# *Solar Thermal Power Generation*

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## *Glossary*

**conduction band** Excited electronic status of semiconductor materials, with readiness for electron transport.

**heliostats** Plane mirrors that continuously adjust in angle according to the sun's position, so as to reflect a beam of solar radiation to some fixed point in space.

**kilowatt (kW)** A unit of power equal to 1 kJ of energy applied per second. Addition of a subscript "e" indicates electrical energy, subscript "th" indicates thermal energy.

**kilowatt-hour (kWh)** A unit of energy equal to the power of 1 kW applied over the duration of 1 h. Addition of a subscript "e" indicates electrical energy, subscript "th" indicates thermal energy.

**megawatt (MW)** A unit of energy equal to 1000 kW.

**nanometer** A very small unit of length, equal to one one-millionth of a millimeter.

**photovoltaics (PV)** The science behind semiconductor-based solar energy conversion systems.

**pyranometer** An instrument that measures the intensity of total solar radiation.

**pyrheliometer** An instrument that measures the intensity of direct beam solar radiation.

**receiver** A device that intercepts concentrated solar radiation and transforms it into another form of energy.

**secondary concentrator** An arrangement of mirrors to form a light funnel to further concentrate preconcentrated solar radiation that is incident on a receiver.

**stagnation temperature** The equilibrium temperature a solar receiver will reach if the process that normally removes energy is turned off.

**thermal loss** Undesirable transfer of heat away from a solar receiver to the environment.

**valence band** Relaxed electronic status of semiconductor materials.

Solar thermal power generation systems capture energy from solar radiation, transform it into heat, and then use an engine cycle to generate electricity. The majority of electricity generated around the world comes from thermally driven steam-based systems. The heat for these systems is largely provided by the combustion of coal, oil, or natural gas or by nuclear fission. The concept of substituting solar radiation for these thermal inputs leads to the consideration of solar thermal power generation. The second law of thermodynamics expresses the empirically observed fact that the potential conversion efficiency from heat to electricity (work) increases with the temperature of the thermal input available. For solar systems, this naturally leads to the consideration of methods for concentrating solar radiation to achieve high temperatures. Small-scale solar thermal power generation systems were demonstrated as early as the 1860s, mainly in France and the United States. In 2003, the largest examples of solar thermal power plants are the 80 megawatt electric ($MW_e$) parabolic trough systems that have been operating in southern California since the late 1980s. There are nine such power plants with variable sizes that have a combined nominal capacity of 354 $MW_e$ and generate approximately 800,000 MWh (megawatt-hour) of electricity every year. This is sufficient to service a medium-sized city of approximately 200,000 people. These power plants generate electricity on a competitive basis thanks to previous tax incentives, long-term amortization, green-power credits, some natural gas backup, and expert operation and maintenance.

## 1. *THE SOLAR RESOURCE*

The sun is approximately 1.4 million km in diameter and approximately 150 million km from the earth. It is close to 5500°C at its surface and emits radiation at a rate of $3.8 \times 10^{23}$ kW. This energy is supplied by nuclear fusion reactions near its core, which are estimated to continue for several billion years.

The major part (70%) of the solar radiation received on the earth's surface is within the visible spectrum, with a maximum intensity at approximately 500 nm. This is consistent with a "black body" radiating at 5500°C. The intensity of solar radiation reaching the surface of the earth is typically between 900 and 1000 $\mathrm{Wm}^{-2}$ on a clear sunny day at noon.

Only a tiny fraction ($4.5 \times 10^{-8}$ percent) of the total energy radiated by the sun reaches the outer surface of the earth's atmosphere, but this is still equal to approximately $1.6 \times 10^{14}$ kW. Putting this in perspective, the total annual world electricity generation of approximately $1.5 \times 10^{13}$ kWh could be met with a hypothetical solar thermal power generation system (using technology discussed in this article) covering an area of approximately 30,000 $\mathrm{km}^2$, which is approximately equal to the size of Belgium or Taiwan, for example. The total or "global" solar radiation reaching the earth's surface is made up of "direct" and "diffuse" components. Direct radiation can be concentrated with mirrors or lenses that point directly at the sun. It is measured with a pyrheliometer. Diffuse radiation is that fraction that has been scattered by water vapor, particles, or molecules within the atmosphere. It cannot easily be concentrated and makes up approximately 15% or more of the total radiation, depending on the clarity of the sky. Diffuse radiation levels are measured with a pyranometer fitted with a shading device to exclude direct radiation. Together the diffuse and direct components combine to make up the global total and this can be measured with an unshaded pyranometer.

However, there are challenges associated with turning this solar energy source into continuous electrical power:

- The solar radiation reaching the surface of the earth is diffuse ($\sim$1000 $\mathrm{Wm}^{-2}$ maximum) compared to other sources of energy, such as fossil fuel flames (megawatts/$\mathrm{m}^2$);
- The sun shines intermittently in a daily cycle, which in turn follows a seasonal variation and is also heavily influenced by local weather conditions;
- The position (azimuth and elevation) of the sun in the sky and hence the angle of incidence of direct beam radiation vary continuously;
- Solar radiation cannot be stored directly, but must be immediately converted into heat, electricity, or chemical energy.

Technological solutions that allow these challenges to be met do exist.

## 2. MAIN SOLAR COLLECTOR SYSTEMS

Various devices for collecting solar radiation thermally have been devised. At the simplest level, a flat metal plate, painted black and placed in the sun, will heat up until it reaches a temperature where the amount of heat that it radiates and loses to the air around it exactly balances the amount of energy it receives from the sun. This "stagnation temperature" occurs at approximately 80°C for a simple flat-plate solar collector. If water, for example, is passed through passages in the plate collector, then it will stabilize at a lower temperature and the water will extract some of the energy in being usefully heated up. This is the essence of solar thermal energy collection.

Greater levels of sophistication are aimed at reducing the amount of "thermal loss" from the collector surface at a given temperature. This allows energy to be collected more efficiently and at higher temperatures. The thermal efficiency of a solar collector can be defined as:

$$\text{Thermal efficiency} = \text{Energy converted}/\text{Solar energy intercepted.}$$

Starting with the flat-plate solar collector, a cover layer of glass helps by cutting down the energy lost by the circulation of cold air across the collector. If metal tubes and glass cylinders are used as collectors instead of plates, then the space can be evacuated, so that air convection losses are largely eliminated. The smart use of coating materials to produce an optically selective surface helps to reduce radiation losses. Such coatings absorb as much as possible of the high-energy (ultraviolet and visible) solar wavelengths while they emit as little thermal radiation (infrared) as possible from the plate. Various combinations of these measures are used in the design of systems for the production of solar hot water that are used around the world for domestic and industrial applications. In principle, solar collectors of this nature could be used for electricity production. However, the comparably low temperatures that are achievable limit the conversion efficiencies that are possible to low levels.

Further increasing the temperature at which energy can usefully be recovered requires some

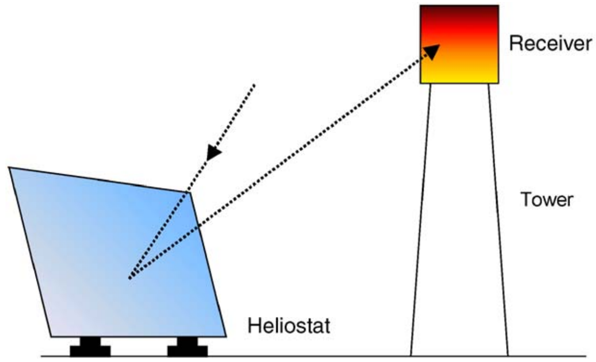

*FIGURE 1* The central receiver concept; a field of plane mirror heliostats all move independently to one another to keep a beam of solar radiation focused on a single central receiver.

method of optically concentrating the radiation so that the size of the absorbing surface and hence its thermal loss is reduced. The conceptually simplest approach is to employ a series of flat mirrors, called heliostats, that are continuously adjusted to direct solar radiation onto the absorbing surface. This is illustrated conceptually in Fig. 1. Large plants called "central receiver systems" or "power towers" have been built based on this principle and are discussed in detail in Section 4.1. The concept can also be adapted to linear absorbers and long strips of flat mirrors to create a "linear Fresnel" concentrator.

Alternatively, the mathematical properties of a parabola can be exploited for solar energy concentration. The equation for a parabola in the $x$–$y$ plane is:

$$y = x^2/4f.$$

Rays of light parallel to the $y$ axis of a mirrored parabola will all be reflected and focused at the focal point at a distance $f$ from the vertex. As illustrated in Fig. 2, this effect can be used in a linear arrangement, where a mirrored "trough" with a parabolic cross section will concentrate solar radiation onto a line-focus when it is pointed directly at the sun. The largest solar thermal power plants thus far constructed employ this principle. They are discussed in Section 4.2. Alternatively, a mirrored dish with a parabolic cross section (a paraboloid) will focus solar radiation to a point focus (see Fig. 3). Paraboloidal dish systems are discussed in Section 4.3. Both dishes and troughs require continuous adjustment of position (or at least frequent readjustment) to maintain the focus as the sun moves through the sky.

Similar focusing effects can obviously be achieved with lenses of various kinds, but this has not been employed on the scales needed for solar thermal power systems.

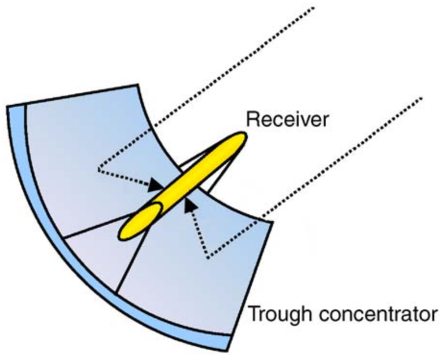

*FIGURE 2* A parabolic trough concentrator focuses solar radiation onto a linear receiver when faced directly toward the sun.

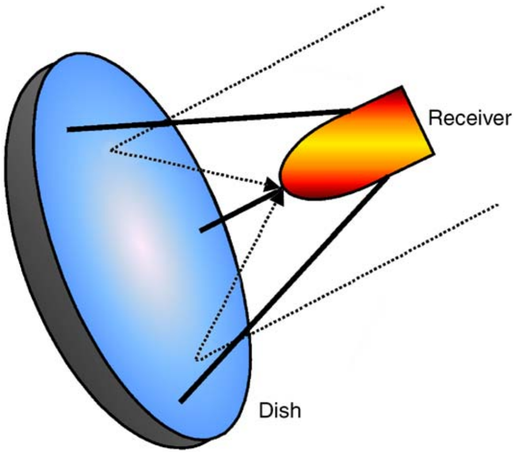

*FIGURE 3* A paraboloidal dish concentrator focuses solar radiation onto a point focus receiver.

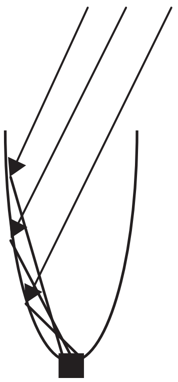

*FIGURE 4* A nonimaging concentrator concentrates solar radiation without the need to track the sun.

Another alternative, which potentially avoids the need to track the sun, is to employ "nonimaging" concentration. As illustrated in Fig. 4, this involves the construction of a mirrored "light funnel" of some

*TABLE I*

*Typical Operating Temperature and Concentration Range of the Various Solar Thermal Collector Technologies*

| Solar collector technology | Typical operating temperature (°C) | Concentration ratio | Tracking | Maximum conversion efficiency (Carnot) |
|---|---|---|---|---|
| Flat-plate collector | 30–100 | 1 | — | 21% |
| Evacuated-tube collector | 90–160 | 1 | — | 38% |
| Solar pond | 70–90 | 1 | — | 19% |
| Solar chimney | 20–80 | 1 | — | 17% |
| Linear Fresnel reflector technology | 260–400 | 8–80 | One-axis | 56% |
| Parabolic trough collectors | 260–400 | 8–80 | One-axis | 56% |
| Heliostat field + central receiver | 500–800 | 600–1000 | Two-axes | 73% |
| Paraboloidal dish concentrators | 500–1200 | 800–8000 | Two-axes | 80% |

kind. Such a device will be able to collect rays into its aperture over a range of incidence angles and cause them to exit through a smaller aperture via multiple reflections. Nonimaging concentrators have thus far not found application as the "primary" means of concentration for solar thermal power systems but they are frequently applied as "secondary concentrators" at the focus of central receivers, dishes or troughs, where they serve to further reduce the size of the focal region.

The rays of light from the sun are not exactly parallel. This means that even a perfect optical system will produce an image of finite size, with an intensity distribution that is a maximum in the center and tapers off to zero at the edges. Imperfections in mirror shape and tracking accuracy have the effect of further spreading out the sun's image.

Each of these approaches to solar energy collection has a typical ratio of collected radiation intensity to incident solar radiation intensity, termed the "concentration ratio." Table I summarizes the options discussed and lists typical concentration ratios, the resultant operating temperatures, and the consequent thermodynamic limiting efficiency with which electricity could be produced. The limiting conversion efficiency arises from the second law of thermodynamics. The maximum efficiency for conversion of heat from a constant high temperature source is given by:

$$\text{Maximum conversion efficiency} = 1 - T_{\text{cold}}/T_{\text{hot}}.$$

This is the "Carnot limit." (Note that "absolute" temperatures must be used in the equation, usually degrees Kelvin, equal to °C + 273.15.) Real solar thermal power generation systems typically achieve approximately one-third or less of the ideal maximum Carnot efficiency.

Although higher concentration ratios give higher efficiency, they also lead to potentially higher complexity and cost. The ultimate challenge with solar thermal power systems is to produce the desired output as economically as possible. This invariably means that a tradeoff between system efficiency and capital investment drives the design process.

The three main solar thermal concentrating technologies are discussed in detail in this article as they constitute the bulk of the commercial development efforts undertaken in the area of solar thermal power generation.

## 3. *ENERGY COLLECTION AND CONVERSION*

A solar thermal power system can be presented schematically as shown in Fig. 5.

All systems begin with a concentrator, followed by a receiver that catches the concentrated radiation and converts it to another form (typically thermal energy). At this point there are two options: either the energy is further converted to the final form desired (i.e., electricity) or it is transported to another location for final conversion. The choice of the transport path provides the option of storage in the intermediate form before going to final conversion. There is also the option of designing an energy storage system after final conversion.

### 3.1 Receiver Types

Receivers are often built with a cavity geometry; this gives a higher effective "absorbtivity," maximizing the amount of radiation absorbed and also reducing the surface area susceptible to radiation and

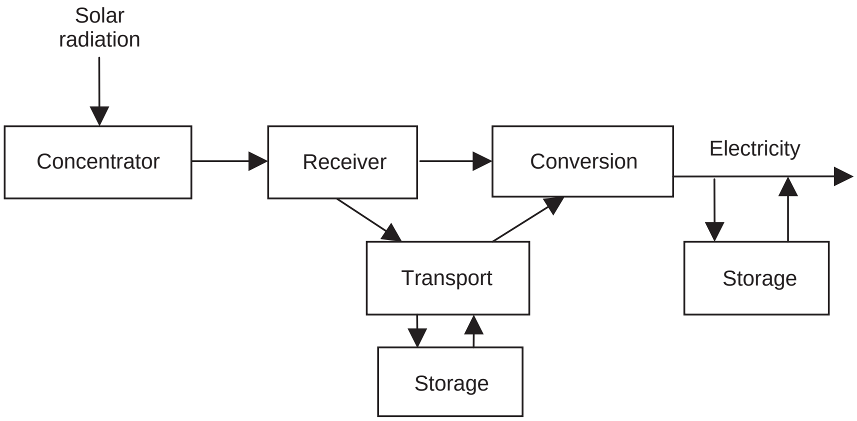

*FIGURE 5* Schematic representation of the component parts of a solar thermal power system.

convection losses. Notable exceptions include the single-tube receivers with evacuated insulation used on the Californian parabolic trough power plants and the cylindrical externally irradiated receivers used on power tower systems with a completely surrounding heliostat field. There are several methods for construction. Four of the commonly used approaches are discussed here.

#### *3.1.1 Tubular Receivers*

The conceptually simplest thermal receiver type involves circulating the working fluid or heat transfer fluid through directly irradiated tubes. The tubes can be arranged to form a cavity by winding a single tube to form a helical cylinder. An alternative is arranging a number of parallel straight tubes around the outside.

Tube receivers provide a simple and reliable way of designing for high system pressures. There are issues associated with thermal cycling (particularly for steam receivers) and flow balancing in multiple parallel tube receivers.

#### *3.1.2 Volumetric Receivers*

Volumetric or direct absorption receivers aim to have the radiation absorbed by surfaces directly in contact with the working fluid. This is often achieved by having a window in front of a cavity receiver that contains an absorbing matrix, over which a fluid passes. Windows are generally made of quartz because of its superior ability to handle thermal gradients. Matrices are often ceramic (such as a foam or ceramic formed into spikes). Such receivers have been used for chemical reactors, with a catalyst impregnated in ceramic foam, and for heating air. If air is being used at atmospheric pressure, then the window is not essential.

#### *3.1.3 Heat-Pipe Receivers*

A major issue with receivers is matching the incident flux to the requirements of the energy conversion system. A very effective approach to this is the “heat pipe” receiver. The idea is to use a container with a liquid/vapor mixture. The container will be essentially all at the boiling temperature corresponding to the pressure. In regions where heat is added, liquid will evaporate, whereas it will condense where heat is extracted. The result is a “black box” of extremely high effective conductivity. Sodium (boiling point 883°C at atmospheric pressure) is favored for solar applications. This approach has been used with central receiver systems, Stirling engines, and chemical reactor receivers.

#### *3.1.4 Solid-State Receivers*

Solid-state receivers are based on the application of semiconductor materials that are designed as directly irradiated photovoltaic or thermoelectric devices. These systems produce low-voltage direct current electric power that is then transformed to higher voltage alternative current for use.

### 3.2 Heat Transport Mechanisms

Various methods are employed for the task of energy transport within solar thermal power plants. Five major heat transfer mechanisms for solar application are discussed here.

#### *3.2.1 Oil*

The Californian parabolic trough power plants employ a synthetic heat transfer oil. The oil is circulated through the receivers and brought back to the centrally located power plant where a heat exchanger is used to raise steam for power generation. It has the advantage of providing stable and predictable receiver operation. Oils, however, have the disadvantages of slowly decomposing when operated at high temperatures and of environmental as well as fire hazards when leaking. The oil lines must be adequately insulated and design allowance must be made for adequate pipe expansion.

### 3.2.2 Steam

If the final conversion process is based on a steam Rankine cycle, then it makes sense to collect the energy as steam in the first place. The major challenge with direct steam generation, however, is the rapid thermal cycling that can occur in tubular receivers. At the point in the receiver where the tubes "dry out," the internal convective heat transfer coefficient is much less than in the regions where tubes are in contact with water. Problems arise because some sections of the tubing are exposed to rapidly alternating exposure to vapor and liquid. This causes localized thermal cycling and leads to fatigue of the metal. Insulation of pipe work and allowance for expansion is needed, as are sophisticated rotary joints to allow for solar concentrator tracking.

### 3.2.3 Air

Central receiver systems have been designed, among other options, to use air as heat transfer fluid either in pressurized tubular systems or in atmospherically open volumetric receivers. Systems with air temperatures of up to 1000°C have been extensively tested. Whereas tubular receivers allow for high-pressure operation with associated potential for conversion efficiency gains in gas turbines, the volumetric air receiver concept achieves very effective heat transfer from sunlight to air with minimized thermal gradients. Metallic mesh receivers have been used for temperatures of up to approximately 700°C and ceramic matrix elements for higher temperatures. Hot air from volumetric receivers can be used to heat chemical reactor tubes or boiler tubes in exactly the same way as if they were fired with fossil fuels. This provides for a uniform and controllable method for heating.

### 3.2.4 Molten Salt

A direct competitor to the air-based system for central receivers is molten salt. It offers the advantages of a high-specific-heat, single-phase fluid in the receiver and can also provide effective energy storage using insulated tanks. A disadvantage is that all pipes must have a provision for external heating to keep the system warm overnight and to facilitate cold starts (melting point of typical nitrate salts vary between approximately 140 and 260°C). Molten salts are corrosive and react with air and water if leaks occur. The usual nitrate salts employed, though, are environmentally benign fertilizer salts.

### 3.2.5 Chemical

Thermochemical cycles with fluid reactants can provide energy transport and storage. If energy is converted chemically at the receiver, then the use of counterflow heat exchangers means that reactants to and from the receiver are at ambient temperature. Hence, chemical systems not only provide an elegant way of storing energy, they also provide simple heat-loss-free energy transport. Pipes no longer need insulating, they neither expand nor contract, and much simpler mechanisms such as flexible joints are able to get through the axes of rotation.

## 3.3 Conversion Systems

There are three main thermo-mechanical conversion systems that are being applied with solar thermal power technologies. These are Rankine cycle, Stirling engine, and Brayton cycle systems.

### 3.3.1 Rankine Cycle

Steam-based Rankine cycles are responsible for the majority of electric power generation in the world. The technology is readily applicable to solar thermal systems as long as the energy collected can be transported to a central power block. Water is first compressed by a feed-water pump and then boiled and superheated (up to approximately 500°C) before being expanded through a turbine that turns an electric generator. The low-pressure steam is then condensed in a heat exchanger and fed back to the feed-water pump to be reused. Steam Rankine cycles have been, and continue to be, employed with parabolic trough, paraboloidal dish and central receiver solar thermal power plants.

Organic Rankine cycles are identical to steam-based Rankine cycles with the exception that organic fluids are employed. Organic fluids such as toluene have a lower liquid-to-gas phase change temperature than water/steam and therefore employ a lower-temperature heat input of typically between 80 and 280°C. Flat-plate, trough, dish, and solar pond systems have all been demonstrated to be suitable solar collector systems for organic Rankine cycle power generation.

#### *3.3.2 Stirling Engines*

The most extensive development of engine systems for direct solar operation has been based on the Stirling cycle, invented in 1816. The Stirling cycle employs external heating and cooling of its working fluid. The ideal cycle is made up of a constant-volume heating step from a sink temperature to a source temperature, augmented by isothermal heating, followed by a constant-volume cooling step to a sink temperature, and finished by further isothermal cooling. Dish/Stirling systems achieve very high net solar-to-electric conversion efficiencies, with the solar power world record for a precommercial 25 kilowatt electric ($kW_e$) unit being 29.4%.

In solar applications, Stirling engines commonly use helium or hydrogen as the working fluid. Kinematic (crankshaft-coupled) and "free-piston" engine versions are the two main concept variants developed worldwide. In a free piston engine, a floating-drive piston bounces back and forth between gas volumes at either end of a single cylinder. The piston itself serves as a linear generator. The result is a minimum number of moving parts. Solar receiver designs for Stirling engines have employed either directly irradiated fine-tubing for heating the working fluid or heat transfer heating via sodium heat pipe systems. Hybridization with fossil-fuel firing for 24 h operation has been demonstrated.

#### *3.3.3 Brayton Cycle*

The Brayton cycle is the basis of the conventional gas turbine. The cycle involves adiabatic (i.e., insulated) compression of a gas by a compressor turbine, constant pressure addition of heat, and adiabatic expansion in an expansion turbine (usually attached to the same shaft as the compressor), followed by constant pressure cooling. In a fuel-fired system, the heat addition is carried out in a combustion chamber and gases are exhausted after expansion, either with or without heat recuperation. For solar applications, heat recuperation is economically warranted for efficiency gains and gas fuel back-up advised for system control purposes as well as on-demand operation regardless of time of day.

#### *3.3.4 Others*

There are many other ways to convert thermal energy into work, many of which can potentially be applied to solar thermal power generation systems. They include, for example, the following:

- Thermoelectric converters produce electricity directly from heat. Semiconductor-based systems work in an analogous way to photovoltaic (PV) cells. Excitation of electrons from the valence band into the conduction band of the semiconductor material occurs via thermal excitation rather than individual photon absorption;
- Thermo-photovoltaics use PV cells tailored to infrared thermal radiation wavelengths to convert the radiation re-emitted from heated surfaces; and
- Magneto-hydrodynamic converters use the expansion of heated, ionized gas through a magnetic field to generate a potential difference.

## *4. DEVELOPMENTS OF CONCENTRATOR SYSTEMS*

The three major solar thermal concentrating technologies, central receivers, parabolic troughs, and paraboloidal dishes, are discussed in more detail in this section.

### 4.1 Central Receiver Systems

The central receiver (or power tower) concept was first proposed by scientists in the U.S.S.R. in the mid-1950s. The first experiment was established in Sant' Ilario near Genoa, Italy, in 1965 by Professor Giovanni Francia. He installed 120 round mirrors, each the size of a "tea table," focusing on a small steam generator on top of a steel frame. The product was superheated steam (500°C, 10 MPa).

Central receivers have the advantages that large-area radiation collection to a central point occurs optically and that all the energy conversion takes place at this single fixed point. This avoids the need for energy transport networks and allows investment to improve the efficiency and sophistication of the energy conversion process to be made more cost-effectively. Associated disadvantages are that they must be built as single large systems, without the modularity benefits of distributed systems, such as troughs or dishes. The fixed position of the receiver also means that heliostats do not point directly at the sun for the majority of the time. The amount of collected solar radiation per unit area of mirror is therefore less than with the other solar concentrating technologies.

Major investigations during the past 20 years have focused on four heat transfer fluid systems. They are water/steam, sodium, molten salt, and air (see Section 3.2). An overview of the main grid-connected central receiver research facilities and demonstration

*TABLE II*

***Summary of Grid-Connected Central Receiver Research Facilities and Demonstration Power Plants Built over the Past 20 years***

| | Net electric power | Total reflector area | Heat transfer fluid | Effective storage capacity (electrical or thermal) | Period of service |
|---|---|---|---|---|---|
| Eurelios (Italy) | 1 MW | 6216 $m^2$ | Water/steam | 0.5 $MWh_e$ | 1980–1984[a] |
| Sunshine (Japan) | 1 MW | 12,912 $m^2$ | Water/steam | 3 $MWh_e$ | 1981–1984[a] |
| IEA-CRS (Spain) | 0.5 MW | 3655 $m^2$ | Sodium | 1.0 $MWh_e$ | 1981–1985[b] |
| Solar One (United States) | 10 MW | 71,447 $m^2$ | Water/steam | 28 $MWh_e$ | 1982–1988[c] |
| Solar Two (United States) | 10 MW | 81,344 $m^2$ | Molten salt | 107 $MWh_{th}$ | 1996–1999[d] |
| CESA-1 (Spain) | 1.2 MW | 11,880 $m^2$ | Water/steam | 3.5 $MWh_e$ | 1983–1984[b] |
| Themis (France) | 2.5 MW | 10,794 $m^2$ | Molten salt | 12.5 $MWh_e$ | 1983–1986[b] |
| MSEE (United States) | 0.75 MW | 7845 $m^2$ | Molten salt | 2.5 $MWh_e$ | 1984–1985[b] |
| SES-5 (former Soviet Union) | 5 MW | 40,584 $m^2$ | Water/steam | 1.5 $MWh_e$ | 1985–1988[b] |
| Weizmann (Israel) | 0.5 MW (since 2001) | 3472 $m^2$ | Beam-down concept | None | 1988–today[b] |

[a] Dismantled.
[b] Continued operation as research facility until today.
[c] Converted to Solar Two.
[d] Mothballed.

***FIGURE 6*** A 120 $m^2$ heliostat for central receiver power plants. Source: Sanlucar-120.

power plants built over the past 20 years is given in Table II.

Thus far, power generation has been via conventional steam Rankine cycles at the base of the tower. In early systems, tubular receivers were built to produce superheated steam directly. Thermal problems associated with the unsteady boundary between liquid water and steam in the tubes, however, motivated a move to secondary heat transfer fluids, such as sodium, molten salt, or air. Liquid sodium provides good heat transfer behavior, but carries the disadvantage that all the transport piping must be heated above sodium's melting point (close to 100°C). The possibility of leaks also poses a significant fire risk. The use of molten salt avoids the fire risk but is well suited to storage in tanks to allow power generation when there is no sun. As a downside, the nitrate salt mixtures commonly used have a melting point of between 140 and 260°C and corrosion challenges arise if leaks occur. Being the most environmentally friendly heat transfer fluid, air has been extensively and successfully tested at scales of up to 3 megawatt thermal ($MW_{th}$).

Heliostat fields can either surround the tower or be spread out on the shadow side of the tower. Whereas externally irradiated cylindrical receivers are predominantly employed for surround fields, cavity receivers are used with one-sided heliostat fields. System designers have developed optimization strategies that determine the best arrangement for a given number of heliostats. These take into account the effects of shading between heliostats during the course of the day, the spread of the field, and the optical inefficiency that increases as heliostats are further from the tower.

Two generic approaches to heliostat design have been used. The most obvious is a plane structure with rigid mirror facets mounted on it. The structure sits on top of a pedestal with a drive arrangement that allows for two-axes tracking of the sun. The other alternative is termed the "stretched-membrane" approach. As the name implies, membranes are stretched across a circular frame in a manner similar to a drum skin. Thin stainless steel sheets covered with thin-glass mirror tiles are used successfully. A variety of reflective polymer films have also been tested over the years, but face issues of limited durability. Focusing of this heliostat concept is achieved by applying a small vacuum inside the drum. In this way heliostats can focus their own sun image onto the tower receiver rather than directing a plane beam at it. Figure 6 illustrates an example of a rigid mirror facet heliostat design. Development trends have suggested that larger heliostats might be more cost-effective. Current optima are between 100 and 150 $m^2$.

The largest central receiver solar thermal power plant demonstrated thus far is the "Solar Two" plant in southern California. This plant is an updated version of the previously operated "Solar One" system. Extra heliostats were added and the receiver was converted from direct steam generation to molten salt. Figure 7 shows the Solar Two plant in operation and Fig. 8 is a schematic illustrating the operating principles. When the solar field is operating, the molten nitrate salt moves from a "cold" (288°C) storage tank via the receiver at the top of the tower, where it is heated, to the hot storage tank (566°C). Independently of the solar energy collection process, salt from the hot tank is passed through a heat exchanger where heat is transferred to produce superheated steam, with the salt passing back to the cold storage tank. The steam is used in a conventional steam turbine power plant for electricity generation.

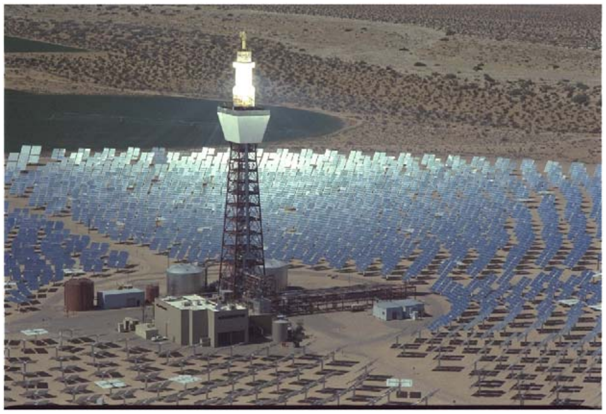

*FIGURE 7* The "Solar Two" (previously "Solar One") central receiver power plant in operation. Source: Sandia National Laboratories.

The Solar Two plant has 1018 heliostats of 39.1 $m^2$ plus a further 108 heliostats of 95 $m^2$. Under nominal conditions, 48 $MW_{th}$ is concentrated onto the receiver that sits at the top of a 91 m high tower. Steam is produced in the heat exchangers at 10 MPa and 538°C and the net electrical output is 10.4 $MW_e$.

One of the newest developments in the central receiver area is the "beam-down" concept proposed and tested in part by the Weizmann Institute of Science in Israel. Rather than converting the concentrated solar energy at the top of the tower in a receiver, a hyperbolically shaped secondary mirror directs the converging radiation vertically downward to a focal point at the bottom of the tower. On the ground, an additional nonimaging mirror concentrates the radiation further before the concentrated sunlight is captured by a volumetric receiver. This receiver is capable of reaching very high air temperatures to power, for instance, a Brayton cycle gas turbine.

## 4.2 Trough Systems

Solar thermal power in the form of mechanical energy for water pumping was established for the

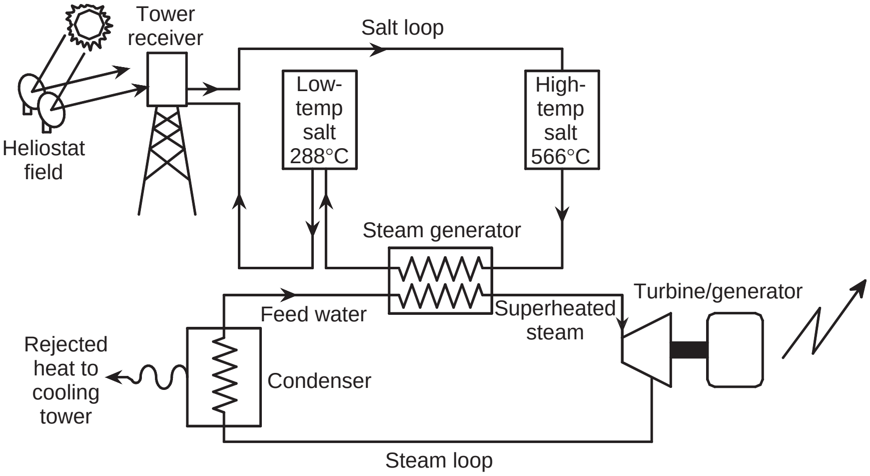

*FIGURE 8* Schematic of "Solar Two" operation.

first time by Frank Shuman near Cairo in 1913 (~40 kW). It incorporated a water/steam operated parabolic trough array (five units, 4 m × 62 m each) and a low-pressure condensing steam engine. Solar electric trough development was continued in the mid-1970s by the U.S. Department of Energy. The first experimental system started operation in 1979. At the same time, a private research and development company from Israel decided to design and commercialize parabolic trough "solar electric generating systems" (SEGS) in southern California. This decision was strongly motivated by favorable power purchase agreements and tax credits offered in the state of California.

Nine SEGS power plants were built between 1984 and 1989, with a combined capacity of 354 MW$_e$. These investor-owned, natural gas-assisted power plants have not only been operating on a fully commercial basis ever since, but have also been continuously improved. They operate beyond their nameplate capacity, generating important solar peaking power for the southern California grid, at the world's most competitive solar power prices.

During the early 1980s, small, trough-based solar thermal demonstration power systems were constructed in the United States, Japan, Spain, and Australia. Table III lists the details of these plants. Specifications for the nine SEGS plants are given in Table IV.

Figure 9 shows one of the SEGS plants and Fig. 10 illustrates the operating principles schematically. A synthetic heat transfer oil is pumped through the trough solar collector array and heated to 400°C. This oil is then used to produce steam in heat exchangers before being circulated back to the array. The steam is used in a conventional steam turbine-based electricity-generating plant. Although some hot oil-based energy storage was provided in the first plant, the SEGS systems overall rely on natural gas firing to provide continuous operation when the sun is not available. The special tax law for these power plants limits the fossil-fuel cofiring to a maximum of 25% per annum of the total heat energy supplied to the boilers.

The SEGS troughs are built using a galvanized steel space frame. This frame supports 4 mm thick toughened glass mirror facets that are shaped by heating and molding the raw glass to match the parabolic profile, before silvering. Each mirror facet is supported at four attachment points. The most

*TABLE III*

*Details of the Main Small, Trough-Based Solar Thermal Demonstration Power Plants*

| | Net electric power | Total aperture area | Heat transfer fluid | Effective storage capacity (electrical or thermal) | Duration of service |
|---|---|---|---|---|---|
| Coolidge (United States) | 0.15 Mw | 2140 m$^2$ | Synthetic oil | 5 MW$_{th}$ | 1980–1982 |
| Sunshine (Japan) | 1 Mw | 12,856 m$^2$ | Water/steam | 3 MW$_e$ | 1981–1984 |
| IEA-DCS (Spain) | 0.5 Mw | 7622 m$^2$ | Synthetic oil | 0.8 MW$_e$ | 1981–1985 |
| STEP-100 (Australia) | 0.1 Mw | 920 m$^2$ | Synthetic oil | 117 MW$_{th}$ | 1982–1985 |

*TABLE IV*

*Details of the Californian Parabolic Trough "SEGS" Solar Thermal Power Plants*

| | Net electric power | Total aperture area | Duration of service |
|---|---|---|---|
| SEGS I | 13.8 MW | 83,000 m$^2$ | 1984–present |
| SEGS II | 30 MW | 19,000 m$^2$ | 1985–present |
| SEGS III | 30 MW | 230,000 m$^2$ | 1986–present |
| SEGS IV | 30 MW | 230,000 m$^2$ | 1986–present |
| SEGS V | 30 MW | 251,000 m$^2$ | 1987–present |
| SEGS VI | 30 MW | 188,000 m$^2$ | 1988–present |
| SEGS VII | 30 MW | 194,000 m$^2$ | 1988–present |
| SEGS VIII | 80 MW | 464,000 m$^2$ | 1989–present |
| SEGS IX | 80 MW | 484,000 m$^2$ | 1989–present |

recently constructed systems (termed LS-3) are 5.76 m wide and 95 m long, resulting in a total aperture of 545 $m^2$ each. Two hundred twenty-four glass mirror facets are used and a geometric concentration ratio of up to 80:1 is achieved. The trough units are lined up in north–south rows and track the sun from east to west during the course of the day. Each parabolic trough has its own positioning and local control system.

*FIGURE 9* View of SEGS trough-based solar thermal power plant in southern California. Source: Kramer Junction Operating Company.

The receiver units of the SEGS troughs consist of a stainless steel tube 70 mm in diameter, covered by a Pyrex glass envelope that is sealed to the tube via metal bellows at each end. The space between the steel and glass is evacuated to minimize thermal losses. The surface of the stainless steel absorber tubes is coated with a selective surface that absorbs up to 97% of the incident solar radiation while minimizing the amount that is radiated at thermal (infrared) wavelengths. The combination of trough and receiver is capable of operating at temperatures in excess of 400°C. However, the synthetic heat transfer oil becomes chemically unstable and begins to break down at temperatures above 300°C. Approximately 350 $m^3$ of oil circulates in each of the 30 $MW_e$ plants. Depending on the operating regime, this oil may need to be replaced at rates of up to 6% per year as a result of thermochemical breakdown.

Each of the latest SEGS plants employs a steam turbine with a reheat cycle and multiple extractions. With steam inlet conditions of 10 MPa and 370°C, thermal-to-electric conversion efficiencies of approximately 37% are achieved, giving overall peak solar-to-electric conversion efficiencies of up to 24%.

Regular maintenance is required for all solar thermal power plant systems. For the SEGS plants, routine cleaning and replacement of broken mirror facets and receiver modules forms a major part of the maintenance program. Major improvements have been realized over time.

Research and development on parabolic trough systems has continued since the SEGS plants were completed. A major area of investigation has targeted the replacement of the heat transfer oil with direct

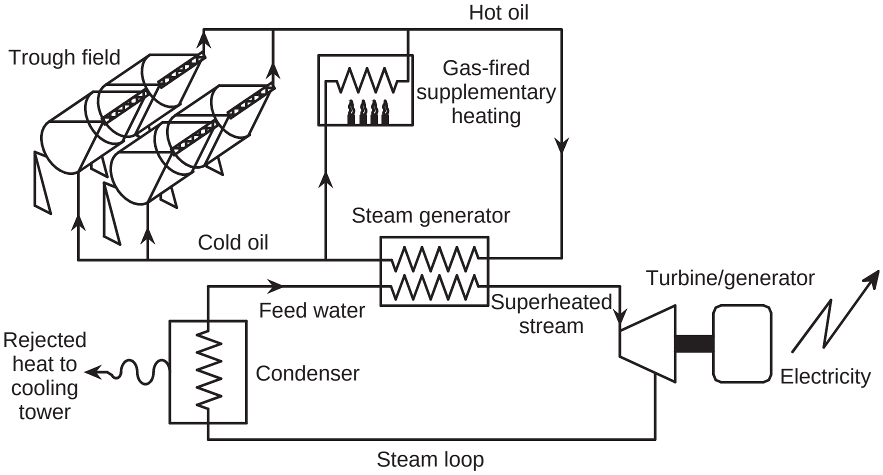

*FIGURE 10* Schematic representation of SEGS plant operation.

generation of steam in the receivers. Direct steam generation allows collection of energy at higher temperatures as well as elimination of one heat-exchange step and thus improves the efficiency of the steam turbine. It also avoids the need to replace the costly oil and eliminate the inherent fire risk. When attempting once-through-to-superheat boiling, the challenge is in managing the rapidly changing thermal stresses induced in the receiver tube by the unsteady, localized movement of the liquid/vapor phase boundary when boiling is occurring.

In a variation of linear focusing technology, compact Fresnel-type concentrator systems are being developed at various places around the world. This concept dates back to the 1950s and is much like a linear version of a central receiver system. Fixed linear receivers are illuminated by a series of long, narrow mirrors that track the sun individually in a single axis. If several receiver rows are installed side by side, then the individual mirror units can switch from one receiver to another depending on the relative optical efficiencies at different times of the day. Alternatively, a secondary concentration of the reflected light near the receiver can be used to ease precision and costs of the linear primary solar concentrator.

## 4.3 Paraboloidal Dishes

The first realization of a solar dish concentrator/engine system design dates back to 1864. The Frenchman Augustin Mouchot built a variety of "thermo-piles" and "solar engines" using conical mirrors. There are many designs and states of development of paraboloidal dishes.

Paraboloidal dish concentrators must point directly at the sun for proper operation. This necessitates two-axes tracking mechanisms. There are two main approaches to this: "altitude/azimuth" tracking or "polar/equatorial" tracking. In the first approach, the dish is mounted with a horizontal axis pivot (to allow altitude adjustment) plus a vertical axis pivot (to allow azimuth adjustment). A polar/equatorial system has a main axis of rotation, the angle of which is adjusted on a daily basis so that it is at a right angle to the sun's noon elevation. With the polar axis correctly adjusted, tracking during the day involves following the sun from sunrise to sunset on a constant basis with a single axis of movement. Altitude/azimuth arrangements have the disadvantage that both actuators must work throughout the day and the azimuth adjustment must be relatively rapid near midday for high sun elevations. Despite this, it is sometimes used for pragmatic structural design reasons.

Dish-based solar thermal power systems can be divided into two groups: those that generate electricity with engines at the focus of each dish and those that use some mechanism to transport heat from an array of dishes to a single central power-generating block. From a research and development perspective, dish systems have two major advantages over central receivers in particular, in that a single dish prototype can be constructed and tested relatively economically. Furthermore, for the dish/engine approach, a single module on its own can demonstrate the operation of the full system. Consequently, there have been well over 40 different dish prototypes developed thus far, by both research institutes and private engineering companies.

The variations in structural design of dish concentrators are very similar to the different types of heliostats used with central receivers. Possible different approaches include the following:

- A space frame structure that supports a number of rigid mirror elements held in a paraboloidal orientation;
- A single rigid paraboloidal surface covered with mirror elements;
- A single, mirrored, stretched-membrane that is pulled into a near-paraboloidal shape on a drum-like structure; and
- A space frame supporting a series of small stretched membrane mirror facet elements.

The high concentration ratios achievable with dish concentrators allow for efficient operation at high temperatures. Stirling cycle engines are well suited to construction at the size needed for operation on single-dish systems and they function with good efficiency, with receiver operating temperatures in the range of 650 to 800°C. To achieve good power-to-weight ratios, working gas pressures in the range 5–20 MPa are employed and the use of high-conductivity gases, such as hydrogen or helium, gives improved heat transfer. Dish/Stirling units of 25 $kW_e$ have achieved solar-to-electric conversion efficiencies of close to 30%. This represents the maximum net solar-to-electric conversion efficiency yet achieved by any nonlaboratory solar energy conversion technology.

Figure 11 shows two dish/Stirling system operating in southern Spain. The dish is fitted with a 10 $kW_e$ two-cylinder kinematic Stirling engine. One-millimeter-thick, back-silvered glass mirror facets are employed to achieve very high focusing accuracy.

***FIGURE 11*** Paraboloidal dish solar concentrator with a receiver-mounted Stirling engine operating in southern Spain. Source: Schlaich, Bergermann, and Partner.

Including various alternative versions of the generic system, over 80,000 h of cumulative on-sun operating time have thus far been clocked with dish/Stirling systems.

The largest distributed array/central plant solar thermal power system that has yet been demonstrated is the "Solarplant-1" system built in southern California in 1983–1984. A photograph of this system is shown in Fig. 12. It consisted of 700 dishes with a total collecting area of 30,590 $m^2$. The dishes generated steam in their cavity receivers, with 600 of the dishes producing saturated steam at approximately 6 MPa (275°C) and the remainder taking the saturated steam to a superheat of 460°C. The steam was transported through an insulated pipe network to a central steam turbine-based generating plant that produced a nominal output of 4.9 $MW_e$. The dishes were constructed with multiple stretched-membrane mirror elements. The plant ceased operation in 1990.

The world's largest solar dish, with an aperture of 400 $m^2$, is shown in Fig. 13. It was developed for use in distributed systems similar to Solarplant-1. Two prototypes are in operation: one at the Australian National University in Canberra, Australia and the other at the Sde Boquer Desert Research Centre of the Ben Gurion University in Israel. These dishes have triangular mirror panels supported on a hexagonal aperture space frame structure. Altitude–azimuth tracking is employed, with the horizontal axis near the base of the dish so that it can be parked in a horizontal position relatively close to the ground. This helps to reduce wind resistance and thus improve storm survivability. The Canberra dish has a cavity receiver based on a single helical winding of tubing to serve as a once-through-to-superheat boiler producing superheated steam at 5 MPa and 500°C. Although intended for operation in large arrays, the prototype system is connected to a small reciprocating steam engine that is capable of generating up to 45 $kW_e$ for the local electricity grid. The thermal efficiency from sun to steam is between 85 and 90% and, in a large steam turbine-based system, production of electricity at a rate of approximately 100 $kW_e$ per dish would be expected.

***FIGURE 12*** Seven hundred dishes producing steam for a central turbine system. Source: LaJet.

***FIGURE 13*** The world's largest 400 $m^2$ solar dish system. Source: Australian National University.

Research and development on paraboloidal dish systems around the world strive to improve and develop dish designs to reduce the costs and to optimize the reliability and efficiency of conversion systems. A number of groups are investigating the use of small solar-driven gas turbines at the focus of dishes (dish/Brayton systems). Such systems offer the potential for high-efficiency operation and moderate maintenance requirements.

Chemical conversion systems are also investigated using paraboloidal dish concentrators. High-temperature reversible chemical reactions, such as methane re-formation (up to 900°C) or ammonia dissociation (up to 700°C), can be used to store heat energy in chemical form. The resulting chemical products, such as hydrogen and carbon dioxide, are stored and transported at ambient temperature and thereafter recombined in an exothermic reaction to provide the heat for power generation on a continuous, 24 h basis.

## *5. ECONOMICS*

Solar thermal power generation technologies have achieved impressive development progress over the past two decades. Some of this progress, most notably with parabolic troughs, has resulted in successful technology commercialization, delivering the lowest-cost solar power yet achieved.

Given the very many different technology routes, development status, application options, and project sizes, solar thermal power generation technologies cannot be compared, let alone summarized, on a one-line economic basis. It is, however, valuable to look at the achievements, status, and trends of capital costs, operation and maintenance costs, and levelized electricity costs. These costs are strongly dependent on the country and on site-specific labor-rate structures. Although some general observations can be made, it is not necessarily valid to translate costs experienced with a particular project in one country to operation in another by a simple exchange-rate conversion.

### 5.1 Capital Costs

Capital costs arise for land, site preparation, construction work, solar collectors, power conversion units, the balance of plant including controls, and infrastructure as well as services such as engineering, project management, and commissioning.

Depending on the plant capacity, its technical complexity, the chosen location (geophysics, climate, access, water, etc.), and the choice of storage and/or fuel hybridization or back-up, solar thermal power plant capital costs over the past two decades have varied greatly between approximately U.S. $3000 and U.S. $9000 per kilowatt of nominal plant capacity.

Economies-of-scale progress with the Californian SEGS parabolic trough plants has shown that a cost reduction of typically between 12 and 16% has been achieved on doubling of the plant capacity.

In 2003, 10 to 50 $MW_e$ power plants are offered for approximately U.S. $2500–$3000 per kilowatt, whereas 0.5 $MW_e$ to 10 $MW_e$ power plants require investment capital of U.S. $3000–$5000 per kilowatt of nominal plant capacity. Smaller projects, such as one-off 10–25 $kW_e$ dish/Stirling units, cost approximately U.S. $6000–$7000 per kilowatt.

Given that solar thermal power generation technologies are comparably “low-tech” offerings based primarily on structural and civil engineering skills and efforts, cost reduction curves are quite predictable. Performance improvement, manufacturing progress, economies-of-scale, and options of hybridization as well as energy storage dominate cost reductions, indicating trends toward capital costs of approximately U.S. $1500–$2500 per kilowatt.

### 5.2 Operation and Maintenance Costs

Operation and maintenance (O&M) costs are composed of labor and materials costs. The split between these two varies according to technology choice, remoteness of location, labor rates, and water costs, with typical ratios of approximately 1:2 for large power plants and 2:1 for small power plants.

Whereas current commercial solar thermal power plants have typical O&M costs in the range of U.S. $0.025–$0.035 per net kilowatt-hour of power generated, continuous optimization efforts indicate a strong trend toward U.S. $0.01–$0.015 per kilowatt-hour for utility-scale power stations in the range of 50–100 $MW_e$ over the next decade.

### 5.3 Levelized Electricity Costs

Levelized electricity costs (LECs) are averaged electricity costs calculated on a simple basis of fixed economic parameters and a straight-line depreciation of capital cost over the duration of the project life. Technologies as well as projects are difficult to compare due to the large variety of design- and finance-specific parameters chosen.

Nevertheless, when analyzing well-demonstrated, megawatt-scale projects on a comparative basis of 30 years of project life, 8% real discount rate, 1% insurance rate, straight-line depreciation, and 0% income tax rate, typical LECs of U.S. $0.12–$0.16 per kilowatt-hour result. Small-scale, one-off projects, such as dish/Stirling systems, are likely to achieve LECs of U.S. $0.20–$0.30 per kilowatt-hour once technically matured and commercially operated. Following the ongoing efforts and predictions of major project developers, megawatt-scale solar thermal power plants are likely to ultimately generate LECs of U.S. $0.05–0.1 per kilowatt-hour.

## 6. OUTLOOK

The future of solar thermal power generation holds great commercial promise and a broad spectrum of interesting new opportunities. Among these possibilities are 24 h solar-only power generation thanks to thermal and/or thermochemical energy storage, the re-formation and synthesis of high-value fuels and fine chemicals, the thermal and/or thermochemical production of hydrogen, and the detoxification of hazardous waste.

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