OPTIONS FOR HYBRID SOLAR AND CONVENTIONAL FOSSIL PLANTS

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Abstract—*Renewable energy sources continue to add to the electricity supply as more countries worldwide mandate that a portion of new generation must be from renewable energy. In areas that receive high levels of sunlight, solar technology is a viable option. To help alleviate the capital cost, dispatchability, and availability challenges associated with solar energy, hybrid systems are being considered that integrate concentrating solar power (CSP) technology with conventional combined cycle (CC) or Rankine cycle power blocks. While briefly discussing Rankine cycle applications, this paper focuses primarily on the most widely considered hybrid approach: the integrated solar combined cycle (ISCC) power plant. The paper examines the design and cost issues associated with developing an ISCC plant using one of the three leading CSP technologies—solar trough, linear Fresnel lens, and solar tower.*

Keywords—*combined cycle (CC), concentrating solar power (CSP), concentrating solar thermal (CST), heat transfer fluid (HTF), integrated solar combined cycle (ISCC), linear Fresnel lens, renewable energy, solar tower, solar trough*

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INTRODUCTION

More and more countries are mandating that a portion of new energy be from renewable sources such as solar, wind, or biomass. However, compared with traditional power generation technologies, renewable energy faces challenges—primarily related to capital cost—that are only partially compensated for by lower expenditures for operation and maintenance (O&M) and fuel. Other challenges include dispatchability and the intermittent nature of some of these energy sources. These challenges can be overcome by using some form of storage. However, large-scale energy storage also has unresolved technical and cost issues.

A viable alternative that helps to alleviate the challenges associated with renewable energy is a hybrid system that integrates renewable sources with combined cycle (CC) or Rankine cycle power blocks. One such hybrid system is the integrated solar combined cycle (ISCC), which uses concentrating solar thermal (CST) energy as the renewable source. In regions with reasonably good solar conditions, CST hybrids involving conventional coal-fired plants are also feasible. For these plants, where steam pressures and temperatures are higher than for ISCC plants, the specific solar conversion technology used dictates how solar is integrated into the plant. Finally, hybrids are possible that combine the different forms of renewable energy to increase daily electricity supply.

The focus of this paper is the ISCC power plant. For comparison purposes, integration options with Rankine cycle power blocks are also briefly discussed. In either case, the integration seeks to achieve efficient operation even though solar energy intensity varies according to time of day, weather, and season.

BACKGROUND

Concentrated sunlight has been used to perform tasks since ancient times. As early as 1866, sunlight was successfully harnessed to power a steam engine, the first known example of a concentrating-solar-powered mechanical device.

Today, conventional CC plants achieve the highest thermal efficiency of any fossil-fuel-based power generation system. In addition, their emissions footprint, including CO_2, is substantially lower than that of coal-fired plants. Properly integrating an additional heat source, such as concentrating solar power (CSP), can dramatically increase CC system efficiency.

> *ISCC is a winning combination for both CC and solar plants in terms of reduced capital cost and continuous power supply.*

ABBREVIATIONS, ACRONYMS, AND TERMS

ACC	air-cooled condenser
CC	combined cycle
CSP	concentrating solar power
CST	concentrating solar thermal
HP	high pressure
HPEC	HP economizer
HPEV	HP evaporator
HPSH	HP superheater
HRSG	heat recovery steam generator
HTF	heat transfer fluid
IGCC	integrated gasification CC
IP	intermediate pressure
IPEC	IP economizer
IPEV	IP evaporator
IPSH	IP superheater
ISCC	integrated solar CC
LP	low pressure
LPEV	LP evaporator
LPSH	LP superheater
LTEC	low-temperature economizer
NREL	(US) National Renewable Energy Laboratory
O&M	operation and maintenance
PG&E	Pacific Gas & Electric
RH	reheater
SAM	(NREL) Solar Advisor Model
SEGS	Solar Electric Generating Station

Compared with the cost of a steam turbine in a standalone solar power plant, the incremental cost of increasing a CC plant's steam turbine size is considerably less. At the same time, the annual electricity production resulting from CST energy is improved over that of a standalone solar power plant because the CC plant's steam turbine is already operating, avoiding time lost to daily startup. Moreover, during solar operation, steam produced by the solar heat source offsets the typical CC power loss resulting from higher ambient temperatures. Thus, ISCC is a winning combination for both CC and solar plants in terms of reduced capital cost and continuous power supply.

When considering an ISCC system, the following must be examined:

- Solar technology to be used and its impact on steam production
- Amount of solar energy to be integrated into the CC
- Optimal point in the steam cycle at which to inject solar-generated steam

EXISTING SOLAR THERMAL SYSTEMS AND THEIR IMPACT ON STEAM PRODUCTION

CSP systems require direct sunlight to function. Lenses or mirrors and a tracking device are used to concentrate sunlight. Each system consists of the following:

- Concentrator
- Receiver
- Storage or transportation system
- Power conversion device

Existing CSP technologies include:

- Solar trough
- Linear Fresnel lens
- Solar tower

Solar Trough

The solar trough is considered to be the most proven CSP technology. Since the 1980s, more than 350 MW of capacity has been developed at the Solar Electric Generating Station (SEGS) solar trough plants in California's Mojave Desert.

The solar trough is a cylindrical parabolic reflector consisting of 4- to 5-mm-thick (0.16- to 0.20-inch-thick), glass-silvered mirrors. (The mirrors may also be made of thin glass, plastic films, or polished metals.) It is designed to follow the sun's movement using a motorized device and to collect and concentrate solar energy and reflect it onto a linear focus.

A specially coated metal receiver tube, enveloped by a glass tube, is located at the focal point of the parabolic mirror. The special coatings aim to maximize energy absorption and minimize heat loss. A conventional synthetic-oil-based heat transfer fluid (HTF) flows inside the tube and absorbs energy from the concentrated sunlight. The space between the receiver tube and the glass tube is kept under vacuum to reduce heat loss. Several receiver tubes are connected into a loop. A metal support structure, sufficiently rigid to resist the twisting effects of wind while maintaining optical accuracy, holds the receiver tubes in position. **Figure 1** shows a solar trough installation.

(Source: Solel)

Figure 1. Solar Trough Installation

Many loops are required to produce the heat necessary to bring large quantities of HTF to the maximum temperature allowable, which is around 395 ºC (745 ºF) because of HTF operational limitations. In locations with good solar radiation, about a 1.5- to 2.0-hectare (4- to 5-acre) solar field is needed to generate 1 MW of capacity.

Hot HTF goes into a steam generator—a heat exchanger where HTF heat is transmitted to water in the first section to convert the water into steam and then transmitted to steam in the second section to generate superheated steam. From this point onward, the power block converting steam into electricity consists of conventional components, including steam turbine, heat sink, feedwater heaters, and condensate and boiler feed pumps.

Advantages of solar trough technology include:

- Well understood, with proven track record
- Demonstrated on a relatively large scale
- May bring projects to execution faster than other competitive CSP technologies

Disadvantages of solar trough technology are related to:

- Maximum HTF temperature, which dictates relative cycle efficiency
- Complexity of an additional heat exchanger between the Rankine cycle working fluid and the solar-heated fluid

Linear Fresnel Lens

The linear Fresnel lens solar collector is a line-focus system similar to the solar trough. However, to concentrate sunlight, it uses an array of nearly flat reflectors—single-axis-tracking, flat mirrors—fixed in frames to steel structures on the ground. Several frames are connected to form a module, and modules form rows that can be up to 450 meters (492 yards) long. The receiver consists of one or more metal tubes, with an absorbent coating similar to that of trough technology, located at a predetermined height above the mirrors. Water or a water-and-steam mixture with a quality of around 0.7 flows inside the tubes and absorbs energy from the concentrated sunlight. At the ends of the rows, the water and steam are separated, and saturated steam is produced for either process heat or to generate electricity using a conventional Rankine cycle power block. **Figure 2** shows a linear Fresnel lens installation.

(Source: Ausra, Inc.)

Figure 2. Linear Fresnel Lens Installation

Advantages of linear Fresnel lens technology over solar trough technology include:

- Direct steam generation without using intermediate HTF
- Less stringent optical accuracy requirements
- Decreased field installation activities because the construction design is geared toward factory assembly
- Use of conventional "off-the-shelf" materials
- Less wind impact on structural design
- Possible improved steam cycle efficiency if the temperature can be increased up to 450 ºC (840 ºF), as some technology suppliers are pursuing

> *How steam generated by a given solar technology is integrated depends on the steam conditions that the technology generates.*

Disadvantages with respect to solar trough technology are related to:

- Less mature, with only recent, relatively small-scale commercial developments
- Lower power cycle efficiency because of lower steam temperature
- Lower optical efficiency and increased heat losses because of no insulation around receiver tubes

Solar Tower

A solar tower is not a line-focus system. Rather, the system consists of a tall tower with a boiler on top that receives concentrated solar radiation from a field of heliostats, which are dual-axis-tracking mirrors. The heat transfer medium can be water, steam, molten salt, liquid sodium, or compressed air. However, in the more conventional arrangement, water is the working fluid. **Figure 3** shows a conventional solar tower installation.

The water temperature is higher, close to 545 ºC (1,020 ºF), in the solar tower system than in the line-focus systems. In addition, the solar tower can be connected to molten salt storage, thus allowing the system to extend operating hours or increase capacity during periods when power is most valuable.

The main advantage of solar tower technology is the ability to provide high-temperature superheated steam. On the downside, the design requires accurate aiming and control capabilities to maximize solar field heliostat efficiency and to avoid potential damage to the receiver on top of the tower.

Figure 3. Solar Tower Installation

Summary

CSP technology provides different options for introducing CST energy into a conventional fossil-fired plant. **Table 1** summarizes the CSP technologies and their associated thermal outputs.

Table 1. CSP Technologies Summary

Technology	Working Fluid	Maximum Temperature, °C (°F)
Solar Trough	Synthetic Oil HTF	395 (745)
Linear Fresnel Lens	Steam	270 (520) (or higher)
Solar Tower	Steam	545 (1,020)

INTEGRATION OPTIONS WITH COMBINED CYCLE POWER PLANTS

ISCC Plants

ISCC plants have been under discussion for many years. **Table 2** lists plants that are proposed, in development, or under construction.

Table 2. ISCC Plants

ISCC Project	Location	Solar Technology	Plant Output, MWe	Solar Contribution, MWe
Kureimat	Egypt	Trough	140	20
Victorville	California (US)	Trough	563	50
Palmdale	California (US)	Trough	555	62
Ain Beni Mathar	Morocco	Trough	472	20
Hassi R'Mel	Algeria	Trough	130	25
Yazd	Iran	Trough	430	67
Martin	Florida (US)	Trough	3,705	75
Agua Prieta	Mexico	Trough	480	31

Questions To Be Addressed

How steam generated by a given solar technology is integrated depends on the steam conditions that the technology generates. It is critical to remember that all power generated in the CC steam cycle is "free," from a fuel perspective. That is, steam cycle power is generated from energy provided in the gas turbine exhaust gases, not by burning additional fuel. Therefore, care must be exercised to not simply substitute fuel-free energy from solar power for fuel-free energy from exhaust gases. When solar energy is being integrated into the CC steam cycle, the goal is to maximize the use of both energy sources. Therefore, the following questions must be answered:

- What solar technology should be used?
- How much solar energy should be integrated?
- Where in the steam cycle is the best place to inject solar-generated steam?

There are no simple answers to these questions. Rather, detailed technical and economic analyses must be performed to evaluate various MWth solar inputs to the CC, different solar technologies and associated steam conditions, and the levelized cost of electricity for the site-specific location under consideration.

Solar Technologies

For discussion purposes, the solar technologies under consideration are to be integrated into a new 2 x 1 CC plant using F Class gas turbines; unfired, three-pressure, reheat heat recovery steam generators (HRSGs); a reheat steam turbine with throttle conditions of 131 bara/566 °C (1,900 psia/1,050 °F) and reheat temperature of 566 °C (1,050 °F); and an air-cooled condenser (ACC).

Because solar technologies are evolving and improving, they have been categorized based on fluid temperature capability:

- High temperature, >500 °C (>930 °F)
- Medium temperature, 400 °C (750 °F)
- Low temperature, 250 °C to 300 °C (480 °F to 570 °F)

Medium-temperature technology is discussed first, because it is the most proven technology.

Medium-Temperature Solar Technology

The solar (parabolic) trough is the most common medium-temperature solar technology. Previous studies indicate that, for parabolic trough systems generating steam up to around 395 °C (745 °F), it is best to generate saturated high-pressure (HP) steam to mix with saturated steam generated in the HRSG HP drum. [1] A schematic of this process is depicted in **Figure 4**.

Integrating HP saturated steam into the HRSG and sending heated feedwater from the HRSG is common in integrated gasification combined cycle (IGCC) plants. A contractor familiar with IGCC integration issues can easily manage ISCC integration issues. The key factor to keep in mind is that in an ISCC plant, it is important

When solar energy is integrated in the CC steam cycles, the following questions must be answered:

- *What solar technology should be used?*
- *How much solar energy should be integrated?*
- *Where in the steam cycle is the best place to inject solar-generated steam?*

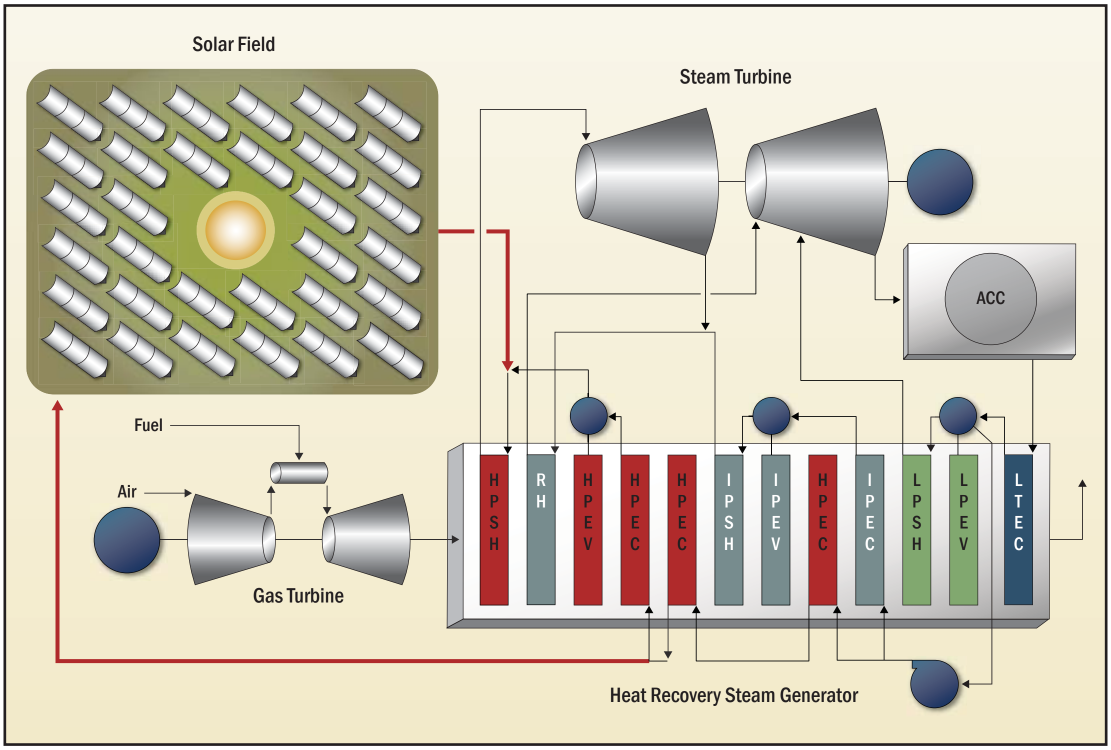

Figure 4. Medium-Temperature Solar ISCC Technology

to take feedwater supply to the solar boiler from the proper location in the steam cycle. The objective is to maximize solar efficiency by maximizing feedwater heating in the HRSG and minimizing feedwater heating in the solar field. For a parabolic trough plant similar to the SEGS plants, the HTF temperature leaving the solar boiler is approximately 290 °C (550 °F). Therefore, allowing for a reasonable approach temperature, the feedwater temperature should be approximately 260 °C (500 °F).

The objective is to maximize solar efficiency by maximizing feedwater heating in the HRSG and minimizing feedwater heating in the solar field.

The most convenient place in the steam cycle from which to take feedwater is the HP feedwater pump discharge. On most modern CC systems, feedwater pumps take suction from the low-pressure (LP) drum. However, the typical LP drum pressure of approximately 5 bara (73 psia) in a three-pressure reheat system results in a feedwater temperature of only approximately 160 °C (320 °F) at pump discharge, which is too low for optimum results. Thus, it is beneficial instead to take feedwater after it has been further heated in the HRSG HP economizers; doing this maximizes the gas turbine exhaust energy used to heat the feedwater, thereby minimizing the solar field size needed to produce a given amount of solar steam. If feedwater is taken from the HP feedwater pump discharge at 160 °C (320 °F) rather than after an HP economizer at 260 °C (500 °F), the solar field would have to be approximately 30% larger to generate enough solar energy to keep the amount of solar steam added to the HRSG the same as when using 260 °C (500 °F) feedwater. This represents a decrease in solar efficiency. Conversely, even though the change in net output drops 11% when the solar field size, hence the amount of solar energy added, is kept constant while the feedwater temperature is increased from 160 °C (320 °F) to 260 °C (500 °F), this configuration results in the highest solar efficiency. These effects of varying the feedwater supply temperature are summarized as follows.

Feedwater Temperature, °C (°F)	160 (320)	160 (320)	260 (500)
Net Solar Energy Added, MWth	96	124	96
Solar Steam Added, kg/h (lb/hr)	173,000 (382,000)	230,000 (507,000)	230,000 (507,000)
Change in Net Output, MWe	37.6	48.1	42.3
Solar Efficiency, %	39.2	38.8	44.3

Solar thermal input to an ISCC can reduce gas turbine fuel consumption, in turn reducing gas turbine power and exhaust energy. For the same plant net output with 100 MWth solar energy input, plant fuel consumption would be reduced by approximately 8%.

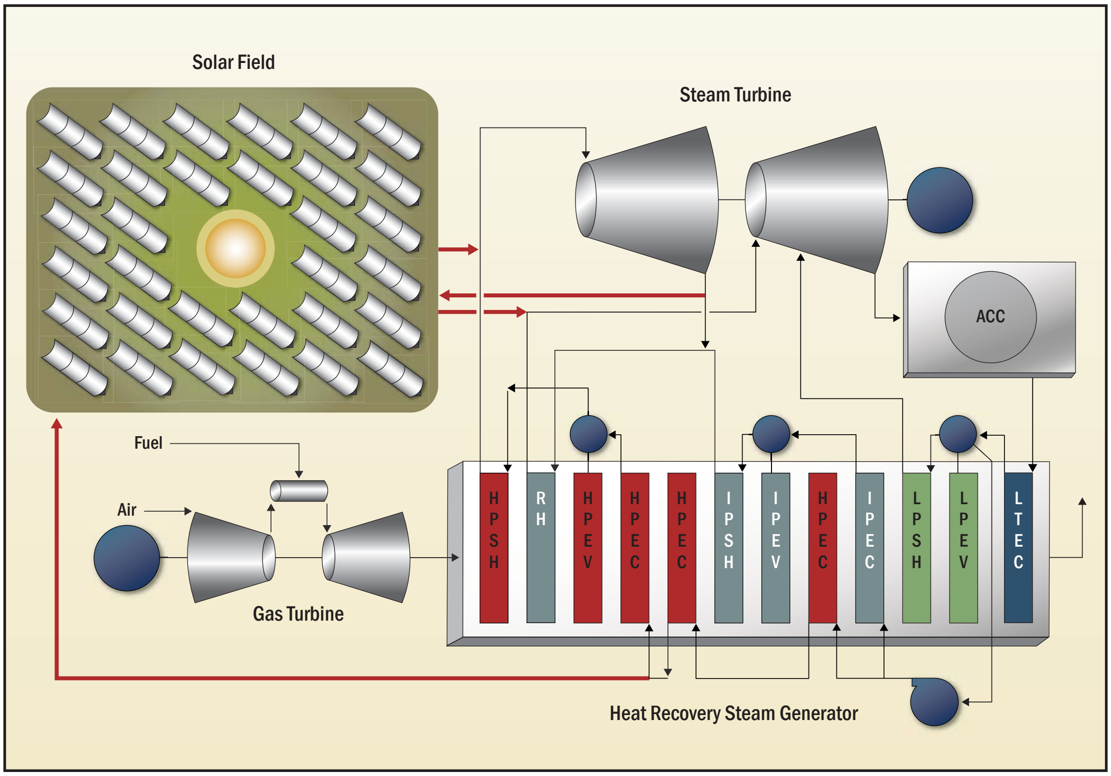

Figure 5. High-Temperature Solar ISCC Technology

In addition to solar troughs, some Fresnel lens systems fall into the medium-temperature category. However, design pressure limitations prevent their use in developing HP saturated steam. Therefore, integrating these systems would be more in line with a low-temperature system.

High-Temperature Solar Technology

Solar tower systems can generate superheated steam—up to 545 °C (1,020 °F)—at high pressure. These conditions allow solar-generated superheated steam to be admitted directly into the HP steam line to the steam turbine. In addition, steam can be reheated in the solar tower like it is in the HRSG. Thus, there is minimal impact on the HRSG because solar steam superheating and reheating are accomplished in the solar boiler. A schematic of this process is depicted in **Figure 5**.

Similar to medium-temperature technology, taking feedwater supply from the optimum location in the steam cycle is important to maximize system efficiency.

A high-temperature system could be used in medium- or low-temperature applications; however, it is doubtful that this would result in optimum application of solar tower technology.

Low-Temperature Solar Technology

Most Fresnel lens systems fall into the low-temperature solar technology category. These systems generate saturated steam at up to 270 °C/55 bara (520 °F/800 psia), although recent technology has been enhanced to reach higher temperatures. This pressure is too low to allow integration into the steam cycle HP system. Therefore, two options exist:

- Generate saturated steam at approximately 30 bara (435 psia) and admit it to the cold reheat line.
- Generate steam at approximately 5 bara (73 psia) and admit it to the LP steam admission line.

A schematic of this process is depicted in **Figure 6**.

Similar to other solar systems, taking feedwater supply from the optimum location in the steam cycle is important to maximize system efficiency. However, in low-temperature systems, there is less flexibility in feedwater takeoff point selection because the takeoff temperature must be below the saturation temperature of the steam being generated.

Economic Considerations

To be able to select the appropriate solar technology for a given site, a detailed economic analysis must be performed to assess capital and O&M costs, performance data, and operating scenarios.

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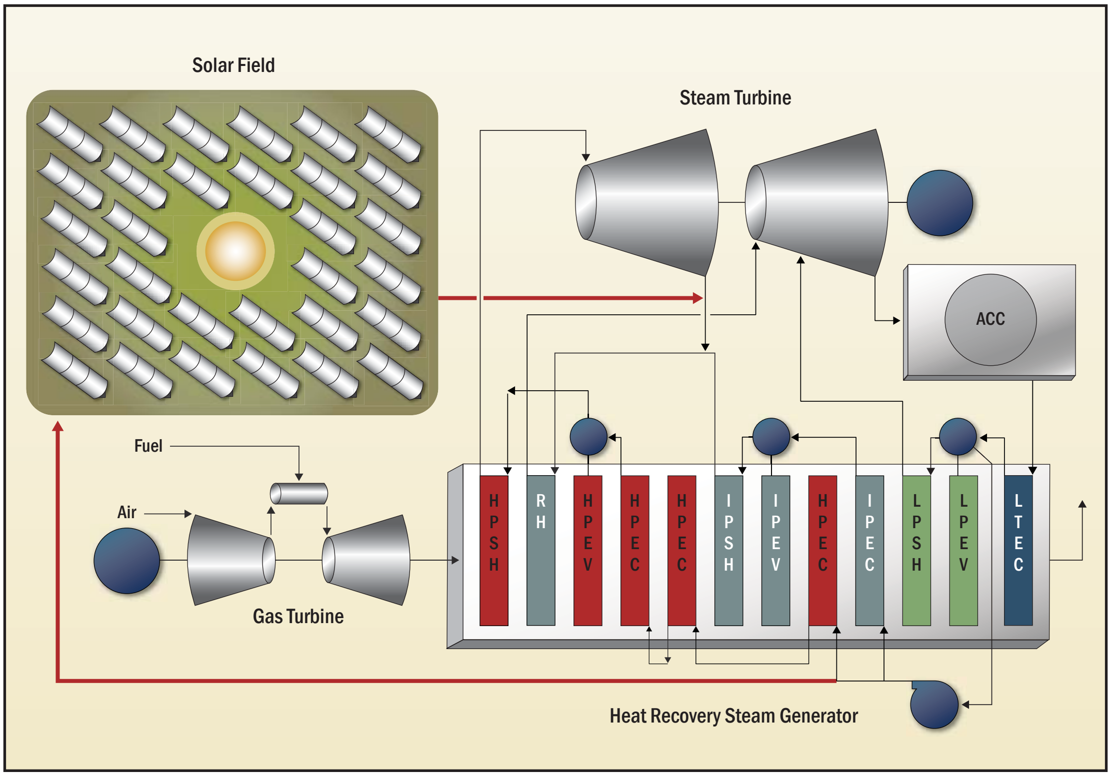

Figure 6. Low-Temperature Solar Technology ISCC

Site data must also be examined to quantify solar facility energy contribution and to define CC performance characteristics. Hourly dry bulb temperature, relative humidity, and solar insolation data for various sites is available from the US National Renewable Energy Laboratory (NREL). This data can be used with software programs, such as the NREL Solar Advisor Model (SAM), to analyze a particular plant configuration. The representative graph shown in **Figure 7** illustrates the results of an analysis of average hourly solar thermal energy production at a particular location versus time of day for January and August.

An advantage of solar energy is that it produces energy when most needed—during peak times of the day and the year.

To analyze a proposed plant configuration, performance characteristics must be defined, conceptual design established, and cycle performance model developed. **Figure 8** shows performance characteristics for a 2 x 1 CC configuration designed to accept 100 MWth of solar energy input in the form of HP saturated steam.

An advantage of solar energy is that it produces energy when most needed—during peak times of the day and the year. Therefore, "time-of-delivery" pricing, where energy payments vary with time of day, can greatly benefit a solar facility. For example, some PG&E power purchase agreements include time-of-delivery pricing that values energy produced during "super-peak" periods (from June through September between noon and 8 p.m., Monday through Friday) at rates almost double the rates at any other time. The pricing structure must be included in the economic analysis to assess the viability of any hybrid solar plant configuration.

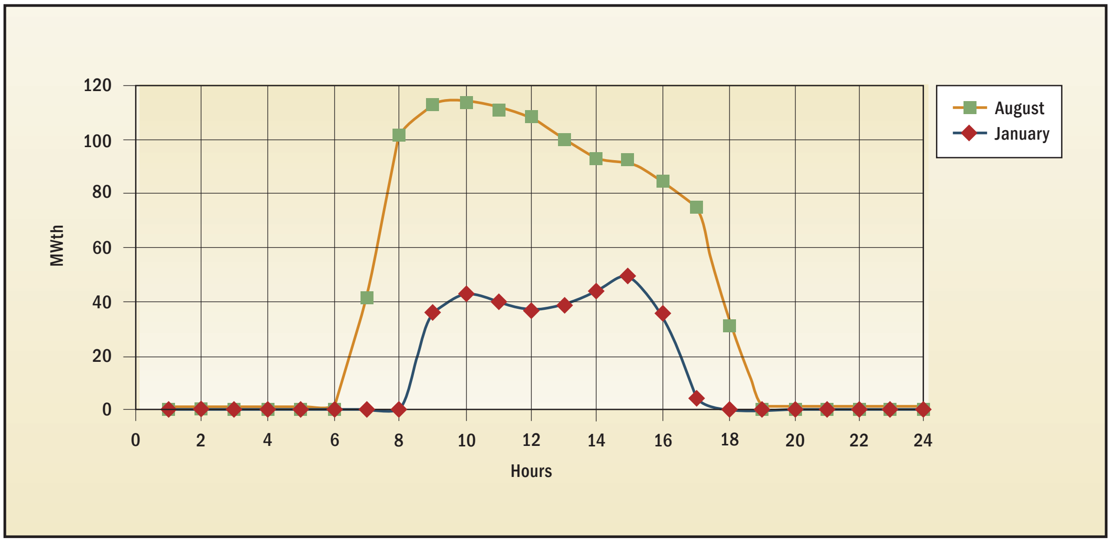

Figure 7. Solar Thermal Energy Production vs. Time of Day

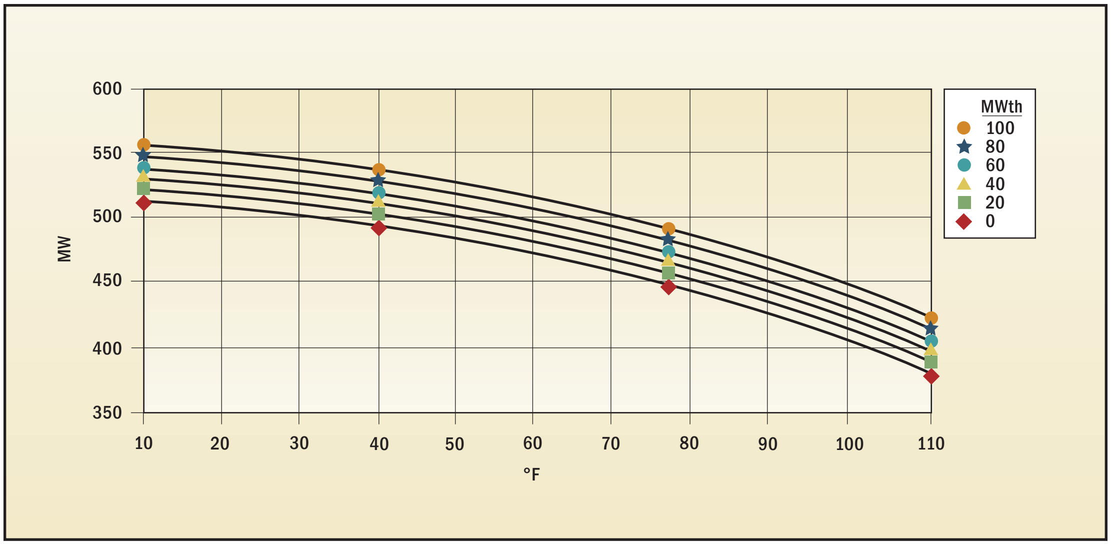

Figure 8. Net Output vs. Ambient Temperature for Various Solar Inputs

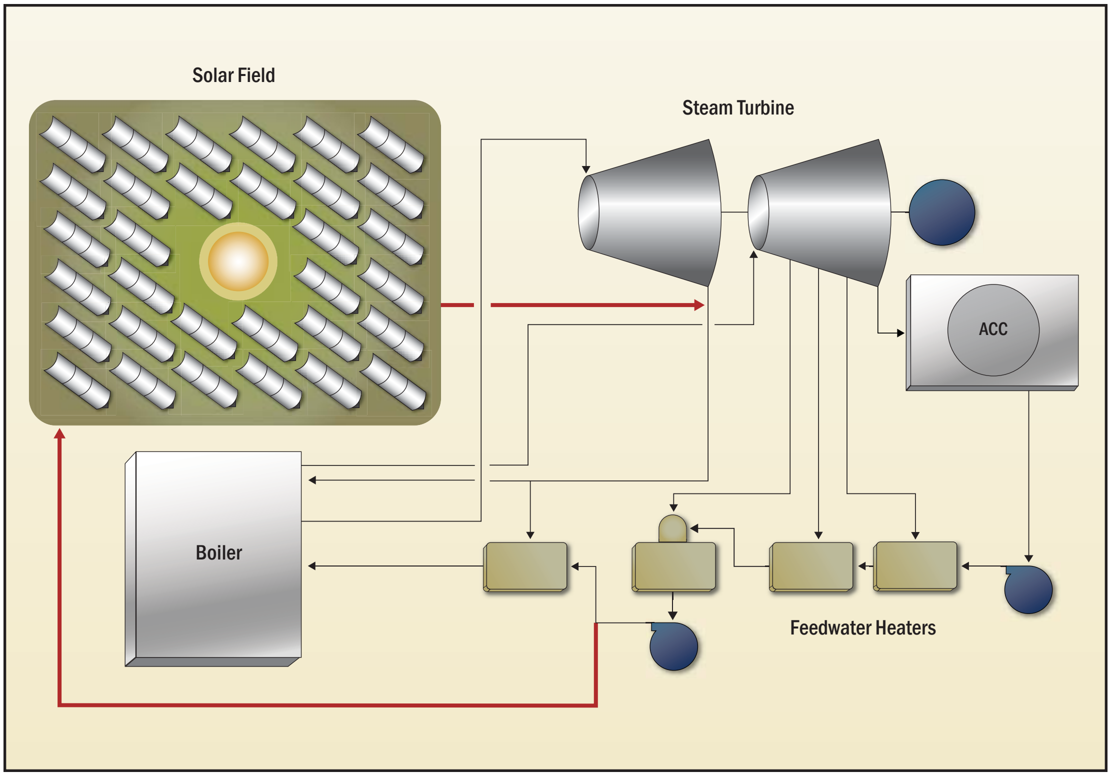

Figure 9. Medium-Temperature Solar Integration with Rankine Cycle Plant

INTEGRATION OPTIONS WITH RANKINE CYCLES

Many issues associated with integrating solar technology with CC plants apply to integrating solar technology with Rankine cycle plants. Similar analyses must be performed to determine the best solar system for the specific plant site and design. However, there are also differences between integrating solar technology with Rankine cycle plants and with CC plants. A major difference is that all electrical power produced in the Rankine cycle plant is generated by burning fuel. Therefore, it can be advantageous to use solar energy to displace fossil fuel energy. In addition, because boiler efficiency typically increases slightly as boiler load is reduced, solar energy can be used to reduce boiler load to save fuel.

Integration options with Rankine cycle plants are discussed only briefly, since integration applications to date have focused primarily on ISCC.

Medium-Temperature Solar Technology

A typical subcritical Rankine cycle power plant has turbine throttle steam conditions of 166 bara (2,400 psia) and 538 °C (1,000 °F). Similar to its application in a CC plant, medium-temperature solar technology can be used to generate saturated or slightly superheated steam for injection upstream of boiler superheater sections. However, integrating solar steam into the boiler proper is a more complex proposition than in a CC plant because of the higher gas temperatures and the need to control fuel firing. Several options involving both water heating and steam generation in the solar field have been examined. [2] These options address using steam or heating feedwater to displace turbine extraction steam to feedwater heaters. A schematic of this process is shown in **Figure 9**. Reducing or eliminating extraction steam to feedwater heaters appears to be the most practical application for medium-temperature solar integration because it avoids complex boiler integration issues.

High-Temperature Solar Technology

Solar tower systems can be used to generate superheated steam for injection into the turbine main steam line. The same amount of cold reheat steam can be extracted and reheated in the solar field, minimizing integration with the Rankine plant boiler. A schematic of this process is shown in **Figure 10**.

Low-Temperature Solar Technology

Options for integrating low-temperature solar technology are limited to generating steam or heating feedwater to reduce turbine extraction steam to feedwater heaters.

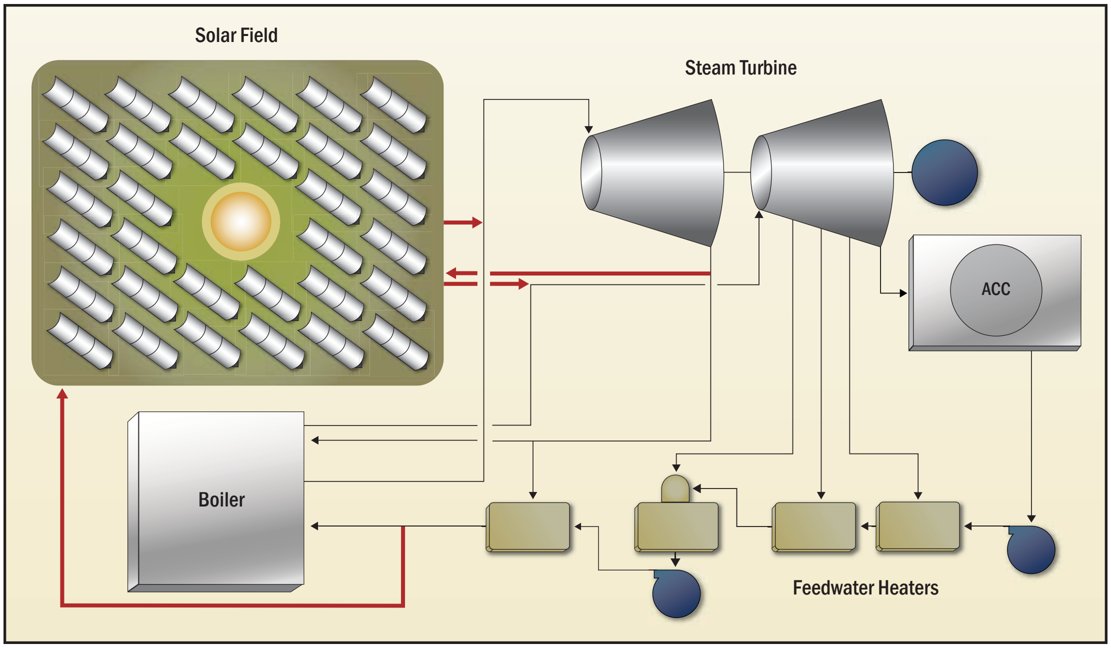

Figure 10. High-Temperature Solar Integration with Rankine Cycle Plant

When dealing with solar hybrid configurations, it is important to assess the impact of steam supply changes on the behavior of the conventional generation facility.

CONTROLS AND TRANSIENT BEHAVIOR

A contractor experienced in IGCC or cogeneration plant design can easily manage the integration and control issues of hybrid plants integrating a solar power source. However, IGCC and cogeneration plants do not experience the solar-sourced steam supply variability associated with solar technology integration. Therefore, when dealing with solar hybrid configurations, it is important to assess the impact of steam supply changes on the behavior of the conventional generation facility. Total system transient behavior, including solar steam source and power plant, should be modeled early in the plant design stage. Complex issues associated with proper transient representation by equipment and controls should be addressed using computer simulation programs. Finally, the complete system should be optimized based on operational and cost considerations. The goal is to create an integrated system capable of predicting steam temperature and pressure variations during steady-state and representative transient conditions.

CONCLUSIONS

Renewable energy sources continue to add to the electricity supply as more countries worldwide mandate that a portion of new generation must be from renewable energy. In areas that receive high levels of sunlight, solar technology is a viable option.

The solar trough, linear Fresnel lens, and solar tower technologies most widely used to concentrate solar thermal power are evolving and improving. Solar trough is considered the most proven CSP technology and has been implemented in the SEGS plants in California, as well as in other areas of the world.

Regardless of the option selected to develop a hybrid solar and conventional fossil plant, determining the optimum solar field is a site-specific task that must consider the grid requirements and operational profile of the steam cycle components at night or during periods when the solar energy is not available.

A carefully planned and executed hybrid plant, such as an ISCC, that integrates CST energy with existing fossil energy sources is a winning combination for both the solar field and the power plant, resulting in:

- Higher CC system efficiency
- Smaller CC plant carbon footprint
- Larger renewable energy portion of new generation
- Minimized effect of the intermittent nature of solar energy supply

It is expected that the number of ISCC plants will continue to grow worldwide. As this happens, it is likely that the installed solar field price will decrease through economies of scale and increased manufacturing and installation productivity. ■

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BIOGRAPHIES

David Ugolini is a senior principal engineer with more than 32 years of mechanical and cycle technology engineering experience on a variety of nuclear and fossil-fueled power generation plants. He works in the Project Development Group as supervisor of the Cycle Performance Group and is responsible for developing conceptual designs and heat balances for Bechtel’s power projects worldwide. Dave also supervises efforts related to plant performance testing.

Dave began his engineering career by joining Commonwealth Edison Company in 1977 as an engineer at the Zion nuclear power plant. He joined Bechtel in 1980 in the Los Angeles office as an engineer, working first on the San Onofre Nuclear Generating Station and then on the Skagit/Hanford nuclear project. Dave later transferred to the San Francisco office and worked as a mechanical engineer on several projects, including the Avon cogeneration project, the Carrisa Plains solar central receiver project, and two combined cycle cogeneration projects—Gilroy Foods and American 1 .

In late 1989, Dave moved to the Gaithersburg, Maryland, office and became supervisor of the Fossil Technology Group’s Turbine Technology Group, where he directed activities related to developing technical specifications and bid evaluations for gas turbines, heat recovery steam generators, and steam turbines for combined cycle and Rankine cycle power plants. When this group was merged with the Cycle Performance Group, he became deputy supervisor and eventually supervisor.

Dave is actively involved in ASME Performance Test Code committees PTC 52 (solar power plant testing) and PTC 6 (steam turbine testing).

Dave received his BS in Thermal and Environmental Engineering from Southern Illinois University, Carbondale.

Justin Zachary, PhD, assistant manager of technology for Bechtel Power Corporation, oversees the technical assessment of major equipment used in Bechtel’s power plants worldwide. He is engaged in a number of key activities, including evaluation of integrated gasification combined cycle power island technologies; participation in Bechtel’s CO_2 capture and sequestration studies; and application of other advanced power generation technologies, including renewables. Justin was recently named a Bechtel Fellow in recognition of his leadership and development of Bechtel’s Performance Test Group and the key technical support he has provided as a widely respected international specialist in turbo machinery.

Justin has more than 31 years of experience with electric power generation technologies, particularly those involving the thermal design and testing of gas and steam turbines. He has special expertise in gas turbine performance, combustion, and emissions for simple and combined cycle plants worldwide. Before coming to Bechtel, he designed, engineered, and tested steam and gas turbine machinery while employed with Siemens Power Corporation and General Electric Company. Drawing on his expertise as one of the foremost specialists in turbo machinery, he has authored more than 72 technical papers on this and related topics. He also owns patents in combustion control and advanced thermodynamic cycles.

In addition to recently being named a Bechtel Fellow, Justin is an ASME Fellow and a member of a number of ASME Performance Test Code committees.

Justin holds a PhD in Thermodynamics and Fluid Mechanics from Western University in Alberta, Canada. His MS in Thermal and Fluid Dynamics is from Tel-Aviv University, and his BS in Mechanical Engineering is from Technion — Israel Institute of Technology, Haifa, both in Israel.

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Prior to working at Bechtel, Joon was a system design engineer for combined cycle power plant projects, where his duties included preparing heat balance and cycle optimization studies and technically evaluating major equipment. He was also a mechanical engineer for pipeline, refinery, and petrochemical plant projects overseas.

Joon holds an MBA from the University of Chicago Booth School of Business, Chicago, Illinois; an MS in Mechanical Engineering from Seoul National University, Korea; and a BS in Mechanical Engineering from Konkuk University, also in Seoul, Korea. He is a registered representative of the Financial Industry Regulatory Authority (FINRA).