

Concentrating Solar Power

Robert F. Boehm

Distinguished Professor of Mechanical Engineering
Director of the Energy Research Center
University of Nevada Las Vegas (UNLV)
Las Vegas, NV 89154-4027 USA

Abstract

Several approaches to concentrating solar power systems are reviewed. With the current heightened interest in renewable energies, terrestrial locations where concentration can be used effectively will potentially benefit from a large number of new systems on the market, as well as the enhancement of technologies that have been applied previously. Included are both thermal-based systems and photovoltaic (PV) systems. In this summary, several categories of concentrating technologies of current interest are discussed as are storage issues. Tradeoffs between the different approaches are noted, and some prospects for the future are hypothesized.

Introduction

Concentrating solar systems have been in existence since the time of ancient Greece. Legend had it that the Greek Archimedes used mirrors to burn the sails of attacking Roman ships at Syracuse, but this is probably a myth [Butti and Perlin 1980]

The world has seen many kinds of concentrating solar power systems conceived over the years. Developments that can be attributed to the modern thrust of this started approximately at the beginning of the 20th century, and there has been increasing interest recently.

It is the intent of this presentation to give a state-of-the-art review of concentrating technologies and to discuss the tradeoffs of the various approaches. This will not be a step-by-step tabulation of all systems examined in the past but rather a discussion of issues. Both concentrating solar thermal and concentrating solar PV will be discussed. All of these technologies come under the general name of concentrating solar power (CSP).

CSP Issues

Concentration opens a number of opportunities for solar power systems. In thermal systems, concentration allows much higher temperatures to be generated than would be possible with simple flat plate systems. This, in turn, results in higher temperatures within the associated thermal engine. As is well known from Second Law of Thermodynamics ideas, higher temperatures result in higher engine thermal efficiencies. Another benefit of concentration that goes hand-in-hand with this one is that the profile of the heated element is relatively smaller than flat plate systems

(comparing energy harvested per unit area of collector). This allows special attention to be given to minimizing the heat loss from the receiver elements.

In PV systems, concentration permits tradeoffs between solar cells, which are generally more expensive, against tracking mechanisms and support structure, which are generally less expensive in comparison to the PV. Concentration allows for each PV cell to produce proportionally more power. One negative aspect for concentration for PV cells, unlike solar thermal systems, where concentration raises the temperature of the receiver in both cases, is that increasing temperature usually decreases cell efficiency. So there may be more power out of the cell with concentration, but the efficiency of operation of each cell is lower than the comparable one sun system, all other aspects being equal.

Direct beam radiation is required for concentrating systems to be effective. Diffuse components of the radiation are not of value in these approaches unless the concentration is small. In addition, large amounts of flux are preferred to make the capital investment in these systems more profitable. Several locations in the world meet this requirement. For example, the solar radiation resource in the US is shown in Figure 1. This resource is enormous, as shown in Figure 2 which is a representation that an area of land approximately 100 miles (161 km) on a side could furnish all of the US's electricity needs with current technology. However, several issues come into play when the choices of locations for concentrating solar plants are selected. For these plants, only the beam radiation is to be considered. Also, rugged landscape is to be shunned. Generally a relatively flat area is preferred. When these factors are considered, the areas where plants can be located are far less numerous. See Figure 3. Here all land areas with greater than a 3% grade have been eliminated. Another factor that comes into play that is depicted here is that the plant has to be near a major power corridor. Construction of large lengths of major power lines can be extremely expensive.

Figure 1. Shown is the map of the US indicating the average annual solar radiation per unit area per day. Courtesy the US Department of Energy.

Figure 2. In this representation from the US Department of Energy, the fact is depicted that the total electricity requirements of the US could be furnished from solar energy falling and converted on a 100 mile x 100 mile (161 km x 161 km) area of the state of Nevada.

Figure 3. This plot of the southwestern US and northwestern Mexico shows the direct normal solar flux only on land that has less than a 3% grade. Major transmission lines are also shown. (From NREL.)

Concentration can be accomplished in a variety of ways in two general categories: single axis (line focus) and dual axis (point focus) tracking. There are many kinds of single axis approaches because of a fixed axis (which can be fixed in a variety of ways) in one dimension and a moveable

one in the other. In all of the concentrating systems, the beam can be developed either by refracting or reflecting the incident energy. Generally applications of refracting systems are less frequently used in practice, and these are usually for PV systems.

Lastly, but certainly not least, cleaning is required for the concentrating elements of all CSP systems. Some geographic areas will be more prone to lens or mirror soiling than others, but cleaning is a necessity. Usually water is used for this purpose, so some water must be available for these kinds of systems even if it is not used for cooling purposes. Some treatments are available that facilitate rain running off of surfaces quickly if they are oriented in a direction that gravity can be of assistance. It is desirable to have surfaces that stow facing downward during periods of darkness and inclement weather to minimize the cleaning requirements.

Concentrating Solar Thermal Power Generation Approaches

Trough Technology

This approach uses a fluid circulating through a field of collectors where energy is reflected from a very large dimension parabolic trough (often aluminized or mirrored in some way on the inner side) to a small tubular arrangement along the axis. The small tube is often a metallic absorber where the fluid flows and a glass tube concentrically located around it to increase the resistance to heat loss.

Between 1984 and 1990 the Israeli company Luz International built several plants using this technology in the Mojave Desert region of California. An interesting analysis of this development is given in the book by Berger [1997]. In all, a total of 364 MWe of these plants were constructed. Each of these series of plants was over 15% more cost efficient than its predecessor [Ricker 2008].

Solargenix (now Acciona Solar), recently made further improvements to this technology and built plants that include a 1 MWe organic Rankine cycle plant in Arizona and a 64 MWe (75 MWe maximum capacity) plant in Southern Nevada. The latter is shown in Figure 4. This plant includes 760 parabolic troughs with more than 180,000 mirrors, 18,240 4-m long tubes, and heats the field fluid to 390°C (735°F).

It is usually the case that an organic fluid circulates through the field and returns hot to a heat exchanger where the heat is transferred to steam. The steam then traverses a conventional Rankine cycle engine.

Figure 4. Nevada Solar One, a 64 MWe plant owned by Acciona Solar began power production near Las Vegas during 2007. (From Acciona).

Several other companies have begun to develop potentially large solar thermal plants that also use a line focus approach. One of the concepts being used is to replace the parabolic trough with a

segmented set of nearly flat mirror facets that can individually follow the sun. One such manufacturer is Ausra Power (Palo Alto, California) that is using a technology that was developed in Australia. See Figure 5. The benefits from this approach are claimed in the field design. The facets are lower to the ground and offer a smaller wind cross section than do parabolic troughs. Also, the receiver tubes are stationary, so no flexible connections are required between trough segments as is the case with the parabolic troughs, and thus the new design is claimed to be able to handle high-pressure steam in the field. No heat exchanger would then be required to remove heat from the field fluid for the Rankine cycle fluid for these types of designs.

Figure 5. A newer concept of a line focus solar thermal plant has been put forth by Ausra Power. In this approach, long and transversely nearly flat facets each rotate on the ground to focus the direct beam radiation on a fixed receiver overhead. (Compliments of Ausra Power).

Power Tower (Central Receiver) Systems

In the power tower system, a large number of ground-mounted mirrors are made to follow the sun on a nearly instantaneous fashion, reflecting the sunlight to the top of a centrally located tower where a receiver section is located. The receiver design could take a variety of forms, but a typical one is a series of parallel tubes that cover the outside of the structure. Depending upon the type of fluid circulating through the receiver (both steam and molten salt have been used in various experiments that have been performed previously), there may or may not need to be a heat exchanger to transfer the collected heat into steam for the conventional power block. Heat rejection systems for these types of units are either wet or dry cooling towers. Of course, the latter use no water for cooling (ideal in desert areas), but operate at a slight decrease in engine efficiency compared to wet cooled systems.

These kinds of systems can be large. The original unit was Solar One, located just outside of Barstow, California, which is also in the Mohave Desert region. See Figure 6. The tall tower was illuminated by a surround field of 1818 heliostats. Each of the heliostats had an area of 40 m². The unit produced 10 MWe when the receiver fluid was steam. A later modification to the plant enlarged the field somewhat and used molten salt mixture of 60% sodium nitrate and 40% potassium nitrate as the receiver fluid, with a heat exchanger to transfer the heat to steam for the power block. Some degree of thermal storage was incorporated into both configurations. When steam was the receiver fluid, an organic heat transfer fluid was used as the storage medium. When molten salt was used as the receiver fluid, it served as the storage medium.

Figure 6. An overhead photo of Solar One near Barstow, California, is shown. Note the surround heliostat field that is on the order of 800 m across the horizontal direction. (From Google Earth.)

Abengoa Solar has two tower projects in Spain. See Figure 7. One, PS10, is a tower that generates 11 MWe. To do this, it uses 624 heliostats that are each 120 m² in area. Unlike Solar One in California, this plant does not use a surround field. Rather it has a north-side field, which

Abengoa feels is more efficient for their location. Next to PS10 is PS 20 that should generate 20 MWe. This is slated to come on line in 2008-2009 time frame.

Figure 7. This photo shows PS 10 in operation in the background and PS 20 under construction in the foreground. (From Abengoa Solar.)

More recently some smaller configurations of these types of systems have been proposed. When smaller towers are considered, the fields are smaller and several units might be located in adjacent spaces, perhaps more than one feeding a given power block.

Dish Stirling Systems

These units are usually found on a dish arrangement where both the mirror facets and the engine/generator follow the sun throughout the day. Unlike the trough and the power tower arrangement, which can be constructed for large power ratings from a single engine, this approach requires many smaller units (typically around 25 kWe each) to be constructed.

The basis of this approach is the Stirling cycle, which is known to be one of the more efficient thermodynamic engines because of nearly constant temperature heat transfer processes. In these devices the working fluid (a gas) is contained in the engine housing and is usually either hydrogen or helium. A low molecular weight fluid is preferred for this application because of its good heat transfer characteristics and low-pressure drop behavior. Ambient air is used for heat rejection purposes. The dish maintains a high solar flux on the heat input area of the engine, and air is circulated over a heat rejection area, usually through one or more compact heat exchangers.

Two different designs of dish-Stirling systems are shown in Figure 8. The one in the right foreground is a design developed by McDonald-Douglas in the 1980's that later sold the terrestrial application rights to Stirling Energy Systems (SES). This type of system demonstrated the highest efficiency conversion rates of sunlight to electricity for any type of system of around 30%. The SES unit used fixed mirror facets and an engine that was developed by the Scandinavian firm Kockums. SAIC International developed the unit shown on the left side, and it used stretched membrane facets that could be focused by exerting a slight vacuum on the chamber behind the membrane in each facet. It used an engine developed by Stirling Thermal Motors (STM). Both units produced an output of nominally 25 kW. When installing these kinds of systems, a significant pedestal has to be constructed that penetrates the ground a distance appropriate to counteract wind loads, but these types of units are designed to move to stow position in very high winds.

Figure 8. Two different designs of dish-Stirling solar devices are shown on the UNLV campus in the early 2000s. The unit on the right is a design owned by SES, and on the left is a design from SAIC International. (Courtesy of UNLV.)

More recently SES in conjunction with Sandia National Laboratories has redesigned several aspects of its system. They have moved toward a more production-oriented design, and several of these units are shown in Figure 9.

Figure 9. Units of the current design of the SES dish-Stirling system are shown here at Sandia Laboratories. (Courtesy of Sandia Laboratories.)

As is the case with both the trough and power tower technologies, several companies are developing dish systems of this design. Although much utility interest in this approach has been expressed, the author is not aware of any systems of this type in actual commercial production.

Tradeoffs between Troughs, Power Towers, and Dish Stirling Systems

- The dish approach currently offers the highest conversion efficiency of sunlight to electricity compared to the other thermal approaches.
- Most operational experience has been demonstrated with trough systems, and these have been shown to offer the lowest cost of produced power.
- Trough and tower systems both operate on Rankine cycles, which, in general, allow the application of commercially-available power blocks as are used in conventional steam power plants.
- Storage, which will be discussed later, is more conveniently applied to the trough and power tower approaches compared to the dish systems.
- Dish systems can theoretically be installed in small increments of units for a large system, so that power can be generated more quickly in the construction phase of the project, and additional power levels can be added quite conveniently at later times.
- Power tower and trough systems have shown best cost effectiveness in very large systems, while the cost effectiveness of Stirling units is less dependent on this aspect. In fact, a few units of Stirling systems can easily be installed to satisfy smaller loads in, for example, remote locations.

Concentrating Photovoltaic Approaches to Power Generation

Overview Comments

In more recent times, attention has been brought to bear on concentrating photovoltaic systems [Swanson 2000]. In the period when his paper was written, CPV systems had not lived up to their promise of large-scale applications, partially because the cost of alternative fuels was relatively low, and flat plate PV developed quite rapidly. The latter had the ability to be applied to roof structures, thus opening a large market for them. Concern about tracker reliability was also a

factor that held back CPV development. Since the market was small, the companies involved in this technology could not realize the economies of mass production and all of the related benefits that this implies.

This situation is obviously changing. For one thing, cell efficiencies have increased substantially over the years. Some of the highest efficiency cells (developed for the space program) that can convert over 30% of the sunlight into electricity, are available but at very high costs. The only possible terrestrial application for these is probably included in a concentrating system. Also, we are facing rapidly escalating conventional fuel prices, driven by higher costs of oil. Swanson [2000] indicated that 10% of the output efficiency goes to pay for everything but the cells, so if efficiency increases, it encourages the application of CPV approaches.

One additional benefit of CPV systems compared to fixed flat plate systems is their ability to capture more of the sun's energy because of their tracking nature, compared to fixed flat plate PV systems. When more efficient cells can be applied to the CPV systems, this can greatly boost the energy generated for this approach. In all, Swanson [2000] discusses the following benefits for CPV compared to fixed flat plate systems.

- Lower cost
- Superior efficiency
- High annual capacity factor
- Fewer material's availability issues
- Less toxic material use (compared to thin film systems)
- Ease of recycling
- Ease of rapid manufacturing capacity scale-up
- High local manufacturing content

For the purposes of this presentation we will put CPV into two imprecise categories: low concentration and high concentration. This is a result, in general, of the temperature of operation and the corresponding quality of cell required to appropriately utilize the concentrated beam. Low concentration will be cells that can be one-sun units, and passive cooling (or no cooling) could always be used. On the other hand, high concentration units will require improved fill factors and some well designed cooling system, either passive or active.

For example, very high concentration systems for PV applications have been reported rendering up to 10^4 suns [Gordon et al. 2004]. These are obviously not production systems, but rather special experimental systems. At the other end of the spectrum, JX Crystals is producing a 3x system [Fraas et al., 2007]. Hence a wide range of concentrations is potentially available for PV systems.

The cells used in these kinds of systems can range from conventional one-sun types up to multi-junction (mj), very high efficiency, types. In between lie high efficiency single junction cells. It had been shown that for high concentration systems' applications, high efficiency single junction cells were more appropriate than mj cells [Slade et al. 2005], but that may be changing in favor of the mj cells as they become more developed for this market.

Unlike concentrating thermal systems, where virtually all concentrators are of the reflecting type, CPV systems can have refracting or reflecting configurations. This is due to the possibility that a given element can focus onto a single cell individually. Typically Fresnel lenses are used for the former and mirror-like reflectors are used for the latter.

Since concentration not only boosts the cell incident flux, it also generates more heat within the cell compared to one-sun situations. When concentrations are sought at very high levels, enhanced heat removal from the cell is almost always called for. This is because most types of cells suffer a decrease in efficiency when the cell temperature increases. See, for example, King et al. [1997].

High Concentration Systems

High concentration systems might be defined as using concentrations above 10, but this is not a precise definition. Many of the systems now being marketed have design concentrations in the range of 100-500x, but 1000x doesn't seem too far from reality.

One of the companies that has been quite active in this field is Amonix, which is located in the Los Angeles, California, area. Recently, Amonix has marketed both a 25 kW system and a 35 kW system with a 350x concentration. More recently they have been evaluating 500x systems. A building block of their systems is a 5-kW Megamodule[®] that consists of many dispersed cells each with a Fresnel concentrating lens mounted on a configuration that assures structural integrity. Cooling of the cells is performed passively using a simply-configured heat sink on the rear side of the system. As is the case with any high concentration system, a two-axis tracker is used to follow the sun across the sky. Their design has utilized high performance silicon cells of their own design, but this might be moving to a mj cell configuration as the latter become more economical. About 20% system efficiency was demonstrated for the former, but the mj cells may boost this to well over 30%. It is anticipated that their Megamodule[®] may experience an enhanced output of nearly 8 kW, compared to the original 5 kW unit, with these types of cells. In a similarity to operational aspects of dish Stirling systems noted above, the system must be mounted on a sunken support structure, and the system goes into stow position (horizontal) when local winds reach high values. A photo of several Amonix high concentration PV (HCPV) systems is shown in Figure 10.

Figure 10. An array of 25-kW Amonix designs in Spain. (From Amonix.)

Another approach to HCPV systems is the use of a dish. Some investigation of this type of system has taken place in the past (see Figure 11). In the figure a design developed by SAIC International is shown. The nominal output of this device was also 25 kW, using fixed facet mirrors. The unit at the focus of the beam looks very much like the Stirling engines shown in Figure 8, but in this case it is entirely a cooling unit for the PV module that is located on the side closest to the facets. In fact, it is made up of four radiators that are similar to those found in trucks, and air is forced through them from a large fan located on the side opposite from the PV array. The latter had high flux cells that were very similar to the ones used on the Amonix units, but in this application they are mounted in a dense array at the focal point of the beam from the dish. They were mounted to a copper plate that had cooling water flowing over the back. A small pump forced the water through

passages in the copper plate and then through the radiators to give up the heat to the ambient air [Mahderekal et al. 2006]. See Figure 12. Performance of this system is reported in a thesis by Newmarker [2007].

Two distinct differences are present between the two HCPV systems shown here. First, in the dish system the flux comes from a large number of facets to a particular point on the PV array. This simplifies the concentration assembly, but it also can cause hot spots to exist. A similar kind of behavior is sometimes demonstrated on dish Stirling units. A second issue that differs between the Amonix unit and the SAIC unit is the cooling approaches used. In the first case the cooling is accomplished in a passive manner, while the latter is performed actively. There are plusses and minuses for each of the approaches, but presumably the active system could offer better control in varying conditions.

Figure 11. A dish-PV concentrating system is shown operating on sun. The concentration is approximately 350x. (From UNLV.)

Figure 12. The schematic design of the assembly at the snout of the dish array shown in Figure 11 is depicted here. (From Mahderekal et al. 2006)

Low Concentration PV Systems

The other end of the spectrum on concentration involves the use of low concentration designs. As was noted earlier this is not a precisely defined category, but it might include concentration ratios of less than 10. For these kinds of systems, the precision of the tracking can be reduced significantly. Also, the heat that needs to be removed from the cells is greatly reduced and may all be done by passive interaction with the ambient conditions. In one such design by JX Crystals, a 3x concentration ratio is used. As was stated by the developer, the bulk of the PV cells is replaced by reflecting aluminum that is on the order of 20 times less expensive than the cells [Frass et al. 2007]. This design uses aluminum “valleys” with conventional cells mounted at the base of the valley. One axis tracking is possible with a carousel type of arrangement in this application. See Figure 13. This unit was installed on a flat roof without roof penetrations. So the assembly can be made without compromising any roofing construction.

A plot of flux levels and power outputs is shown in Figure 14. It is apparent that the output for this one axis system does not precisely follow the DNI as would be expected for a 2-axis system.

Figure 13. The JX Crystals one-axis tracking 3x concentration PV system is shown. (From UNLV).

Figure 14. Normalized power output, normalized normal incidence solar flux and normalized global horizontal solar insolation is shown for a typical clear day in Las Vegas. The normalization for each of the three curves used the peak value for each. (From UNLV.)

Tradeoffs between High and Low Concentration Systems

- Tracking capabilities for high concentration systems must be more precise than is needed in low concentration systems.
- Each cell in a high concentration system produces significantly more power than does each in a low concentration or one-sun system.
- Cell cooling is much more of a concern in high concentration systems than it is in low concentration systems.
- Some low concentration systems can be mounted on roofs without penetrating the roof integrity.
- High efficiency cells that are of high cost will be more cost effective in high concentration compared to low concentration systems. Conventional one-sun cells may be conveniently adapted to many low concentration systems.
- To minimize the costs of the tracking system per unit of power produced, high concentration systems must be on the order of 25-50 kW each to minimize the cost of the tracking system in the overall cost of power. These types of systems must have some carefully-thought plan to minimize wind effects on the stability of the installation.

The Question of Storage

It is often said that solar systems cannot be used to furnish a constant rate of power generation because the sun shines only a fraction of the hours in a day. While this is obviously true about the sun, it isn't the end of the story. The last big frontier in solar power generation is the use of an effective means of storage. This would allow solar energy collected during sunny periods to be used in periods when the solar flux is low or zero in magnitude.

When the CSP system operates on a thermally driven Rankine cycle, the solution is clearly a thermal storage element in the plant design. A larger field than is needed to drive the plant during the day would be used, storing some of the energy to be used at a later time when it is needed. Traditionally storage has not been used to any great extent in solar thermal power plants because there were not incentives for this to happen. However, with the possibilities of solar being called upon to furnish 24-hour-a-day power, the issue becomes quite important.

Two approaches have been used in the past with solar thermal plants. As noted previously in this presentation, earlier designs have used either molten nitrate salts or high temperature heat transfer fluids. When the latter is used, the storage tanks often have a filler inserted, such as stones or

something that is of lower cost than the fluid being used. Molten salt has also been used. The latter cannot be allowed to solidify (cool too low, but still greatly above ambient temperature) unless extensive heat tracing is incorporated in the design.

Designers often favor the two-tank approach in either of these systems. One tank is for hot fluid and the other is for cold fluid. A typical evening will begin with the hot tank full and the cold tank empty. As the hot fluid is used during the night to generate steam, it is returned in a cooled condition to the cold tank. Efforts have examined the use of stratified tanks with hot fluid on the top and cold fluid on the bottom, with a moving boundary between them (thermocline approach).

For dish-Stirling and CPV systems, storage presents a more difficult problem. Perhaps the future will bring some viable possibilities beyond storage batteries, but only time will tell.

Concluding Comments

A review of a variety of approaches of generating electricity using concentrating systems has been given. Both thermally based systems as well as systems that use photovoltaic elements have been included.

Concentration will probably be used far into the future. While some experts anticipate that extremely low cost solar cells (perhaps nanodot or thin film configurations) to have a major impact on the renewable energy market, there will always be a market niche for concentrating systems that can offer major power production capabilities for low cost. In the near term the market for these kinds of systems looks quite promising.

If the lowest cost of large-scale power is sought in the current era, it would have to be thermal approaches using trough and related technologies. This fact has been well demonstrated over the last several decades. Power tower systems may become comparably cost effective, but this will have to be demonstrated with some systems now coming on line.

Developments of high efficiency solar cells are helping to make high concentration PV a possible cost-competitor in the power industry. When high efficiency and high concentration are combined, a very high unit output per cell is possible. Among the benefits resulting from this is a smaller structure to generate the same amount of power.

Low concentration systems may be cost effective in the PV generation field. As one characteristic of this, these systems will install and operate in a simpler manner than will the high concentration variety.

Dish-Stirling systems have held the title for the highest generation efficiency of all systems to date. PV systems are rapidly overtaking the levels shown by the Stirling systems. Major issues in the latter that will impact its market penetration will be ease of mass production and operational reliability.

All thermal systems except the dish-Stirling approach require very large systems to bring down the unit costs. There are certainly economies of scale that can be demonstrated in both the trough and tower technologies. The major benefit to the Stirling systems of large-scale projects is mass production cost benefits.

Thermal storage offers great promise for trough and tower thermal systems. Truly effective storage systems will render these approaches to be base-load sources of electricity.

Electrical storage, as would be needed to augment CPV and dish-Stirling systems, remains problematic for large-scale applications. A good solution is not in sight for this issue.

Acknowledgements

I particularly want to credit the excellent assistance by the various students over the years in the Center for Energy Research, without whom the large scope of work we have carried out would not have been possible. I also appreciate the collaboration of several companies who funded and/or assisted us in a large number of the projects. A great deal of support was received from the US Department of Energy and the National Renewable Energy Laboratory, and that made the whole operation possible.

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