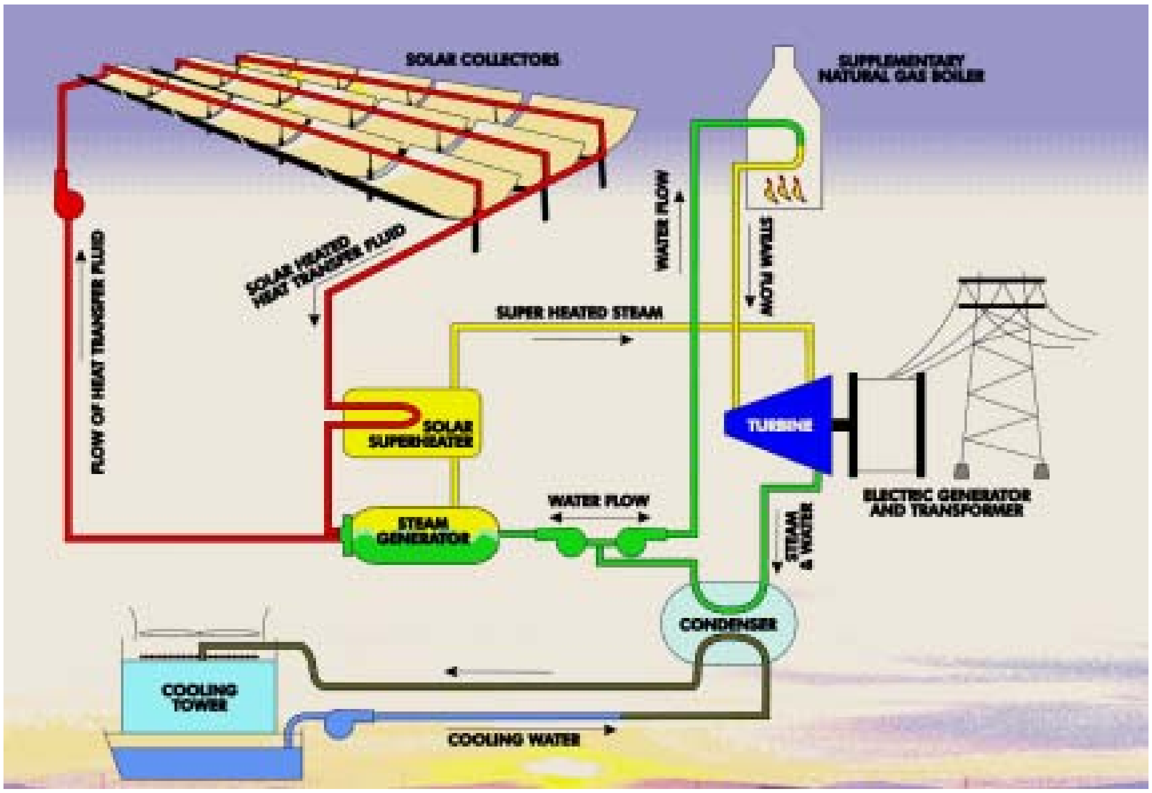
2. CONCENTRATING SOLAR POWER TECHNOLOGIES

2.1 TROUGH TECHNOLOGY

2.1.1 System Description

The collector field in the trough technology consists of a large field of single-axis tracking parabolic trough solar collectors, as shown on the illustration to the right. The solar field is modular and is composed of many parallel rows of solar collectors aligned on a north-south horizontal axis. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid (HTF) is heated as it circulates through the receiver and returns to a series of heat exchangers in the power block where the fluid is used to generate high-pressure superheated steam. The superheated steam is then fed to a conventional reheat steam turbine/generator to produce electricity. The spent steam from the turbine is condensed in a standard condenser and returned to the heat exchangers via condensate and feedwater pumps to be transformed back into steam. After passing through the HTF side of the solar heat exchangers, the cooled HTF is recirculated through the solar field. Figure 2-1 is a process flow diagram for the trough technology.

Figure 2-1 — Process Flow Diagram for Trough Technology



2.1.2 Current Experience

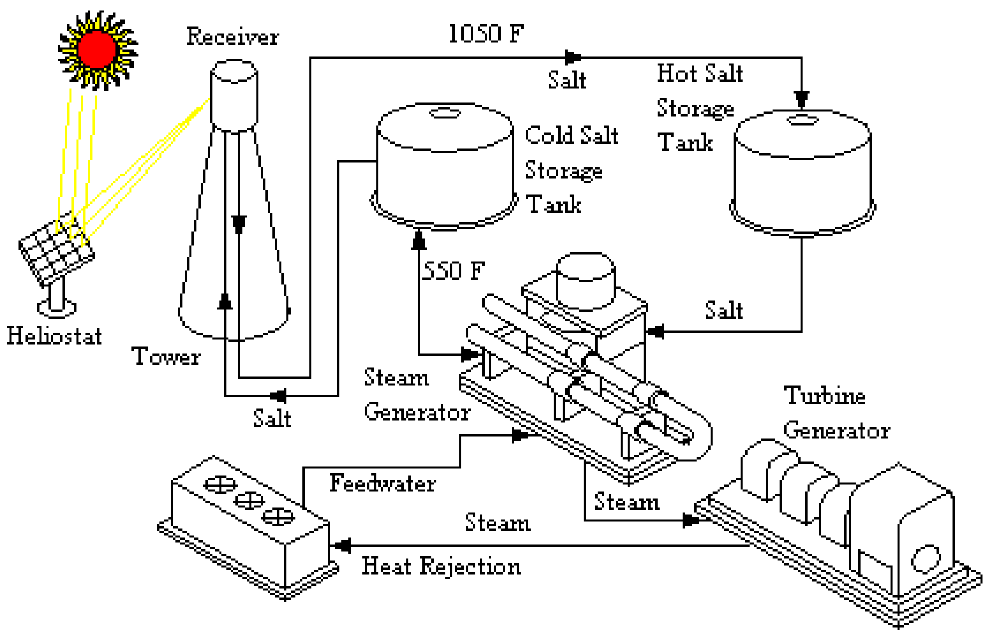
Parabolic trough technology is currently the most proven of the solar thermal electric technologies. The success of this technology is primarily indicated by the operation of nine large commercial-scale solar power plants, the first of which has been operating in the California Mojave Desert since 1984 (SEGS I). These plants, which continue to operate daily, range in size from 14 to 80 megawatts (MW) and represent a total of 354 MW of installed electric generating capacity. SEGS gross production for 1985 to 2001 was 8,305,477 MWh.

2.2 TOWER

2.2.1 System Description

Solar power towers generate electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger (receiver). The system uses hundreds to thousands of sun-tracking mirrors called heliostats to reflect the incident sunlight onto the receiver (see illustration to the right). These plants are best suited for utility-scale applications in the 30- to 400-MWe ranges. In a molten-salt solar power tower, liquid salt at 290°C (554°F) is pumped from a "cold" storage tank through the receiver where it is heated to 565°C (1,049°F) and then on to a "hot" tank for storage. When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine-cycle turbine/generator system. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver. Figure 2-2 is a molten salt power tower system schematic diagram.

Figure 2-2 — Molten-Salt Power Tower System Schematic (Solar Two, baseline configuration)



2.2.2 Current Experience

To date, the largest power towers ever built are the 10-MWe Solar One and Solar Two plants in southern California. Although power towers are commercially less mature than parabolic trough systems, a number of component and experimental systems have been field tested around the world in the last 15 years, demonstrating the engineering feasibility and economic potential of the technology.

The Solar One Pilot plant was an important step in the development of power tower technology and operated from 1982 to 1988. After the initial startup (test and evaluation) phase, Solar One operated reliably.

The goals of the redesigned demonstration plant, called Solar Two, were to validate nitrate salt technology, to reduce the technical and economic risk of power towers, and to stimulate the commercialization of power tower technology. Solar Two succeeded in meeting these objectives and has led to the formation of a commercialization consortia to build the first commercial power tower plant, Solar Tres, in Spain. Solar Two produced 10 MW of electricity with enough thermal storage to continue to operate the turbine at full capacity for 3 hours after the sun has set, proving the ability to dispatch to meet peak utility loads. Solar Two also demonstrated continuous operation for nearly a week, frequently at part-load output.

2.3 INTEGRATION WITH FOSSIL POWER PLANTS

2.3.1 Hybrid

Many solar-fossil hybrid options are possible with natural gas combined-cycle and coal-fired or oil-fired Rankine plants, and may accelerate near-term deployment of projects due to improved economics and reduced overall project risk. One opportunity for hybrid integration is with a power tower hybridized with a combined-cycle plant. In this power boost hybrid plant, a solar-only plant has, in effect, been "piggybacked" on top of a base-loaded fossil-fueled plant. Power is produced in the gas turbine (fossil only) and from the steam turbine (fossil and solar). Steam from the solar steam generator is blended with fossil steam from the heat recovery steam generator (HRSG) before entering a steam turbine.

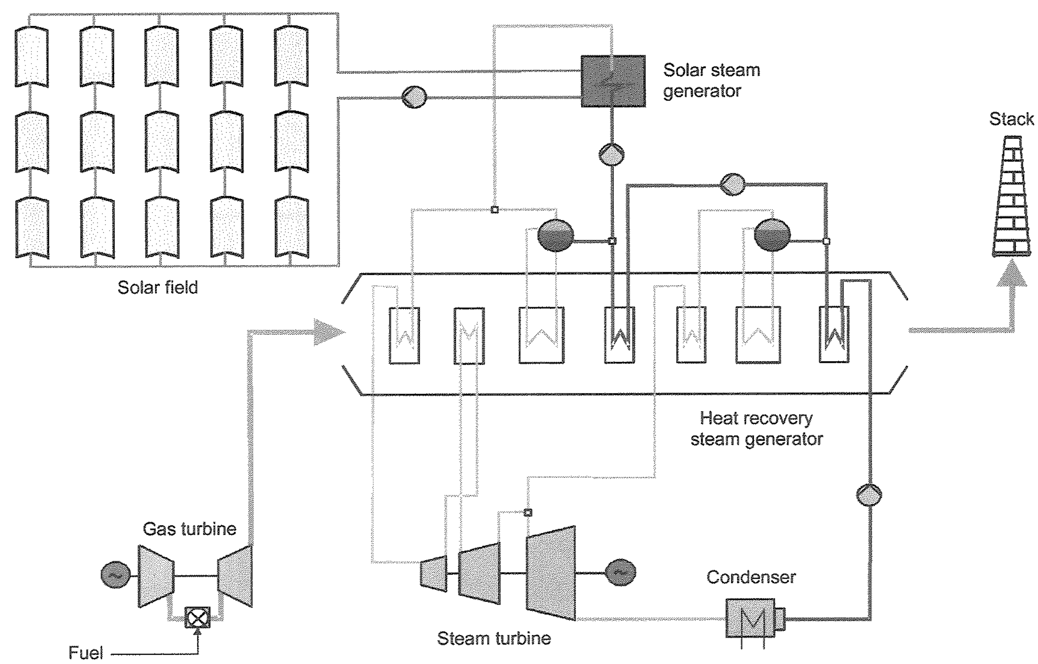
In the power boost hybrid plant, additional electricity is produced by over sizing the steam turbine, contained within a coal-fired Rankine plant or the bottoming portion of a combined-cycle plant, so that it can operate on both full fossil and solar energy when solar is available. Studies of this concept have typically oversized the steam turbine from 25% to 50% beyond what the turbine can produce in the fossil-only mode. Oversizing beyond this range is not recommended because the thermal-to-electric conversion efficiency will degrade at the partial loads associated with operating in the fuel-only mode.

When hybridizing a solar power tower with a base-load fossil-fired plant, solar contributes about 25% of the peak power output from the plant and between 10% and 25% of the annual electricity. (The higher annual solar fraction can be achieved with 13 hours of thermal storage and the lower solar fraction with just a few hours of storage.)

2.3.2 Integrated Solar Combined Cycle System (ISCCS)

The Integrated Solar Combined Cycle System (ISCCS) was initially proposed as a way of integrating a parabolic trough solar plant with modern combined-cycle power plants. The approach reduces the effective cost of the conventional power plant equipment, leveraging O&M and project development costs over a much larger plant and potentially increasing the solar-to-electric conversion efficiency. The initial concept was simply to increase the size of the steam turbine, use solar energy to generate steam, and use the waste heat from the gas turbine to preheat and superheat the steam. The general concept called for doubling the size of the steam turbine in the bottoming cycle. The ISCCS plant would operate at the combined-cycle output during non-solar periods, and then output would increase by up to one third when solar energy was available (referred to as the solar increment). However if the combined-cycle plant is operated in a baseload operating profile, the annual solar fraction (percent of electric generation from solar) will only be about 10%. In addition, detailed design integration issues must be considered to make sure the solar integration does not have a significant impact on the combined-cycle fossil operation. A number of recent studies have looked at the best approaches for this integration. ISCCS plants are being considered for all four of the Global Environmental Facility (GEF) grant projects (India, Egypt, Morocco, and Mexico). Figure 2-3 shows a process flow schematic of a parabolic trough ISCCS plant concept.

Figure 2-3 — Scheme of an ISCCS power plant with a dual-pressure-reheat steam cycle and the usage of solar energy to replace latent heat of evaporation in the high pressure part



Source: Price et al. (2002)

2.4 ADVANCED TECHNOLOGY AND APPLICATION OPTIONS

By charter, this report addresses trough and tower technologies and focuses on Rankine cycle power generation at temperatures in the range of 350°–550°C, as currently being pursued by U.S. industry and the CSP program. For completeness, we have also included here some high-level information on other options, namely variants of trough and tower technology that are being pursued by international competitors, as well as other options for future applications of large-scale CSP technology. This information was supplied by SunLab and has not been verified by S&L.

2.4.1 Advanced Tower Technology

One idea under consideration for future power tower technology is an advanced receiver that is capable of efficiently heating air to gas-turbine temperatures (>1,400°C/2,552°F) and pressures (>1,500 kPa) in conjunction with a high-temperature phase-change thermal storage system. If this can be achieved, large solar-only plants with a combined-cycle power block efficiency of 60% or more might be achieved. In addition, as receiver temperatures exceed 800°C (1,832°F), thermo-chemical approaches to hydrogen generation could be exploited using solar power towers. Another interesting option is the thermo-chemical production of syngas by reforming methane. Since existing natural gas pipelines can accept about 10% hydrogen content, this concept could be used before the development of a hydrogen infrastructure. A CSP plant located in the desert could effectively convert 10% of the downstream gas appliances (water heaters, stoves, industrial equipment, etc.) into "solar-powered" appliances without needing to have any solar facilities on site. Significant research would certainly be required to develop these concepts, and they have not been reviewed by S&L as part of this study.

2.4.2 Current International Development Directions

Internationally, trough or tower technology development, along with related project development, is being aggressively pursued in Germany, Spain, Italy, Israel, and South Africa. While international trough technology is fundamentally the same as that in the United States, there are some differences. European partners (with significant funding from the European Union (EU), national and state programs) have developed and extensively tested a prototype of a competing trough structure (EuroTrough) that will begin full-scale prototype testing at the Kramer Junction solar plant in California in the spring of 2003. Germany and Spain are pursuing steam as a high-temperature working fluid in addition to near-term development based on the same heat transfer oil as used here in the United States. Trough receiver development includes advances by Solel in Israel (which would be implemented by U.S. industry as well); development by the EU (through Germany and Spain) of a completely new heat collection elements (HCE), including an advanced selective surface capable of operation at the temperatures of their steam working fluid (up to 550°C); and a new effort by Schott Rohrglas to develop an entire HCE product. A German/Spanish consortium is in the final stages of planning for two commercial 50-MW trough plants in Spain. Italy has a major new program ($100M) focused on troughs with a molten salt working fluid, to allow both higher temperatures and better integration with storage. Both activities plan to use the Solar Two-proven molten salt technology for storage.

South Africa has extensively assessed both trough and tower technology and recently selected U.S. tower technology (with extensive in-country content and manufacturing) for a 100-MW proposed project. However, in

Europe and Israel, tower technology has evolved quite differently. The Europeans (specifically, the Germans and Spanish) have focused on systems using air as the working fluid. The near-term application pulls air at atmospheric pressure through a porous metal or ceramic mesh (the so-called volumetric receiver concept) illuminated by the heliostat field, generating temperatures of about 700°C, ultimately for use in steam generation at 550°C for Rankine cycles (identical to current U.S. molten-salt system Rankine temperatures). The Europeans have investigated rock and ceramic packed-bed storage options that, while not nearly as efficient as two-tank molten salt systems, have continued to drop in cost through the development process, although they have not yet achieved the costs of molten salt systems. A Spanish/German consortium plans to use this technology in the 10-MW PS10 project, which was expected to begin construction in Southern Spain in late 2002 or early 2003. Because 700°C is a relatively conservative temperature limit for this technology (there are no temperature limits on air, and ceramic receivers of this design can go to much higher temperatures), temperature increases to accommodate advanced steam turbines operating above 600°C are relatively straightforward.

To expand options further, the Germans are also aggressively investigating pressurized volumetric receiver concepts using quartz windows, reflective secondary concentrators, and ceramic mesh absorbers capable of operating at several atmospheres and temperatures of 900°–1,200°C. The quartz windows limit the size of each receiver, so they are packed into hexagonal arrays (the secondary concentrators have a hexagonal entrance aperture) to achieve higher power levels. Individual receiver elements have been successfully demonstrated over the past 10 years, and they are currently testing the first multi-module array (Sugarman et al. 2002). If successful, this technology will ultimately open options for coupling to higher-efficiency Brayton cycles or combined cycles. There are, of course, many technical challenges to this receiver concept (in the secondary reflectors, the windows, and the ceramic mesh durability), and commercial implementation is still quite a few years away, at best. Nonetheless, DOE/SunLab follows the European development closely and considers this technology credible. For a variety of reasons (see advanced applications below), DOE/SunLab has conducted preliminary development in this area in the past, with those investigations ultimately being terminated due to budget restrictions, not a lack of technology promise.

The Israelis have carried this concept one step further, proposing to put a large hyperbolic secondary reflector on top of a tower to “beam down” the concentrated solar energy to ground level (Yogev et al. 1998). This would theoretically allow more options for the high-temperature receiver and coupling of the high-temperature air working fluid to a Brayton cycle or other application. They have successfully demonstrated (without the beam-down mirror) pressurized air volumetric receiver operation at temperatures above 1,200°C (Kribus 2001). They are currently testing a 700-kW beam-down experiment on the tower at the Weizmann Institute of Technology solar power tower test facility. The higher precision required for the heliostat field, as well as thermal and wind loads on the tower-mounted secondary mirror, have limited success to date. This technology likely has years of development ahead, if indeed it will ever be feasible.

2.4.3 Long-Term CSP Advanced Applications Options

Over the last dozen years or so, budget restrictions in the U.S. CSP program have limited the focus to near-term electric power generation options. Since power generation is the simplest interface for CSP technologies and since low-cost, reliable concentrators will be needed for any advanced applications, this continues to be the most productive approach with limited budgets. However, there are a number of potential, long-term applications that take advantage of the high-temperature capabilities of tower technology. These include not only the higher temperature (and thus more efficient) Rankine and Brayton electric power cycles discussed above, but also a range of solar chemistry applications that could potentially make CSP a major source of energy in the fuels and chemicals sector.

For example, the DOE has successfully demonstrated the thermo-catalytic reforming of natural gas and other organics with steam or carbon dioxide (at temperatures of 800°–900°C). The Israelis, Swiss, Germans, and Australians continue to develop this technology today. In this approach, a tower uses reactors similar to the closed volumetric receivers described above, except that a rhodium or another catalyst is dispersed on the surface of the ceramic mesh, directly absorbing the solar energy to produce syngas, hydrogen, and carbon monoxide (Moller et al. 2002). In an open-loop system, the syngas can be further hydrogen enriched via a water-gas shift reaction for several possible applications, including hydrogen production for other uses, including direct combustion, or further conversion to methanol for liquid fuel use. In a closed-loop system, the syngas can be stored (effectively chemically storing solar energy for longer periods than thermal storage) or transported over distances up to a hundred kilometers for process heat or power generation via the reverse reaction (methanation), in which the syngas is converted back to methane for reuse in the solar reactor.

With their high-temperature capabilities, towers (and CSP dish technology) can also be used to drive a number of thermochemical, hydrogen production cycles that operate at 800°C and higher. For example, towers could "fuel" the following thermochemical cycles: the sulfur-iodine cycle currently being investigated by the nuclear industry for powering by a nuclear high-temperature gas-cooled reactor (HTGR); the Zn/ZnO cycle under intensive study in Switzerland and Israel (Wieckert et al. 2002); U.S. activity in methane decomposition (Dahl et al. 2002); and other high-temperature, solar thermal decomposition reactions. While CSP can theoretically generate the temperatures required for hydrogen production by direct water splitting, theory is a long way from practice in both receiver design and separation technology. Nonetheless, high-temperature electrolysis (where a portion of the electrical energy needed for electrolysis is offset by high-temperature thermal energy) is considered feasible in the long term and has been investigated at a variety of institutions.

Finally, technology advancements in the last 20 years have been dramatic (e.g., computers, communications, and biotechnology) and have been characterized by unforeseen developments in other areas of research. It is not unreasonable to expect that, over the course of the next 20 years, we will see advancements not now anticipated in areas such as materials research that could have a significant impact on CSP technology.