiding, and the public is taking a more strategic approach to meeting western energy supply needs.

Flat Panel PV

Flat panel PV is the best-known application of PV modules. Many semiconductor materials can produce electricity, but today crystalline and amorphous silicon solar cells are still the only commercially available flat panel PV cells. The high production cost of PV cells remains the technology's biggest impediment to larger market penetration and large-scale power generation. It is for that reason that PV research in the last decade focused on using alternative semiconductor materials with the goal of achieving lower cost.[2] While progress has been made on that front, it is unclear at this point whether and when exotic PV materials will be able to compete with silicon-based cells.

A unique characteristic of flat panel PV is the fact that it can use both diffused and direct normal radiation. This makes PV most attractive in areas with clouds and haze. But overall radiation levels are likely to be low in such areas as well, and it is questionable whether utilizing a marginal energy resource makes sense in the first place.

Exhibit 37 provides an overview of today's cost and performance of flat panel PV based on data from an ongoing program to install flat panel PV units in the 70-100 kW range.[3] The program has seen module costs drop significantly in recent installations, but the structures necessary to support and connect the modules (balance-of-plant) will continue to comprise a considerable portion of the unit cost. The cost reductions in the program were mainly due to better module-buying strategy rather than module production cost reductions. Even at current annual production volumes, which are already approaching 100 MW, the capital cost of flat panel PV is still very high.

Exhibit 37: Cost and Performance of Flat Panel PV and Concentrating PV

	Flat Panel Photovoltaic (1)		Concentrating PV
	Crystalline Silicon	Amorphous Silicon	
Unit Size	50 x 2 kW =100 kW	50 x 2 kW =100 kW	22–28 kW
Max Conversion Efficiency % (2)	13	6.5	18–19
Generation Threshold W/m^2	≥50 (3)	≥50 (3)	50
Annual Average Efficiency % (4)	11	6	TBD
Annual Avg. Capacity Factor % (4)	24	24	30–32
Equiv. Forced Outage Rate (EFOR)	TBD	TBD	1–3
Off-sun Generation	None	None	None
Acres/MW	3.8	7.6	8–10
Construction Time	2 weeks	4 weeks	3–4 days per unit
Capital Cost $/kW	7,500–8,500		TBD
Fixed O&M $/kW-year	10	TBD	10
Variable Non-fuel O&M $/MWh	10	TBD	10
Production Capacity for U.S. Market MW/year	68	6.5	TBD
Cumulative U.S. Sales	140 MW		0.5 MW
Largest Unit in the U.S.	1 MW		TBD
Demonstrated System Hours	Unknown	Unknown	TBD

SOURCE: National Renewable Energy Laboratory (NREL); Golden, Colorado, private communication; see reference in endnote 3.
(1) Commercially available technologies only. Crystalline silicon modules account for about 90% of the flat panel PV market, while amorphous silicon modules account for the remaining 10%.
(2) At 1,000 W/m^2.
(3) Direct normal and diffuse radiation.
(4) Premium solar resource area. Flat panel PV tilted to latitude.

Concentrating PV

PV cells using multiple semiconductor junctions are capable of converting a much larger spectrum of sunlight to electricity than the single-junction cells used in conventional flat panel PV and thus have much higher efficiencies—up to 30%.[4] Nevertheless, multi-junction cells can be used more cost effectively if sunlight is concentrated first. The same solar module then produces more power than under normal light conditions. For example, if mirrors or lenses concentrate light on multi-junction cells and increase the sunlight concentration by a factor of 10, that cell will produce about 10 times more power than under direct sunlight. Concentrating PV (CPV) uses mirrors or lenses to focus sunlight on high-efficiency cells. The concentrating optics, as in all concentrating solar power technologies, can only focus direct normal radiation, but not diffuse light.

The idea behind CPV is that a few high-performance (and high-cost) PV cells are put to maximum use by concentrating light on them by using either mirrors or lenses. Because the concentrating optics is cheaper than PV modules, this approach is expected to result in an overall lower system cost. Currently, most CPV systems use lenses to concentrate sunlight and employ two-axis tracking mechanics to follow the sun as it makes its way across the sky. Exhibit 37 provides cost and performance data on CPV.

We believe that CPV is a promising form of PV power generation because it uses only one-tenth, or even less, semiconductor material than flat panel PV and it can thus employ more expensive and efficient PV cells. CPV uses cheap lenses to leverage the costly PV modules and is likely to reach a lower cost of power than flat panel PV. Due to the smaller size of the panel per kilowatt, the use of a two-axis tracking mechanism is possible, and worthwhile, which increases overall system efficiency and capacity factors.

While PV benefits from technology transfer from the semiconductor and computer chip industry, solutions to many of the challenges that will make PV economical are not known at this point. As the recent decade has shown, efficiency gains and cost reductions in commercial PV are hard to come by. Nevertheless, research in PV should continue. PV is reliable and requires little maintenance. And CPV has the potential to leverage PV cell performance.

There are inherent advantages to using PV. Besides being able to use both direct and scattered light, PV cells have no moving parts and, because PV uses the photoelectric effect, it can, in theory, reach efficiencies not possible with any practical thermodynamic cycle. Yet, we believe that in the near term PV, especially flat panel PV, will only play a small role in large-scale solar electric generation.

Thermal Solar Power

Thermal solar power plants use the heat of the sun to generate electricity. By itself, the sun's heat would not be enough to power engines or turbines. Therefore, in thermal solar power plants, the sunlight is first concentrated using mirrors either on a single point or on a tube. For this reason thermal solar power plants (and concentrating PV) are collectively referred to as concentrating solar power (CSP) technologies. There are three different thermal CSP technologies: power tower, parabolic trough, and dish Stirling.

The three systems differ in the way they concentrate and collect sunlight, but the final step of generating electricity is identical, in that an engine or turbine is used to convert heat to electric energy (similar to a conventional power plant). The solar collectors concentrate the sunlight, and the light then hits a heat collector, which contains a heat transfer fluid that powers an engine or steam turbine. Simply put, a solar thermal power plant is a conventional power plant using the sun's heat as the energy source. Therefore, thermal power plants can be hybridized with fossil fuels because it is heat, not light as in PV, that powers the plant, and that heat can come from any source.

Power Towers

Two systems were built in the 1980s and 1990s, as demonstration plants. The units operated successfully, but were decommissioned after the demonstration period. Though new power tower systems are not being actively pursued in the U.S., there is activity in Spain on a third power tower (Solar Tres). If successful abroad and if a solar power market develops in the U.S., the companies involved in projects abroad would likely bring the technology back to the U.S.

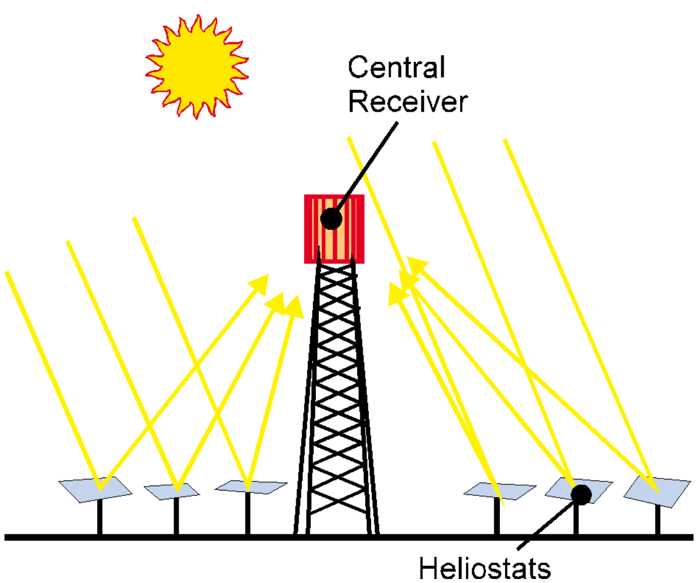
In the power tower concept, a large array of mirrors (called heliostats) tracks the sun in a way that reflects the sunlight onto a central receiver mounted on top of a tower. The sunlight is absorbed and turned into heat, which in turn powers a steam cycle. Exhibit 38 shows the design of a power tower. Parabolic trough plants and power towers can use molten-salt heat storage or fossil fuel hybridization to generate power when the sun does not shine. In molten-salt technology, salt is heated to a point at which it liquefies, hence the term molten salt.

Power towers have some general advantages over other solar generating technologies. Because an array of hundreds of mirrors focuses the light on one central receiver, the temperature of the thermal cycle is very high, resulting in good steam cycle efficiency. Molten salt, the heat transfer and energy storage medium, poses no threat to the environment. The high temperature of the working medium also results in better heat storage cycle efficiencies than is possible with parabolic trough plants.

When heat storage is used, the solar field is usually oversized so that heat can be dumped into storage while the remaining solar field continues to generate enough heat for the plant to continue to operate at its rated capacity. The ratio of solar field thermal capacity to electric capacity is called the solar-to-electric capacity ratio. A solar power plant with a ratio of 1.8 has a solar field that, under normal sun conditions, produces 80% more energy than the plant's electric power rating. A 100-MW plant with a solar-to-electric capacity ratio of 2.0 would have a 200-MW solar collector field.

The electric load shape and associated power prices in a market determine which solar-to-capacity ratio with how many hours of heat storage provides the greatest value to the plant owner. Optimization algorithms are used to determine the plant design. For the Desert

Exhibit 38: Design of a Solar Tower



SOURCE: *Status Report on Solar Thermal Power Plants*, Pilkinton Solar International, 1996. Used with permission.

Southwest, it appears that at today's cost for solar collectors and heat storage, a solar-to-electric capacity ratio of 1.8 with four hours of storage provides the greatest value.[5]

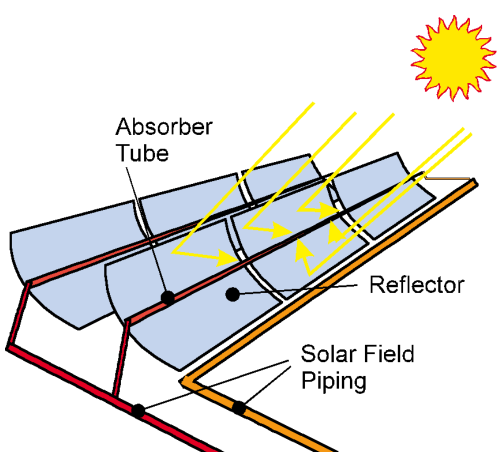
While the two power tower demonstration projects were successful, the units only operated for a limited time, and more long-term experience with the technology would be desirable. In particular, the reliability of the solar receiver at the top of the tower is unclear until longer-term operating experience can be obtained, even though the second receiver built for the Solar Two project verified the design expectations. In the receiver, thin-walled tubing and its joints are subject to considerable thermal stress, which could lead to cracks. However, Boeing Co., the maker of the solar receiver and the molten-salt storage system, has applied its experience from rocket engine nozzle technology, where comparable high heat transfer thin-wall tubing technology is employed, to solar towers, and it is confident that the receiver and storage technology will perform reliably.

On the downside, power towers must take advantage of economies of scale and can only cost-effectively be built in 50- or 100-MW units. Also, power towers require the largest amount of space per megawatt of energy produced of any CSP technology. Detailed cost and performance data are summarized in Exhibit 40.

Parabolic Troughs

The solar field of a parabolic trough plant consists of long parallel rows of trough-like reflectors—typically made of glass mirrors. As the sun moves from east to west, the troughs follow the trajectory of the sun by rotating along their axes. Each trough focuses the sun's energy on a pipe located along its focal line (see Exhibit 39). A heat transfer fluid, typically oil at temperatures up to 400°C (750°F), is circulated through the pipes and then pumped to a central power block area, where it passes through a heat exchanger. The heat transfer fluid then generates steam in a heat exchanger, which is used in turn to drive a conventional steam turbine generator.

Exhibit 39: Design of a Parabolic Trough System



SOURCE: *Status Report on Solar Thermal Power Plants*, Pilkinton Solar International, 1996. Used with permission.

Beyond the heat exchanger, parabolic trough plants are just conventional steam plants. It is for this reason that parabolic trough plants, like power towers, can use heat storage with molten salt, or hybridization with fossil fuel, to generate electricity when the sun does not shine. The relatively low operating temperature of the parabolic trough steam cycle at 400°C (750°F) compared to conventional thermal power stations, or even power towers, limits the efficiency of the plant. This lower operating temperature also results in a lower heat storage cycling efficiency than what can be achieved with power towers.

Several commercial units with sizes up to 80 MW have been built and still operate today ("The 354-MW SEGS Power Plants"). Detailed cost and performance data for parabolic trough plants are summarized in Exhibit 40.

Heat storage for new parabolic trough plants will be accomplished using molten-salt storage. This technology, which was demonstrated with power towers, has not yet seen a commercial application, but it promises to be more economical and safer than the original technology employed at one of the SEGS parabolic trough plants. One of the first SEGS parabolic trough plants used Caloria, a mineral oil, for heat storage, which, like the heat transfer fluid in the collectors of the troughs, is a highly flammable liquid. This 13-MW plant provided three hours of heat storage, but an accident set the storage unit on fire and destroyed it.

This points to a general hazard at parabolic trough plants. The heat transfer fluid in the heat-collecting elements of the solar field is currently a highly flammable organic compound, which is also used in the petrochemical industry. Fires, therefore, pose a danger to parabolic trough plants. However, a similar fire hazard exists at many industrial facilities that handle flammable liquids, including refineries.

Like a conventional steam plant, parabolic trough plants require large amounts of cooling water, which may be difficult to obtain in the desert where solar power plants will be located. Power towers have similar cooling water requirements. Only dish Stirling and PV technologies do not require cooling water.

Improvement in Heat Collector Efficiency

During a site visit at Kramer Junction, California, RDI Consulting toured the SEGS parabolic trough plants. Sunray Energy operates units I and II, and the Kramer Junction Co. (KJC) operates units III through VII, while units VIII and IX, a few miles down the road, are operated by FPL Energy.

The KJC and the FPL units recently received a row of new heat collecting elements (HCE) from the manufacturer SOLEL, a vestige of the former LUZ development company. And at both plants, the plant operators confirmed that the new elements had increased the heat collection efficiency of the HCE by about 18%. This is a significant improvement in the performance of parabolic trough plants and equivalent to a capital cost reduction of the solar field.

Exhibit 40: Cost and Performance of Thermal Concentrating Solar Power Plants

	Dish Stirling	Parabolic Trough	Power Tower
Standard Plant Size	2.5 MW/100 MW	100 MW	100 MW
Max Conversion Efficiency % (1)	30%	24%	22%
Generation Threshold W/m^2	200	300	300
Annual Average Efficiency (2)	21.40%	13.70%	16.00%
Annual Avg. Capacity Factor (2)			
Basic Plant	25.20%	23%	29%
With Thermal Storage (3)	N/A	33% (4 hrs, 1.8 x)	48% (8 hrs, 1.8 x)
With Fossil Fuel Hybridization	N/A	23-95%	29-95%
Equiv. Forced Outage Rate (EFOR) %	5 (estimate)	5	5 (estimate)
Off-Sun Generation	Fossil Hybrid	Heat Storage/Fossil Hybrid	Heat Storage/Fossil Hybrid
Acres/MW of Collectors	4	5	8
Construction Time (4)	3-4 days per unit; 35 days/6 months	12 months	12 months
Incremental Capital Cost			
Basic Plant $/kW	2,650	1,956	2,065
Heat Storage $/kWh	N/A	103	27
Additional Solar Field $/kW	N/A	510	540
Fossil Fuel Hybridization $/kW	Not commercial	196	196
Fossil Heat Rate (HHV) (4)	TBD	10,800	10,000
Incremental Fixed O&M $/kW-year			
Basic	40/2.5	33	30
Heat Storage	N/A	2	1.5
Additional Solar Field Only	N/A	2	1.5
Fossil Fuel Hybridization	N/A	–	–
Incremental Variable Non-fuel O&M $/MWh			
Basic	16.80/15	2	2
Heat Storage	N/A	–	–
Fossil Fuel Hybridization	N/A	–	–
RDI estimated new Capacity (MW) that could be built (5)			
2002	0.7		–
2003	3.1	30	–
2004	27.5	100	50
2005	75	200	50
2006	100	300	150
Total	206.3	630	250
Cumulative U.S. Installations	118 kW	354 MW	10 MW
Largest Unit in the U.S.	25 kW	80 MW	10 MW (decommissioned)
Demonstrated System Hours	80,000	300,000	2,000

(1) At 1,000 W/m^2.
(2) Premium solar resource area.
(3) The number of hours of full-load heat storage and the solar-to-electricity ratio are given in parentheses, e.g. "(3 hrs, 1.6 x)" means three hours of full-load electric generation from heat storage and a solar field, which is oversized by 60% with regard to the electric capacity of the power island.
(4) Based on natural gas.
(5) Assumes sufficient tax or buydown incentives and private sector financing, but no government-backed programs, such as loan guarantees.

Dish Stirling

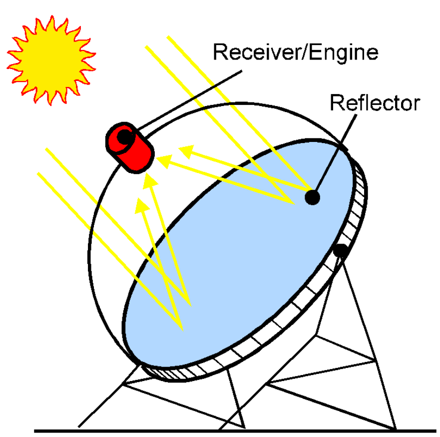
A dish Stirling system consists of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point. These concentrators are mounted on a pedestal and can pivot on two axes to follow the sun. This two-axis tracking mechanism allows the capture of the highest amount of solar energy at any time possible. A schematic of the dish Stirling principle is shown in Exhibit 41, and a photo of a dish Stirling system owned and operated by Stirling Energy Systems (SES) is shown in Exhibit 42.

The concentrated heat is utilized directly by a heat engine mounted on the receiver, which moves with the dish structure. Stirling cycle engines are currently favored for power conversion. All practical and commercial dish systems currently use Stirling engines. Dish Stirling systems achieve peak efficiencies of up to 30% (net). The typical value for a unit's peak electrical output is about 25 kW.

Conceptually, the dish Stirling system is the simplest of all thermal solar technologies, but the Stirling motor that converts the heat is a sophisticated closed-cycle motor that is highly specialized for this application. Stirling motors are not found in many applications. They are used as an ultra-quiet motor in attack submarines and for small power generation units (gen-sets). However, market penetration of Stirling gen-sets is marginal due to the dominance of the combustion motor (diesel gen-sets).

Stirling motors have accumulated tens of thousands of operating hours on dish Stirling systems; one dish Stirling unit owned and operated by SES is 17 years old and demonstrates that most of the materials that were used are durable. This system has operated, albeit with interruptions, for over a decade and a half. Newer units, manufactured for Science Applications International Corp. (SAIC) by STM Power, have not worked quite as reliably as expected, and this has raised questions about Stirling motor reliability. The motors used by SAIC and manufactured by STM Power are different from the motors used by SES but there are some concerns as to whether new units based on SES' design will work as well as its existing motors that were built over a decade ago.

Exhibit 41: Design of a Dish Stirling System



SOURCE: *Status Report on Solar Thermal Power Plants*, Pilkinton Solar International, 1996. Used with permission.

It is for that reason that both SES and STM Power have engaged in serious evaluations of their motors. Both companies are confident that new motors could be produced in large numbers at low cost and would be more reliable than current motors. However, doubts remain, because the performance of laboratory bench prototype Stirling motors, which are fired by natural gas, does not translate well into solar applications. This is because the solar flux that hits the heater head of a dish-mounted Stirling motor is less homogenous, resulting in thermal stress and pressure differentials in the pistons of the motor.

Aside from questions about the reliability of the Stirling motor, the dish Stirling is the quintessential thermal solar power plant:

- Its two-axis tracking mechanism allows it to maximize solar energy collection.
- The generation threshold is relatively low.
- The unit ramps to grid synchronization within a minute.
- It has the highest efficiency of any solar generating technology.
- It requires the least amount of land in relation to peak capacity and energy production.
- Its high engine-operating temperature allows air cooling, thus eliminating the need for cooling water.

Exhibit 42 shows SES' dish Stirling system.

Dish Stirling units share many characteristics with wind turbines. Like wind turbines, dish Stirling units are intermittent energy sources, have only a pedestal as footprint, can be built within days (actual assembly takes only a few hours), and come in small unit sizes and are thus modular. Tactics for marketing dish Stirling plants, therefore, could emulate some of the market penetration tactics used for wind turbines. They also allow for smaller solar farms that may fit better into renewable energy portfolios and can be expanded in modules. In contrast, a 100-MW parabolic trough plant requires an all-or-nothing investment decision of $200 million to $300 million.[6] The same is true for power towers.

Dish Stirling to Set New Efficiency Record

Both SES and STM power are currently aggressively pursuing the introduction of dish Stirling systems into the market and are engaged in the development and construction of new dish Stirling units. Research at SES' existing units has shown that the air-cooling system was originally over-engineered and that decreasing the cooling capacity can reduce parasitic loads. Additional changes to the motor design and the collector system will, in SES' view, improve (net) peak efficiency at its next units by 10% from currently near 30% to 33%. This would set a new

Exhibit 42: SES Dish Stirling System

SOURCE: Stirling Energy Systems. Used with permission.

world record for the efficiency of any solar power generating technology and would increase annual electric output by 6.3%.

Beyond the Economics

In this section we compare some of the characteristics of CPV, dish Stirling, power towers, and parabolic trough, because these technologies are very different from one another.

In this report we have presented both a "distributed" as well as a 100-MW dish Stirling solar power plant, because dish Stirling is modular. Currently, individual units have a capacity of only 25 kW. These units are designed to be eventually fully automated, contain only small amounts of hazardous coolant, and require no cooling water to operate. Further, they make very little noise[7] and have a relatively low profile. For these reasons, dish Stirling can be installed close to residential areas.

Their modularity and easy interconnection make dish Stirling systems attractive for small or mid-sized customers. Even though dish Stirling is more expensive than parabolic trough or power towers today, the amount of capital required to install the first unit is low—around $100,000. This makes dish Stirling systems similar to wind turbines, and their early entry into the market may come from small installations of one or a few dozen dishes.

Most of what we have said about dish Stirling systems also holds for CPV systems. Anticipated CPV unit size is 22-28 kW, similar to dish Stirling, making CPV a direct competitor with dish Stirling. CPV would even be more suitable for distributed installations because of its low O&M needs.

Parabolic trough plants and power towers, in contrast, are large industrial facilities. Economies of scale suggest that unit size should be about 100 MW (electrical). For a parabolic trough, the heat transfer fluid used in the heat-collecting elements of the solar field is currently a highly volatile organic compound and is hazardous. Because fires in parabolic trough plants are serious threats (and have occurred), these facilities must be built away from residential or industrial areas, with associated investments in transmission lines. Also, land below the solar collectors needs to be kept free of all vegetation in order to avoid grass or brush fires that would have the potential to destroy the solar plant. This weed control is currently done using herbicides, which may concern local environmental agencies as well as customers who are shopping for green power. Wind loading is also a greater problem for parabolic trough than for dish Stirling units.

Power towers avoid the hazardous heat transfer fluid by using molten salt. The salt is non-toxic and, in fact, is used as a plant fertilizer. Soil sterilization is not required because the focal point of the mirrors is at the top of the power towers—far off the ground—and no volatile heat transfer fluids are present. Of all CSP technologies, power towers are the most visible due to the tall receiver tower, and they occupy more land per megawatt-hour produced than any other CSP technology.

Parabolic trough plants and power towers also require large amounts of cooling water—commensurate with those of other steam plants, for example, coal. Only natural gas–fired combined cycle plants can achieve lower water requirements, and they only consume about one-half to one-third of the cooling water required by a steam plant. Solar resources are greatest in desert areas, but here water is a scarce and precious commodity. Therefore, the fact that cooling water is required for parabolic troughs and power towers is a big drawback for these technologies. Both power technologies could, however, address this issue by employing dry cooling or a mix of dry and wet cooling. However, these technologies, which are available to any thermal power plant—solar, coal, or nuclear—result in a higher parasitic load and thus in a lower net efficiency of the plant.

Parabolic trough plants and power towers can incorporate heat storage and fossil fuel hybridization, which allows them to displace existing capacity from the market, as we have shown in the section, "Using Supplemental Off-Sun Power." Their ability to dispatch power also allows them to earn a higher average price for power.

The monthly energy production of parabolic trough plants is more seasonal than for other CSP technologies. Parabolic troughs show a much greater drop in output toward the winter than dish Stirling, CPV, and power towers. This is because the latter three technologies use two-axis tracking systems while the solar fields of a parabolic trough plant are composed of rows of parabolic troughs that only pivot on one axis. This results in less efficient tracking of the sun in general and in particular during the winter months.

The efficiency of dish Stirling power plants is the highest of all solar technologies, and as little as four acres of land are required per megawatt of power. This means that a dish Stirling system can produce 60% more solar electric energy on the same plot of land than, for example, a parabolic trough plant.

It is our view that an emerging solar power market will shake out the mix of solar power generating technologies. Dish Stirling, CPV, parabolic trough, and power tower are such fundamentally different technologies that all could have a place in the market, at least initially. The optimal supply solution will be influenced by many factors, including economics, aesthetics, environmental concerns, availability of cooling water, practicality, safety, and funding. Nevertheless, CPV and dish Stirling will be in direct competition, as will power towers and parabolic troughs.

Existing Solar Power Plants in the West

While PV cells are often associated with solar power, only 2.5 MW of utility PV solar power operate in the West. The majority of this capacity has been built under the TEAM-UP program of the Solar Electric Power Association since 1996.[8] The largest facility is a 1-MW PV system owned and operated by the Sacramento (California) Municipal Utility District. In contrast, nine units of thermal solar plants using parabolic troughs located in the Mojave Desert near Kramer Junction, Daggett, and Harper Lake in California have been delivering 354 MW of power to Southern California Edison (SCE) for over a decade.

The parabolic trough plants are hybridized with natural gas and can deliver round-the-clock power. However, by U.S. federal law, the energy supplied by natural gas is limited to 25% of the total effective annual thermal plant energy output. During California's energy crisis in 2000 and 2001, these plants were able to forgo the use of natural gas and continue to deliver power to SCE, thus providing a hedge against volatile fuel prices.

The 354-MW SEGS Power Plants

The 354 MW of parabolic trough solar power plants, called Solar Electric Generation System (SEGS), in the California Mojave Desert in the vicinity of Barstow, were built over a seven-year period in the late 1980s and early 1990s. The plants were developed by LUZ International Ltd., a U.S. firm with strong ties to Israel, and each plant is owned by a separate limited partnership. Over the course of the project development, the unit size increased from 13.8 MW to 80 MW. The first unit had a capacity of 13.8 MW; six subsequent units were 30 MW each; and the last two units had a capacity of 80 MW each. SEGS I had two large (hot and cold) storage tanks for heat storage that allowed the plant to operate off-sun for nearly three hours at full load. Subsequent plants utilized a gas-fired boiler or heater to selectively supplement solar electricity production during peak demand periods.

In the 1980s, the state of California strongly encouraged renewable power production. As a reaction to the second oil price crisis, when the crude oil price rose to nearly US$40 per barrel, tax incentives were given to independent renewable power projects. Further, the California Energy

Commission required utilities to buy energy from so-called "qualifying facilities" (QF) under the federal Public Utilities Regulatory Policy Act (PURPA) at high fixed prices under long-term standard offer contracts. Between 1984 and 1991, first under private agreements and then with the help of the attractive standard offer long-term power purchase agreements plus federal and state tax incentives, LUZ erected the nine parabolic trough solar power plants in the Mojave Desert. To build these plants, $1.3 billion was raised—initially from private risk capital investors and next, with increasing confidence in the maturity of the technology, from institutional investors.

The first step occurred in 1983 when LUZ negotiated a 30-year contract with SCE to sell electricity from the first two plants—a 13.8-MW facility followed by a 30-MW plant. Subsequently, the standard offer 30-year power purchase agreements that were in place for the third to seventh units had fixed energy payments for the first 10 years and energy payments based on the avoided fuel cost of the electric utility for the remaining 20 years, which were initially linked to the price of fuel oil and later to natural gas. For the eight and ninth plants, the initial 10-year period of fixed energy payments was eliminated. However, the standard offer capacity payments were fixed for 30 years for the third through ninth plants. Given the expected high oil and gas prices in the early 1980s, the forecast revenue stream was very good.

However, several developments changed the economic environment that LUZ encountered by the time the seventh unit was completed.[9] First, additional new QF capacity with increasingly better heat rates had entered the market and thus lowered the avoided cost to utilities. Secondly, when oil and gas prices rapidly fell in the middle of the 1980s and remained at a low level, non-fixed energy payments dropped. Both effects significantly reduced the revenues projected for potential owners. These and other market factors translated to a higher return on investment being demanded by investors.

Up through the seventh plant, the capacity was artificially limited to 30 MW by FERC rules, but this limitation was then lifted, allowing much larger 80-MW plants. Other technical changes by LUZ, while beneficial, increased the perceived risk to investors, again raising the bar on the required return on investment. In 1985, the investment tax credit legislation expired, requiring year-to-year extensions to maintain this important incentive. During this time, LUZ also encountered difficulties with union labor issues, with premium payments to suppliers due to the tight schedules, high internal financing costs, and pressure from investors to offer even more attractive returns.

Despite these barriers, LUZ continued its development with two 80-MW units. Late approval to construct from the California Energy Commission, an early end date on the tax subsidy, and problems with construction management led to significant construction cost overruns by the completion of the ninth unit. While LUZ still achieved the construction of the plant, the company was financially weakened.

During the 1991 development of the 10th plant, another regulatory issue added further grief and accelerated the end of the parabolic trough success story. The state of California recognized the greater property requirements for solar plants in comparison to conventional fossil fuel-fired power stations and, therefore, exempted the solar system part of the plant from the state property tax. This exemption expired at the end of 1990 and was not renewed until May 15, 1991. This additional constraint, combined with the December 31, 1991, requirement for interconnection of the plant to benefit from the available tax credits, meant that the 10th plant had to be constructed in about seven months, a period that was not manageable without high added costs. This circumstance plus the other growing financial barriers resulted in the inability of LUZ to obtain construction financing. This situation, combined with a generally weak financial condition, forced LUZ to file for bankruptcy in mid-1991.

The bankruptcy of LUZ, however, did not result in closure of the nine parabolic trough plants, as each was owned by a limited partnership with a small LUZ involvement. The main need was to replace the LUZ entity that operated and maintained the plants under contract. Today, units I and II are operated by Sunray Energy; units III through VII are operated by KJC Operating Co.; and FPL Energy operates units VIII and IX. All units continue to operate with mixed success. Notably, the Kramer Junction site, with SEGS III-VII, has set performance records in recent years and has systematically lowered its O&M costs. All nine plants deliver reliable power to southern California.

The demise of LUZ teaches some important lessons. Consistency and stability of tax and energy policies are essential. Specifically, for highly capital-intensive new technologies, stable policies are a prerequisite in an early development stage. The unpredictable changes experienced in this particular case not only exhausted LUZ financially but put additional risk and insecurity on the investors.

Exhibit 43: Units III Through VII of the LUZ Parabolic Trough Solar Power Plant in the Mojave Desert, Kramer Junction, California

SOURCE: National Renewable Energy Laboratories (DOE). Used by permission.

Endnotes

[1] Associated Press, "Solar Gets Its Day in the Sun," NYTimes.com, accessed August 5, 2001.

[2] National Renewable Energy Laboratory, *Photovoltaics: Energy for the New Millennium*, January 2000.

[3] Solar Electric Power Association, *Large System Cost Report*, October 2000, Washington, D.C.

[4] National Renewable Energy Laboratory [2].

[5] This is, therefore, the design of the parabolic trough proxy plant with storage in our financial analysis (see "The True Cost of Using Solar Power").

[6] Smaller parabolic trough plants can be built, but these plants would forgo some of the lower costs that result from economies of scale.

[7] There is some noise from the fan of the cooling element, but it is comparable to the noise from a car fan.

[8] Solar Electric Power Association [3].

[9] For an excellent discussion of the LUZ story written at the time by a LUZ executive, see Michael Lotker, *Barriers to Commercialization of Large-Scale Solar Electricity: Lessons Learned from the LUZ Experience*, SAND91-7014, Sandia National Laboratories, November 1991.