CONCENTRATED SOLAR THERMAL PLANTS DOWNSTREAM OF THE SOLAR FIELD—DESIGN/OPTIMIZATION OF THE ASSOCIATED POWER GENERATION CYCLE

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Abstract—*While major design efforts are dedicated to developing and improving solar energy collection technologies, the downstream power generation cycle is often considered a straightforward exercise. The diverse nature of the heat sources and their cyclic behavior make the design of the turbo-machinery and associated balance-of-plant equipment quite different from those used in conventional fired power plants. The high capital cost of these renewable facilities and the limited hours of operation are powerful drivers to increase equipment efficiency and reduce startup time.*

This paper reviews state-of-the-art hardware selection and design considerations for several solar thermal technologies (tower, trough, and linear Fresnel lens) from an engineering, procurement, and construction (EPC) contractor's perspective. Topics addressed include the benefits and limitations of each method and the impact of flow and temperature on cycle efficiency. The turbine design challenges posed by repeated fast startups and plant size optimization are examined, with a special emphasis placed on heat sink design due to water scarcity.

Finally, the authors offer recommendations for achieving a balance between the economics of generation, the cost of equipment, and the reliability of the downstream power generation system.

Keywords—*concentrated solar thermal plant (CSP), heat sink, power generation cycle, solar thermal technology, steam cycle, thermal analysis, turbine*

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INTRODUCTION

In the design and development of concentrated solar thermal plants (CSPs), major effort is devoted to improving the solar energy conversion to steam. Use of sophisticated tracking and controls, better optics, and improved tube coatings are just a few of the elements employed by CSP technologies designers to achieve their goals. However, the optimization of heat input to the system is only half of the effort. The remaining part—processing the heat into electric power using well-known conventional thermodynamic cycles such as Rankine, Brayton, or Stirling—is the subject of this paper. Special emphasis is given to the main components of a steam cycle: turbine and heat sink.

The nature of the solar heat source and its cyclic behavior make the design of turbo-machinery power generation equipment quite different from that of steam turbines used in conventional power plants. The high capital cost of renewable facilities and the limited hours of operation are powerful drivers to increase turbo-machinery efficiency. Proven technology will therefore be a key advantage in the current project financing situation.

For high temperature applications such as the power tower or in medium temperature solar trough collector fields, the paper addresses the unique requirements for performance, integration, and fast startup of the turbines, including the effect of various thermal storage options. Since most of the concentrated thermal solar applications are in arid regions, heat sink selection (air-cooled condenser [ACC], hybrid, Heller tower, etc.) and how it affects plant design and performance are emphasized in the discussion. The paper also reviews the state-of-the-art hardware designs for each application from an engineering, procurement, and construction (EPC) contractor's perspective.

EXISTING SOLAR THERMAL TECHNOLOGY CONCEPTS AND EFFECT ON STEAM PRODUCTION

CSP systems require several components to produce electricity: (1) concentrator, *Optimal plant size selection is a complex task requiring a detailed analysis of each specific location.*

ABBREVIATIONS, ACRONYMS, AND TERMS

ACC	air-cooled condenser
Btu	British thermal unit
CSP	concentrated solar thermal plant
DC	direct contact
EPC	engineering, procurement, and construction
HP	high pressure
HTF	heat transfer fluid
LSB	last-stage blade
LP	low pressure
O&M	operation and maintenance
TTD	terminal temperature difference

(2) receiver, (3) storage or transportation system, and (4) power conversion device. Several types of technologies are available, including:

- Solar tower
- Trough
- Linear Fresnel lens

CSP technology type determines the options for interface with a conventional fossil-fired plant. **Table 1** summarizes the types of technology and their thermal outputs.

Table 1. Summary of Concentrated Solar Technologies

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

CYCLE CONFIGURATION

Plant Size

Defining plant size is related to CSP technology as well as the availability of appropriate steam turbines and heat sinks. Size can sometimes also be dictated by local legislation and permitting. For example, Spain's maximum plant size is set at 50 MW; no such legal limitations exist in the United States. Plants capable of generating more than 200 MW with trough or tower configurations are being planned. The economy of scale for cost and performance is expected to yield the most suitable plant size based on land available for the solar field, standardization to reduce capital cost, and increased availability. Note, however, that only a detailed analysis of each specific location can provide a definitive answer to the question of size.

Number of Feedwater Heaters

Increasing the number of feedwater heaters improves plant efficiency but also increases the cost. **Figure 1** presents a typical plant configuration including an auxiliary boiler.

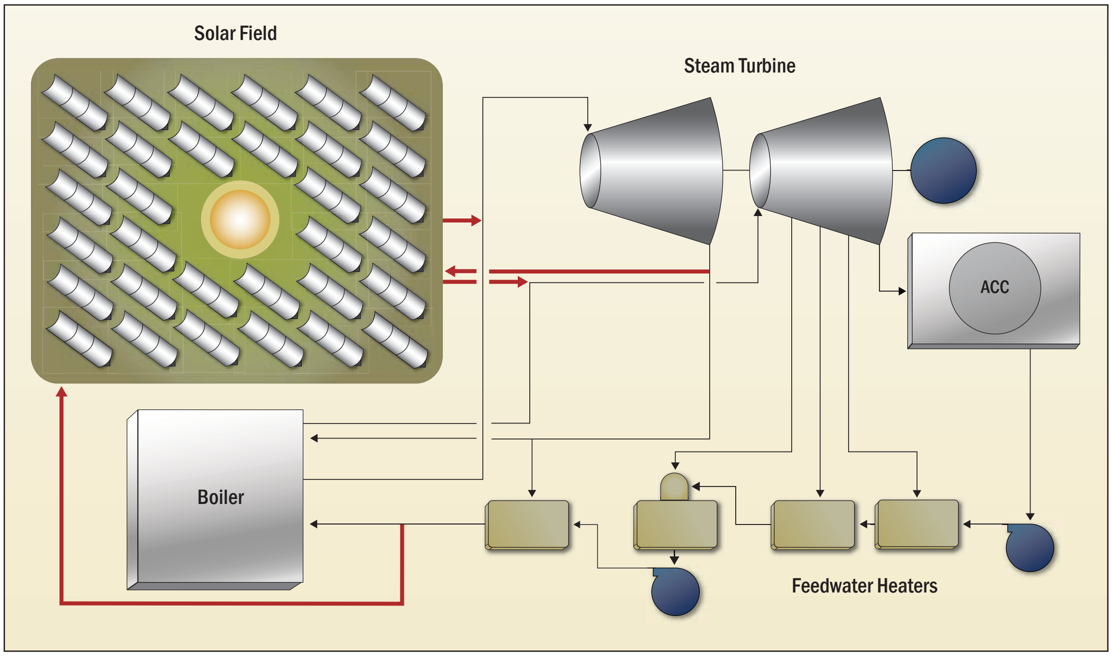

Figure 1. Typical Plant Configuration

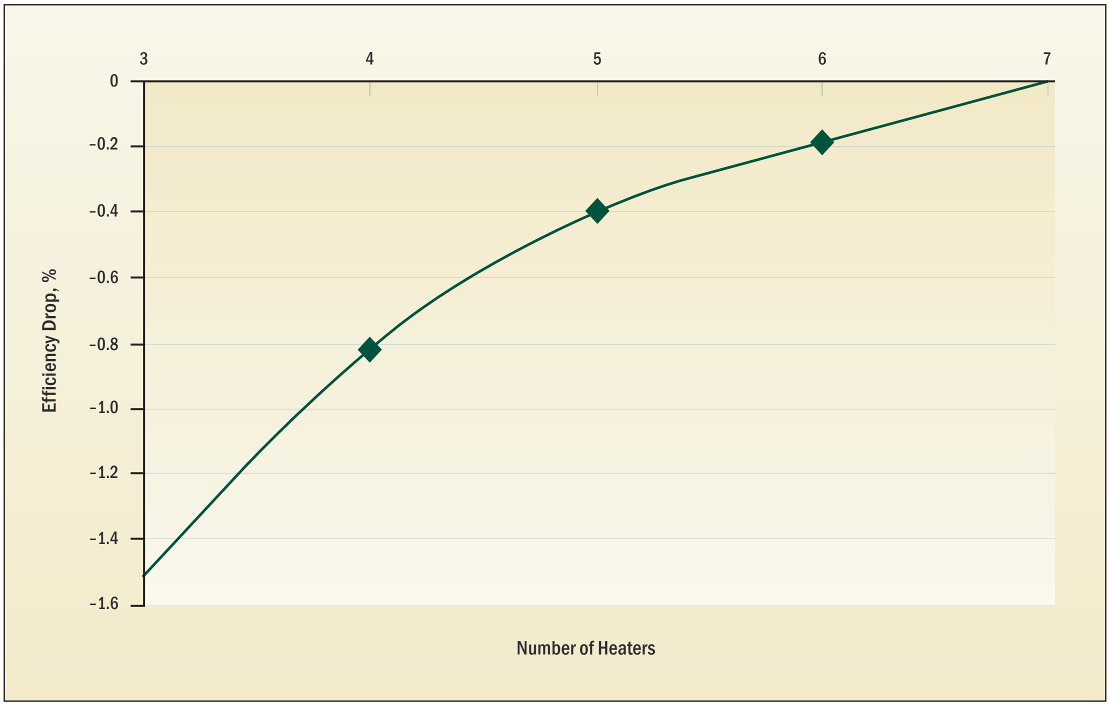

Figure 2. Cycle Efficiency versus Number of Feedwater Heaters

The number of feedwater heaters used affects steam cycle efficiency.

Figure 2 depicts the change in steam cycle efficiency that results from reducing the number of feedwater heaters. If four heaters are used instead of seven, cycle efficiency is reduced by 0.8%. Depending on the solar multiplier and the economics of the plant, shutting down or throttling heaters could have a positive effect on the plant output. It is imperative that the steam turbine is designed in such a way that it can receive the additional steam available when the feedwater heaters are out of service.

Reheat Options

The decision to use a reheat cycle versus a non-reheat cycle is a function of low-pressure (LP) turbine exhaust moisture levels and the desired throttle conditions that provide the optimum plant-efficiency-to-capital-investment ratio. The renewable technology that is used will provide restrictions on the throttle and reheat temperatures. For example, a power tower plant can have main steam temperatures of around 538 °C (1,000 °F), while a parabolic trough plant using heat transfer fluid (HTF) will be limited to around 371 °C (700 °F).

With throttle temperatures relatively fixed, the plant cycle design is reduced to two options:

- Design with a higher throttle pressure that provides a higher efficiency but requires a reheat system to lower exhaust moisture levels
- Design with a lower throttle pressure that requires less initial capital investment, but suffers from lower efficiency

The paper explores these two options using the two throttle temperatures stated above. While such discussion is also pertinent to fossil-fuel-fired plants, the increased efficiency only equates to lower capital cost for solar applications.

Condensing steam turbines commonly operate with saturated steam exhaust conditions. However, if there is too much moisture, the turbine blades will suffer from erosion, causing decreased efficiency and eventually leading to an earlier than normal overhaul. It is common to see reheat turbines designed to safely operate with 8% exhaust moisture content, while non-reheat turbines are allowed to go to 11% moisture. This analysis uses these values as design constraints.

For those steam turbines of interest to designers of renewable resource power plants, isentropic efficiencies can vary from 80% to 90%. Temperature versus entropy diagrams can illustrate the performance impacts via available heat energy for the use of reheat versus non-reheat cycles. It is at this end that we arbitrarily choose 85% isentropic efficiency to form a basis for our comparisons. Furthermore, the LP exhaust pressure is kept constant to aid in comparison.

Reheat or non-reheat—this is the challenge for plant cycle design.

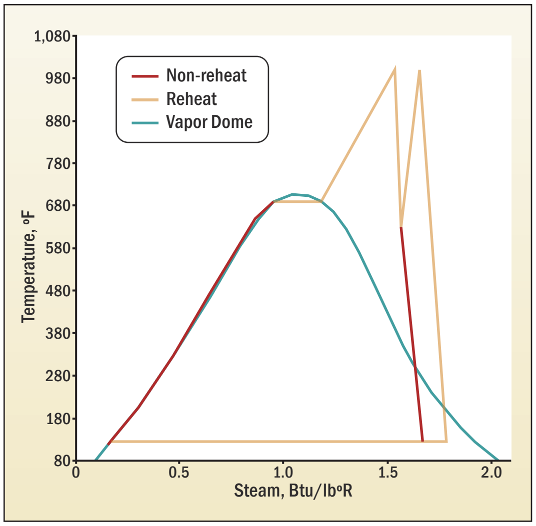

Figure 3. Reheat versus Non-Reheat for Constant Main Steam Conditions

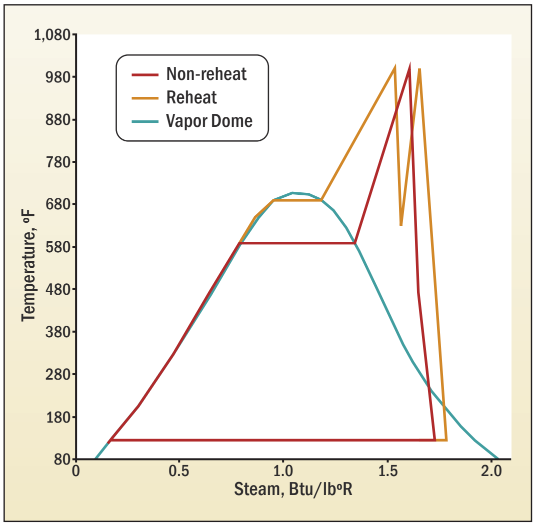

Figure 4. Reheat versus Non-Reheat for Constant Exhaust Conditions

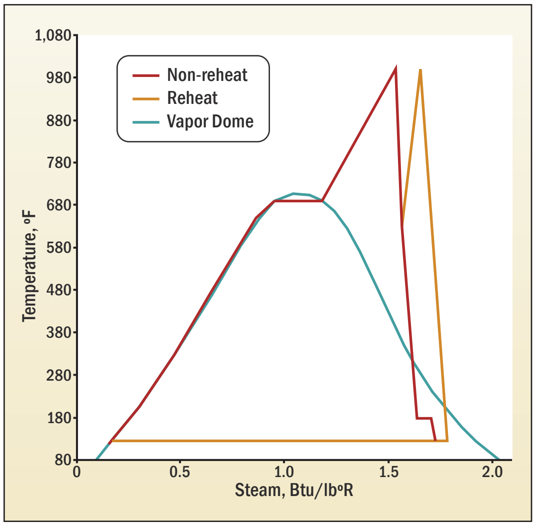

Figure 5. Reheat versus Non-Reheat for Constant Exhaust Conditions with Moisture Reduction

Figure 3 shows a typical reheat cycle versus a non-reheat cycle designed at the same combination of main steam temperature and pressure. The reheat option has a moisture content of 8%, while the non-reheat section has a moisture content of 14.6%. The higher moisture content in the LP section should be avoided.

Figure 4 compares a reheat cycle with a non-reheat cycle, both designed with a throttle temperature of 538 °C (1,000 °F) but with a lower throttle pressure in the non-reheat case to maintain an acceptable moisture level.

Reduction in the turbine throttle pressure has protected the LP turbine blades from erosion caused by high moisture levels. However, the amount of recoverable energy has been reduced as well. This is represented as the area encompassed by the red, non-reheat line compared to the area encompassed by the orange, reheat line. For the cases used in this study, the amount of heat available for conversion to power is 18% lower in the non-reheat case. The magnitude of the reduction in recoverable energy will vary with the temperature and pressure constraints imposed by the renewable resource. **Figure 5** shows a comparison of a reheat cycle and a non-reheat cycle designed with a throttle temperature of 371 °C (700 °F) and a lower throttle pressure to maintain an acceptable moisture level.

The ratio of recoverable energy has shifted (by a magnitude of 9%) in favor of using the non-reheat cycle by using a lower throttle temperature. Therefore, the performance advantage that the reheat cycle had in the 538 °C (1,000 °F) case has been reduced when using a throttle temperature of 371 °C (700 °F). This performance is summarized in **Table 2**. This trend indicates that there is a point where the performance gains of using a reheat cycle are outweighed by the additional capital investment required.

One further option is to borrow an idea from the nuclear power industry, where moisture removal is added near the final stage of the LP turbine. Table 2 presents a summary of this option's performance for a 538 °C (1,000 °F) throttle temperature case with a single-stage moisture removal section that has a moisture removal effectiveness of 40%. As shown in the table, throttle pressure for this moisture removal case can be maintained at the reheat level while moisture is kept at a safe level; however, there is a 12% reduction in available heat energy. These performance losses are less than in the case where throttle pressure was lowered. Note that the data is qualitative due to the

Table 2. Summary of Thermal Analysis Results

Parameter	Units	538 °C (1,000 °F) Reheat	538 °C (1,000 °F) Non-Reheat Constant Pressure	538 °C (1,000 °F) Non-Reheat Reduced Pressure	538 °C (1,000 °F) Non-Reheat Moisture Removal	371 °C (700 °F) Reheat	371 °C (700 °F) Non-Reheat Reduced Pressure
Heat Input	Btu/lb	1,706.2	1,544.9	1,542.3	1,581.9	1,471.4	1,392.7
Heat Rejected	Btu/lb	942.0	874.1	911.3	911.2	942.0	911.3
Heat Available	Btu/lb	764.2	670.8	631.1	670.7	529.4	481.4
LP Efficiency	–	44.8%	43.4%	40.9%	42.4%	36.0%	34.6%
Exhaust Moisture	–	8.0%	14.6%	11.0%	11.0%	8.0%	11.0%

theoretical basis of using this technology—which is derived for much larger applications—and viewing it solely from a thermodynamic point of view. A quantitative analysis would require further investigation by the steam turbine manufacturers.

The choice of whether to add reheat to the cycle can hold serious consequences for performance and the initial capital investment required for construction of the plant. LP turbine exhaust conditions must be maintained at sufficiently low moisture levels to ensure long and reliable operation. The previous cases have shown performance reduction on the basis of available energy, but it is important to note that the reheat option's performance increase comes at the price of increased heat transfer surface area. It is to this end that plant efficiency must be evaluated in addition to plant output.

Either additional initial capital must be invested to keep turbine throttle pressure up and increase performance with a reheat cycle, or throttle pressure can be allowed to fall with a lower initial capital investment and lower performance. The use of moisture removal stages offers a compromise between reheat and non-reheat throttle pressures but requires further quantitative analysis from turbine manufacturers. In summation, in today's renewable technologies market, it is imperative that a comprehensive engineering analysis of various turbo-machinery options be conducted to ensure that capital investment is optimized for the renewable resource being used.

HEAT SINK CONSIDERATION

In this section, three heat sink options are described. Since heat sink selection is dictated not only by cycle design, but also by availability of water, a detailed discussion is needed. More often than not, solar plants are located in desert regions where solar availability is desirable but water is scarce. Therefore, heat sink designs typically use either dry cooling or some type of hybrid (combination of wet and dry) technology.

Heat sink selection is dictated not only by cycle design, but also by availability of water.

Air-Cooled Condenser

In an ACC (see **Figure 6**), heat is transferred from the steam to the air using fin tube bundles. The ACC tube bundles have a relatively large tube side cross-section and are usually arranged in an A-frame configuration, resulting in a high ratio of heat exchange surface area to plot area. The tubes are kept cool by the heat that is conducted across the tube thickness to the finned outer surface. Air is continuously circulated over the (dry) outside surface of the tubes. Heat

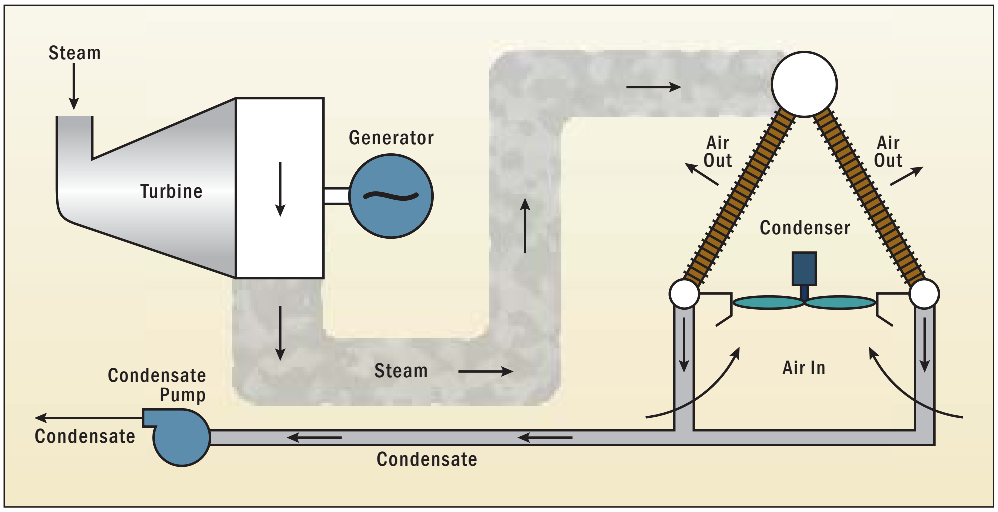

Figure 6. Air-Cooled Condenser

transfer from this outside surface of the tubes to the air takes place by forced convection heat transfer (heating of the air). No evaporation of water is involved.

Thus, for ACCs, the condenser performance with regard to turbine exhaust pressure is directly related to the ambient (dry bulb) air temperature as well as to the condenser design and operating conditions. This results in a higher turbine backpressure for given ambient atmospheric conditions, with a resultant decrease in turbine generator output when compared to wet cooling technologies, whose performance is dictated by the lower wet bulb temperature. An ACC eliminates the entire circulating water system, circulating water pumps, and surface condenser.

A number of heat sink solutions using either dry cooling or hybrid (combination of wet and dry) technology offer optimization tools to designers.

Parallel Condensing Wet/Dry System (the GEA PAC System®)

In this type of hybrid system, exhaust steam from the steam turbine is separated into two streams. One stream flows into a water-cooled surface condenser, while the other is directed to an ACC. Condensate from the surface condenser and the ACC can be collected in a common hotwell. Water consumption is controlled by the distribution of the heat load between the two condensers.

The parallel condensing wet/dry system (PAC System) developed by GEA Power Cooling, Inc. (see **Figure 7**) should not be confused with a hybrid plume-abated cooling tower, which is used primarily to reduce the visible plume from a wet cooling tower. A hybrid cooling tower has practical limits to the amount of heat that can be rejected in the dry section, since the latter is sized for plume abatement only. With the PAC System, there is complete flexibility in the amount of heat rejected in the dry section.

The dry section of the PAC System employs direct condensation in contrast with other hybrid systems, which are indirect condensing systems (i.e., water is cooled through both the wet and dry sections and then pumped through a common condenser). As a result, the dry section of the PAC System can efficiently reject a substantial amount of heat even on hot days, thereby reducing peak water usage. During cooler periods, the amount of heat rejected in the dry section can be increased up to 100% if so designed, further reducing the plant's water consumption. An additional benefit of the PAC System is the reduction of plume. Plume can be reduced or eliminated entirely when danger of icing exists simply by shutting off the wet section.

Heller System

The Heller system (see **Figure 8**) is an indirect dry cooling technology that requires a separate condenser and circulating water pump. The heat is initially exchanged in a condenser to a closed water circuit, where the heat is rejected to

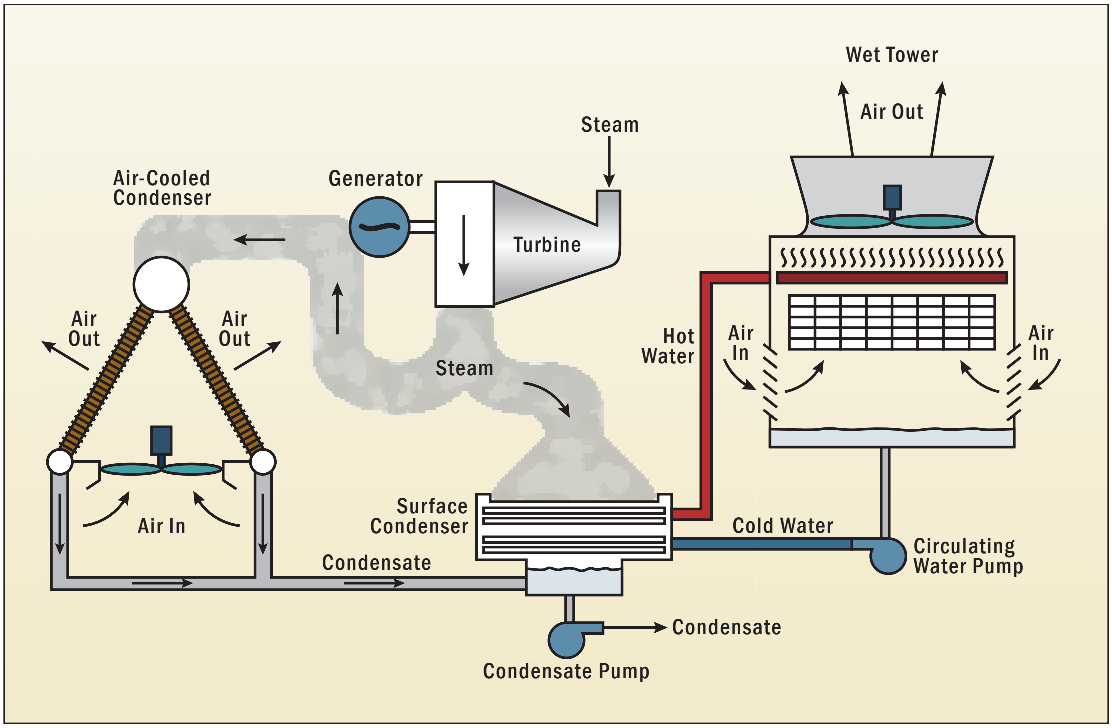

Figure 7. Parallel Condensing System

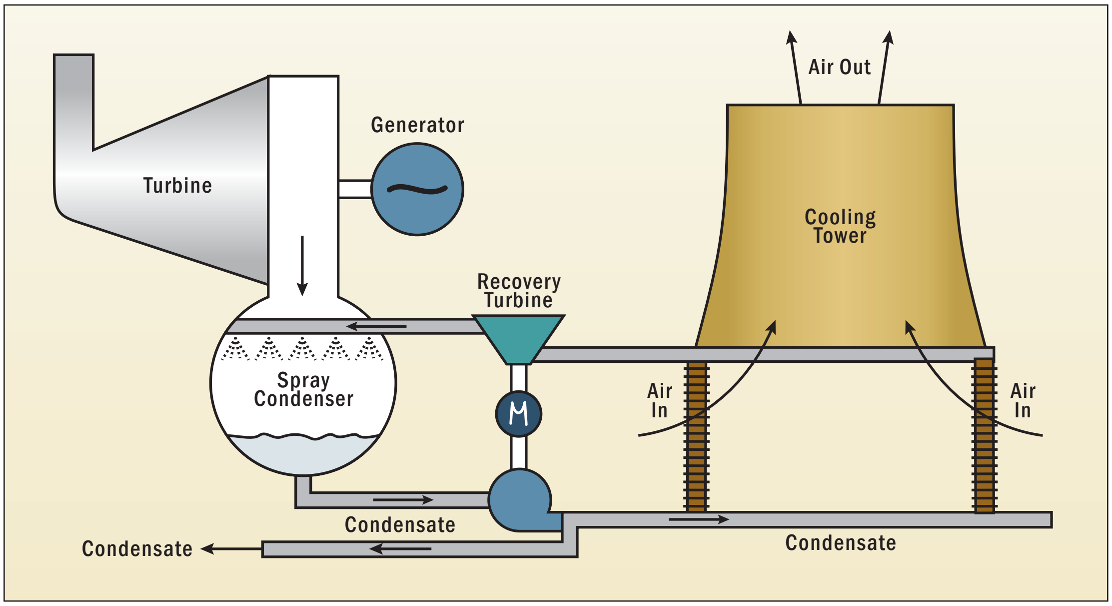

Figure 8. Heller System

ambient air utilizing a dry tower with water-to-air heat exchangers, typically in a natural draft configuration (although mechanical draft is also available). The tower may be equipped with a peak cooling system that, during hot ambient conditions, sprays water on part of the heat exchanger bundles for peak shaving purposes. A direct contact (DC) jet condenser is typically used, since it is characterized by low terminal temperature difference (TTD) values, but surface condensers have been utilized as well. Because Heller systems are indirect, there is no need for a large diameter steam duct between the steam turbine and condenser.

There is no general solution for determining the most suitable heat sink. As mentioned before, many considerations should be weighed before a final decision is made. Capital cost, scarcity of water, and plant location are some of the many determining factors. Experienced plant design firms could also assist in the selection process.

STEAM TURBINE

Requirements

The steam turbine requirements for solar applications are quite different from those for conventional steam turbines used in fossil applications. Equipment suppliers must provide some important features, including:

- Modular design
- Capability to accommodate variable high-pressure (HP) flows and high LP flows
- Fast and easy assembly
- Robust design for daily startup (low mass rotors and casings, reduced seal leakages, etc.)
- Fast responding controls
- Capability to operate at high backpressure due to extensive use of ACC for solar applications
- High-quality materials of construction to support cycling operation

It should be emphasized that steam turbine startup and warming must be done as quickly as possible. Designers should consider using a conventional natural gas-firing system to ensure that the warmup of the steam lines and turbine casing is done before sunrise.

In terms of thermal performance, the turbomachinery should meet the following requirements:

- High efficiency to reduce solar field
- Low minimum load capability
- Convenient steam extraction locations
- Flexibility to cope with thermal transients
- Proven technology

The main goal of a solar power plant is to produce as many megawatt-hours per year as possible. At the beginning and end of the day, solar radiation is substantially lower. Therefore, to maximize power production, the turbine should be capable of operating at extremely low loads. While a conventional steam turbine's minimum load is about 12% to 15% of the base

Solar applications require a dedicated steam turbine with features quite different from those of a conventional steam turbine used in fossil applications.

load, turbo-machinery designers for these special applications should find innovative solutions to continuously operate at 3% to 5% of the base load. This is not a trivial task due to the effects of low flow on fixed exhaust geometry and high ventilation losses.

The turbo-machinery for solar applications should meet the following requirements:

- Achieve environmental emissions requirements
- Offer design simplicity
- Achieve high availability and reliability
- Provide low operation and maintenance (O&M) cost

Optimum equipment selection requires site-specific detailed analysis.

Turbine Backpressure

During the steam turbine selection process, it is important to consider exhaust backpressure and last-stage blade (LSB) design. As evidenced by **Figure 9**, a larger exhaust blade will not necessarily provide the optimum solution for the system. In reality, a 26-inch blade yields a lower power loss than a 33.5-inch blade as exhaust pressure increases.

Startup

Another important factor in selecting the most appropriate turbine is the startup time. In the absence of natural gas or another heat source to facilitate the startup procedure by warming up the lines, valves, and turbine casing, the ability of the turbine to accept steam at lower temperatures becomes a significant consideration. **Figure 10** depicts such a scenario. It can be seen that despite heat input from the solar field reaching substantial heat generation much faster, the turbine startup requires almost 40 minutes to produce any power and almost 80 minutes to reach full power. This behavior has a direct effect on the number of kilowatt-hours produced annually. Efforts should be dedicated to improve startup time, either by use of conventional heat sources or by use of thermal storage.

SUMMARY AND CONCLUSIONS

While a significant effort has been dedicated to solar field improvements, a comprehensive understanding of the interaction between the solar field and the heat energy conversion system is required in order to develop a successful project. Selection of the two major components—the turbo-machinery and the heat sink—must be coordinated and integrated to meet the specific site requirements.

The unique requirements of solar power plants have created specific types of turbo-machinery. The continuous demand for renewable energy will lead to the development of more efficient and reliable equipment.

Optimum equipment selection requires detailed analysis of site-specific climate conditions, commercial drivers, and equipment capability to respond to intermittent heat source behavior. Selection of experienced power plant design and construction firms could certainly facilitate the process. ■

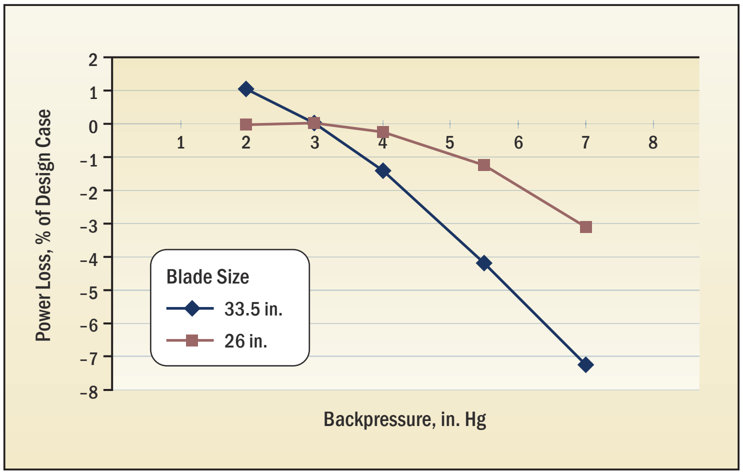

Figure 9. Power Loss versus Steam Turbine Backpressure

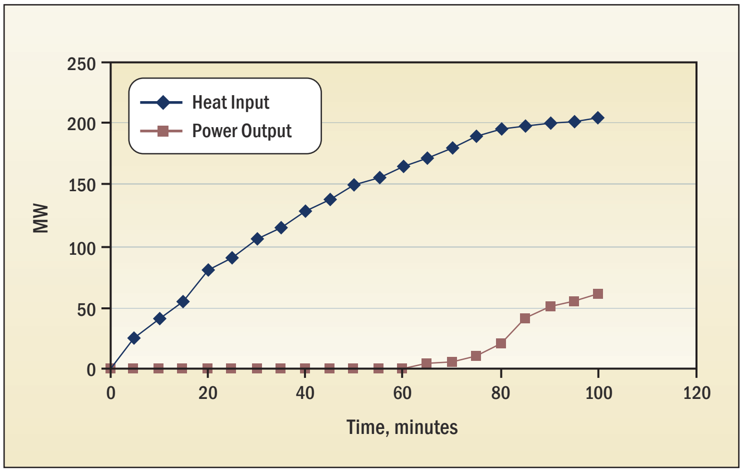

Figure 10. Turbine Startup Curve

TRADEMARKS

PAC System is a registered trademark of GEA Power Cooling, Inc.

BIOGRAPHIES

Justin Zachary, PhD, a Bechtel Fellow and technology manager 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 has more than 32 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, and is a widely respected international specialist in turbo machinery. 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.

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.

Natasha Jones is a mechanical engineering staff specialist in Bechtel's Power Global Business Unit, located in Frederick, Maryland. She has been with Bechtel for 5 years and is currently engaged in cooling system and cooling tower specification, evaluation, and performance testing.

Natasha has co-authored and presented papers at regional and national conferences and presently serves on several Cooling Technology Institute technical committees.

Natasha has a BS in Chemical Engineering from Colorado State University, Fort Collins.

Aslan Golant is a mechanical engineer in Bechtel's Power Global Business Unit, located in Frederick, Maryland. During his 4 years with Bechtel, Aslan's time has been split between the Project Development Group cycle analysis team and field support for the Elm Road project. On the cycle analysis team, he analyzes thermodynamic cycles and builds models to provide power plant performance predictions and optimization. Earlier, at the Elm Road jobsite (two supercritical coal plants in Oak Creek, Wisconsin), he provided senior engineering support and operational experience to assist the project in obtaining substantial completion.

Aslan spent 5 years in the US Navy supervising operation and maintenance of his ship's main propulsion gas turbine engines and ancillary equipment. After leaving the Navy, he moved into the industrial field as a quality test technician conducting first article static and dynamic testing of gas turbine engines. During these earlier phases of his career, Aslan gained 7 years of collective experience in power plant design, operation, and maintenance requirements.

Following the field experience described previously, Aslan enrolled in the University of Illinois at Chicago, graduating Summa Cum Laude with a BS in Mechanical Engineering before being recruited by the Bechtel team.