Technical Paper

Solar power generation systems

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Presented to
The Second Conference on Air Quality
Management in the Electric Power Industry
The University of Texas at Austin
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Babcock & Wilcox

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Abstract

The Department of Energy has embarked on an extensive program to use solar energy to replace fossil fuel. One expanding effort is directed toward generating electric power with solar energy. Stand-alone plants utilizing thermal storage systems when solar is unavailable represents one facet of the program. Another facet involves demonstration and first-generation plants which "repower" present gas- and oil-fired fossil plants with solar energy for both industrial and utility boilers. The steam/water solar steam generators represent the best chance for early demonstration projects, although they have recognized shortcomings in the areas of thermal storage and steam-side pressure drop. Systems with either sodium or fused salts as their heat transfer medium have a greater potential for future development of stand-alone plants.

Babcock & Wilcox, as a supplier of fossil and nuclear steam generators, has been involved in several solar power projects including both water/steam and sodium systems. The paper describes such solar power generation systems.

Introduction

With the ever-increasing oil prices, the Department of Energy has annually increased its budget for alternate or renewable sources of energy, including $121 million in Fiscal 1980 for solar thermal power generation. While some efforts are directed toward industrial applications and small unit projects applicable to decentralized energy systems, the large capacity, central tower receivers for utility-size generating plants will require the major portion of the technological development effort but they also provide the potential for maximum benefit.

The promise of applying solar energy to electric power generation is exciting to the general public and to Congress. The result is political pressures on federal and local governments and on Utilities for early demonstrations of electric power generation from solar sources. There are recognized problems with the application of solar power, however, and they center on the realization that the sun does not shine all the time and not coincident with consumer needs for power generation.

Solar insolation variations

Shown on Figure 1 are the daily (diurnal) and seasonal variations in the sun's energy transmitting patterns, or insolation. The effect of such variations can be planned for in the operation of each unit and its system load control. Variations in cloud cover, however, present the utility with a random and unplanned systems upset. There are differing concerns for either extensive cloud cover that shuts down the entire collection system, or dispersed clouds that block only part of the field for short time intervals. Shown on Figure 2 are examples of selected point cloud cover taken at short time intervals during August over the desert at Daggett, California, where you would expect limited cloud cover.

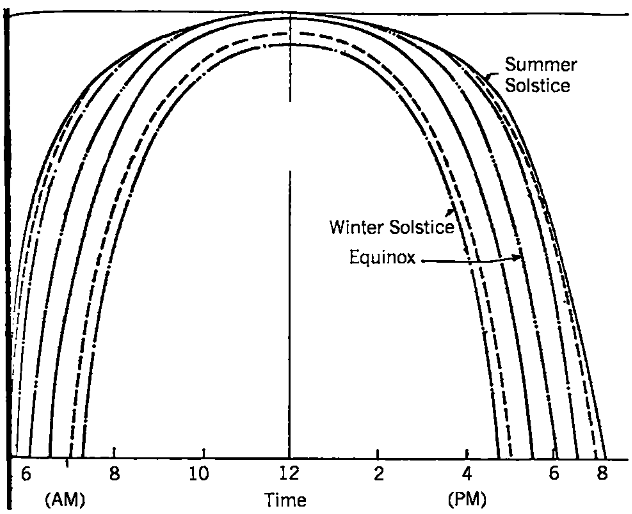


Fig. 1 Seasonal-diurnal variations in absorbed thermal power

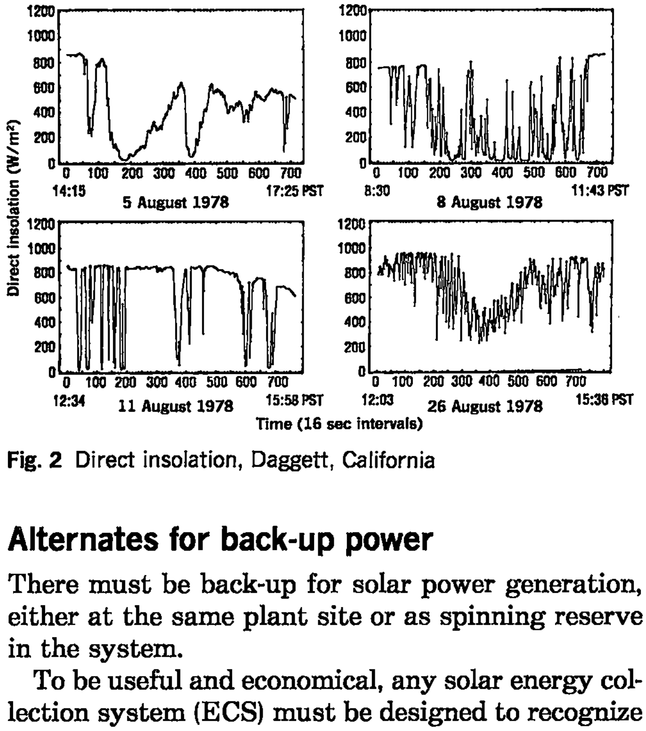


Fig. 2 Direct insolation, Daggett, California

Alternates for back-up power

There must be back-up for solar power generation, either at the same plant site or as spinning reserve in the system.

To be useful and economical, any solar energy collection system (ECS) must be designed to recognize the insolation variations discussed above and generate power at the highest level possible over a predetermined daily time period.

To achieve this goal economically will require first that the capacity of the turbine generator be set relative to the maximum level of solar insolation. Obviously it would be uneconomical to size the turbine generator and balance of plant to match the maximum level of generation which occurs only 1-2 hours on sunny days over most of the year. One back-up approach is to provide for thermal storage using the excess energy, absorbed during the middle of the day, that exceeds the capacity or desired load from the turbine generator. Figure 3 shows a typical daily load cycle for a solar power system using a steam/water receiver with a direct cycle and a thermal storage system. This unit was designed for a solar multiple of 1.4, defined as the ratio of maximum receiver steam flow capacity over the maximum turbine steam flow capacity. This solar multiple is lower than those of most projects which can have more than 2.0. Even units with high solar multiples will be of limited value to a system if heavy clouds occur for more than one day.

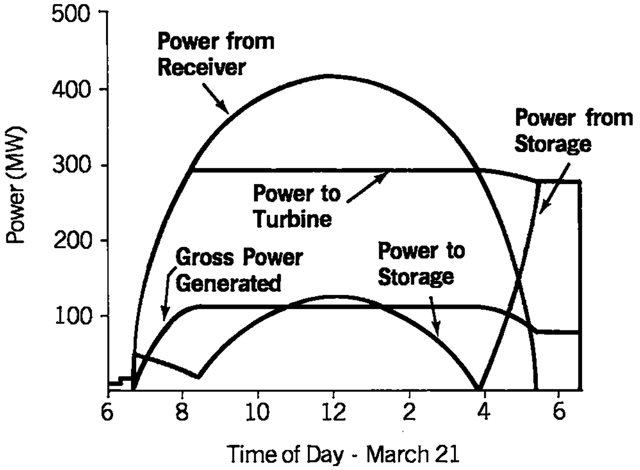


Fig. 3 Power trace for 100 MWe nonreheat system

It is difficult to provide economic thermal storage for a steam/water system. Typically, many steam/water projects use a single fluid or thermocline system using oil and rocks as the thermal storage medium. Unfortunately, only slightly superheated steam is then recoverable for operation of a dual admission turbine, with the steam introduced at a lower temperature stage. The obvious result is a reduction in cycle efficiency and turbine-generator capacity.

A more energy efficient system will consist of at least two stages as shown in Figure 4 and perhaps three or four. Used with the steam/water system (described below) steam at approximately 500 psi and approaching 900F can be recovered for introduction at the reheat turbine inlet, as shown on Figure 5. Note from this figure the low steam temperature recoverable if only a single stage, thermocline system is used.

The steam/water cycles suffer in the charging and discharging of thermal storage when compared to proposed systems where the tower receiver circulating fluid is sodium or fused salts capable of being circulated at 1100-1200F. For such systems the hot circulating fluid can be stored in large tanks for use at any time with little loss in cycle efficiency or turbine generator capacity.

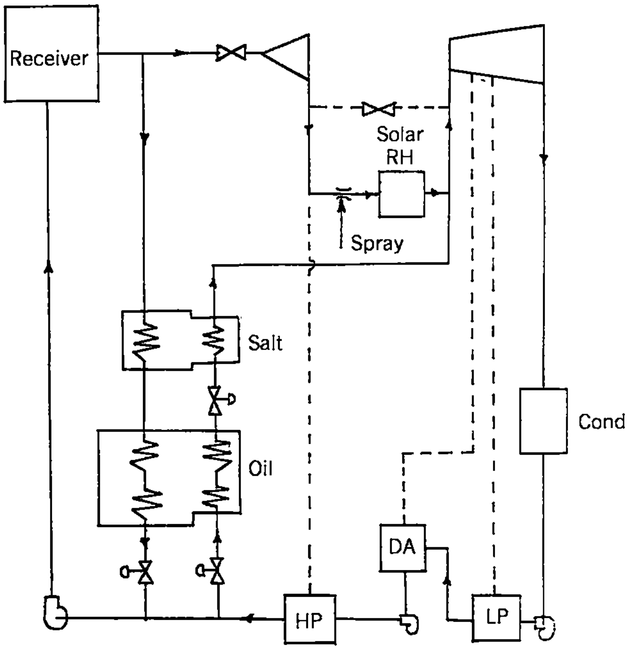


Fig. 4 Working fluid flow diagram scheme A with solar reheater

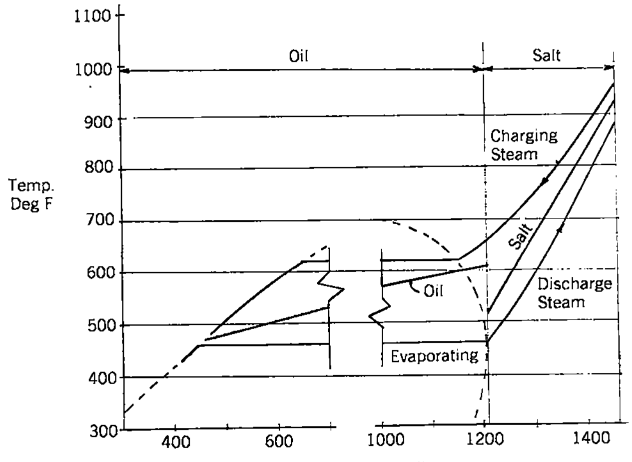


Fig. 5 Temperature enthalpy diagram of the thermal storage system

A second means of providing back-up to a solar receiver and power generation system is a fossil-fired boiler or heat exchanger. One of the best potential approaches for early commercial application of solar power is to install a water/steam solar receiver in parallel with an existing oil- and/or gas-fired boiler where the fuel is to be restricted by government fiat or by cost.

Another fossil back-up for the project, discussed below, is a hybrid system where a fossil-fired sodium heater is to operate in parallel with a sodium-cooled solar receiver.

Steam/water solar receiver

One solar project now being completed by Babcock & Wilcox is the design of an advanced water/steam solar central receiver for a utility-size generating unit of at least 100 MWe. A schematic of the receiver solar collection field and heliostats and associated generating plant is shown on Figure 6. A view of the receiver design is shown on Figure 7, and its features described in Table I.

An obvious objective of any tower receiver is to keep its size as small and its weight as low as possible. This objective requires that all the heat transfer surface be operated at its maximum capability for all the available solar insolation. It is B&W's design criteria, however, that the maximum rates be limited to those within good fossil boiler practice. The superheater absorption limits are more critical, especially for the welded panel construction; thus, the significant insolation unbalance between the north and south fields presents a problem in addition to the potential for excessive absorption rates.

B&W's recommended solution to avoid high absorption rates on the membraned superheater panels is the incorporation of a screen tube design. The conceptual screen tube arrangement and its effect on the peripheral heat transfer is shown in Figure 8. The heat transfer rates are relative and would vary with the size and capacity of the receiver, as well as the north to south flux ratio. Saturated screen tubes within the pumped recirculating system are installed in front of the "light-tight" membrane wall superheater. Their spacing and distribution are varied around the periphery to achieve near-balanced heat absorption in the panels of each superheater pass. The objective and benefits of screen tubes are outlined below.

1. Intercept excessive insolation.
2. Obtain uniform low level heat flux pattern in superheater panels (Fig. 8).
3. Provide efficient cooling by positive nucleate boiling (ribbed tubes).
4. Reduce metal temperatures (use SA-213-T2).
5. Reduce thermal stress.
6. Reduce radiation losses.

Cavity receiver: Based on the expectation that a cavity type receiver would inherently have reduced

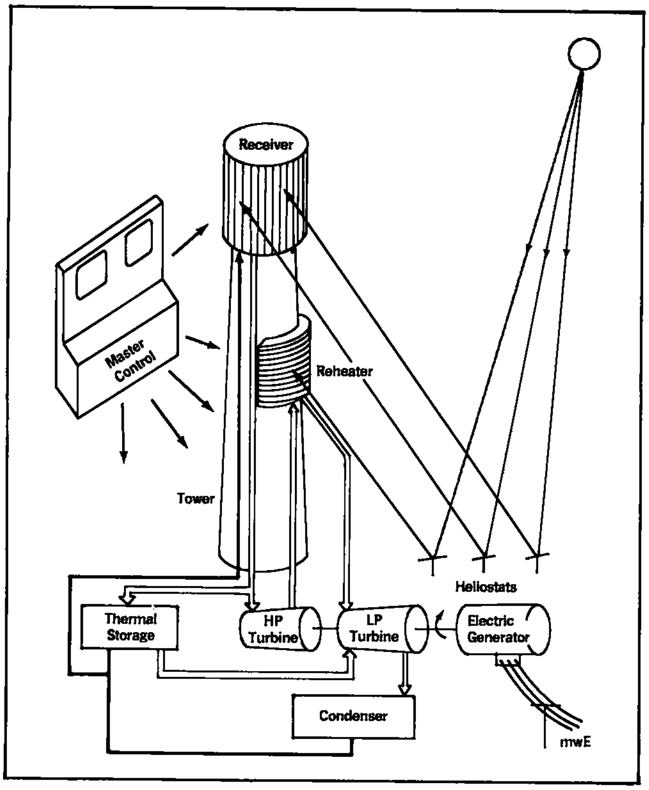


Fig. 6 Solar plant schematic

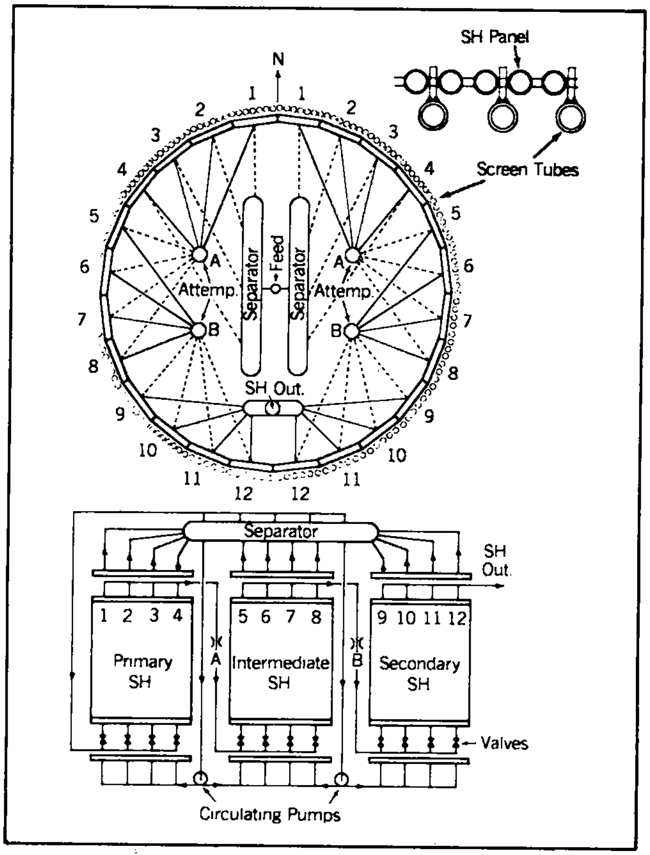


Fig. 7 Solar steam generator with 2 drum and 3 superheater passes

Table I

B&W solar steam generator design features

Proven utility boiler technology

Pump assisted circulation

- Spare pump
- High turndown ratio
- Fast start-up
- Positive flow — unaffected by clouds

Membrane wall panels

Screen tubes to shield the panels

- Utility boiler flux levels on screen tubes
- Low heat flux on superheater tubes

Ribbed tubes — DNB prevention

Two separate (East & West) flow paths

- Maximal solar utilization

Over-surfaced superheater

- Compensation for diurnal and seasonal power
- Continued operation with cloud shadows
- Compensation for variation of feedwater temperature

Spray attemperation — temperature control

Conventional commercial components

Standard ASME code practice

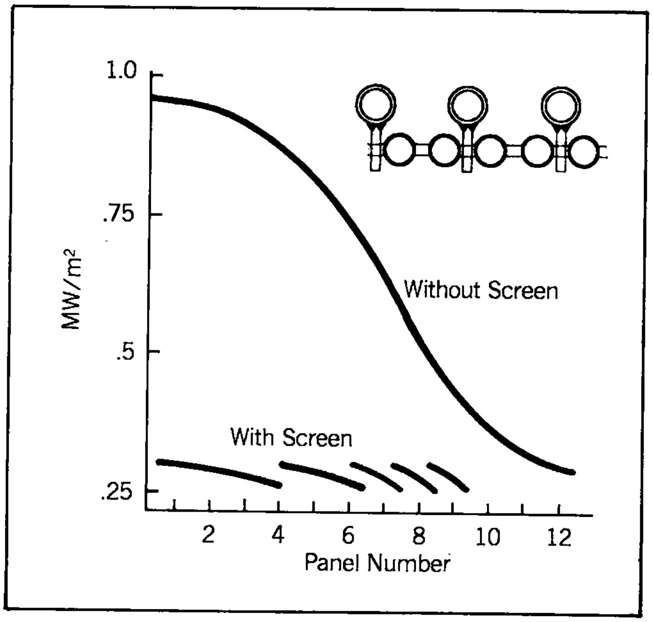


Fig. 8 Panel peak heat flux distribution

radiation losses and thus a higher receiver efficiency and also be less affected by partial cloud cover, a four-cavity receiver was designed as shown in Figure 9. In Figure 10 a comparison is shown of the two types of 100 MWe receivers mounted on their towers. Radiation loss and receiver efficiency benefits were disappointing for a receiver of this size because of the large apertures required to admit adequate insolation. The size and weight of the cavity receiver almost doubled and the cost increased. While the cavity receiver indicated marginal efficiency benefits, the external receiver was selected for the project because of its relative simplicity, smaller size, and lower weight and cost. The cavity receiver has real and potential benefits, however, and may prove to be the better choice for a specific application especially for smaller sizes.

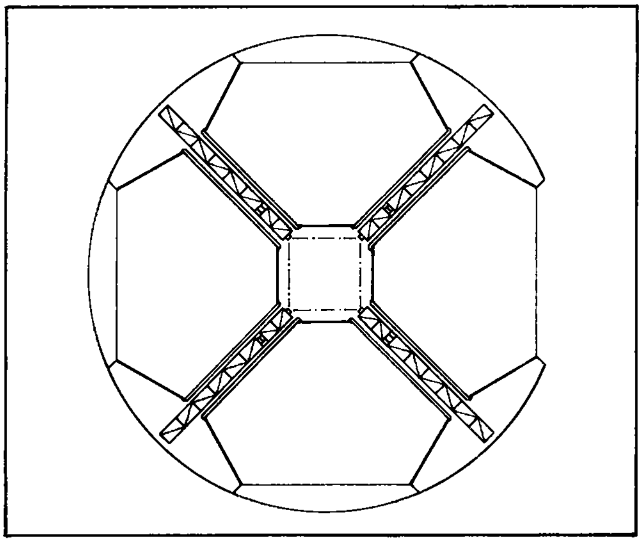


Fig. 9 Four cavities receiver

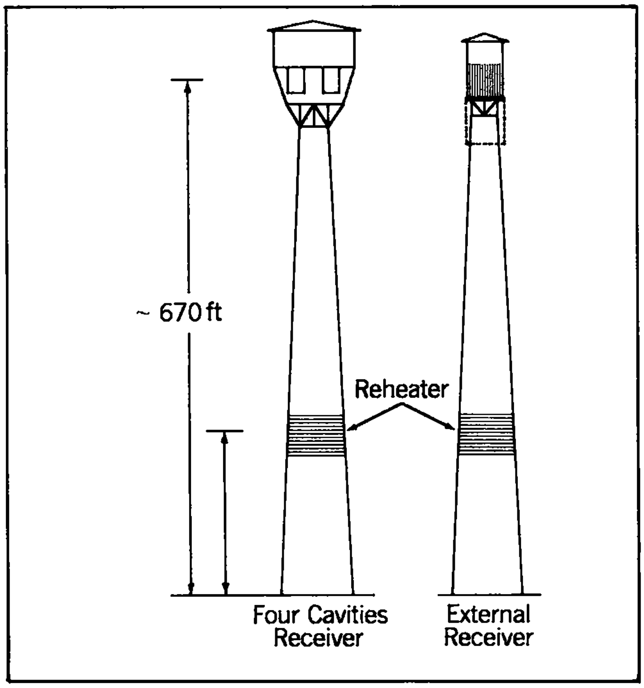


Fig. 10 Receiver comparison

Solar reheater: Applying a solar reheater to a cycle has the added difficulty of the extended cold and hot reheater piping with the potential for increased pressure drop.

The primary efficiency benefit of any reheat cycle is to resuperheat steam temperature at an intermediate point in the turbine, thereby permitting further expansion through the turbine before encountering excessive moisture that results in turbine blade erosion. The limiting factors are the cost of the reheater, piping system, and multiple turbines, and the reheater system pressure drop. The economic consideration for reheater application is whether the value of increased turbine efficiency offsets the increased cost of the reheater plus piping losses. Or is it more economical to resuperheat low pressure steam at some stage of the turbine or to boil and superheat additional steam at throttle pressure for a nonreheat turbine.

Added considerations for evaluating a reheater for a solar heated cycle are the size, type, and temperature of the thermal storage system, and the location of the turbine admission point from storage. Rather than the 300C (570F) steam temperature for turbine admission from storage (considered to date for most steam/water solar cycles), there are several advantages if the steam from storage is admitted at the reheater outlet or IP turbine inlet. This process will require a high temperature, dual-stage storage system. Since it is likely that most solar power plants will have limited condenser cooling water available, the reduction in steam flow to the condenser of a reheat cycle will result in a lower cost for the condenser and circulating water system.

In the application of a solar reheater, the length and size of the piping and reheater, and the resulting pressure drop are vital considerations. These considerations dictate that the location of the solar reheater be low on the tower, or at approximately 50% of the receiver tower height. For several reasons, a north facing only reheater was considered, as conceptually shown in Figure 11. While most of the reheater heliostats are located closest to the tower, a number are discreetly located within the field for normal operation. Others are available for optional focusing on either the HP receiver or the reheater to assist in the control of reheater temperature during seasonal and diurnal cycles, as well as during partial cloud transients.

Based on the potential gain in cycle efficiency and comparable reduction of heliostat cost, as well as the potential benefit to future solar repowering projects, B&W has completed the project using a solar reheater even though the estimated economic benefits are marginal. There is potential for further optimization and improvement, especially in the application and use of a two-stage energy storage system having sufficiently higher discharge temperature 482C (900F) to permit admission at the reheat turbine inlet rather than at a stage equivalent to that for a nonreheat, dual admission turbine.

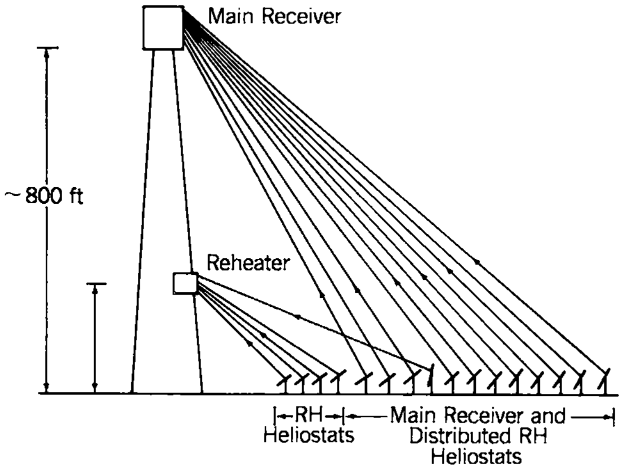


Fig. 11 Sketch of tower-heliostat layout

Hybrid power system with sodium-cooled solar central receiver

As a subcontractor to Rockwell International Corporation, Babcock & Wilcox has recently completed a project involving a hybrid power system with a sodium-cooled solar central receiver and a pulverized coal fired, sodium-cooled heater—both to be operated in parallel to power a turbine generator. The fossil-fired heater was designed by B&W.

A conceptual design of this stand-alone, integrated system is shown in Figure 12. A schematic process diagram is shown in Figure 13.

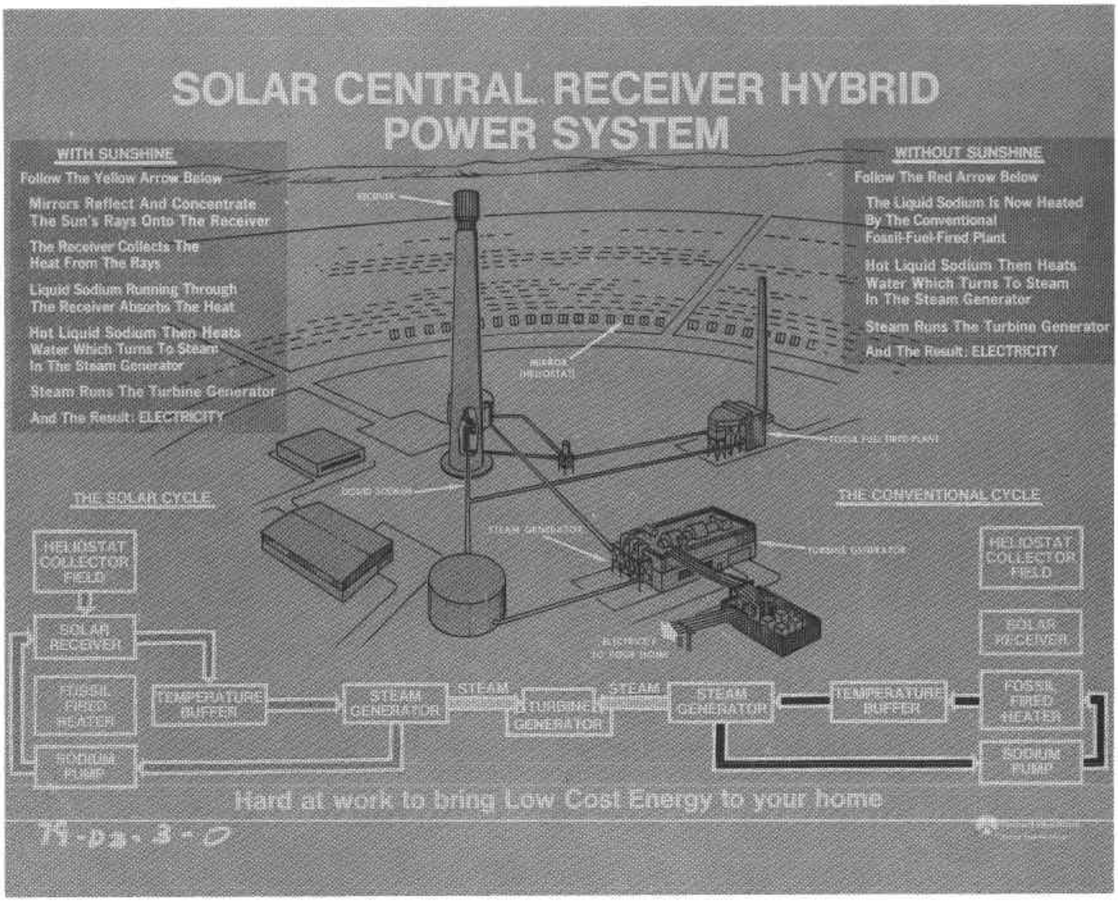
The system requires three sodium heated steam generator components: a steam evaporator, superheater, and reheater. All are heated by sodium from either the solar receiver, whenever insolation is available, or from the pulverized coal fired heater as necessary to meet system load requirements.

With a hybrid system, the need for thermal storage is limited to that required to accept rapid cloud transients. When the receiver is cooled by sodium or fused salts, these circulating fluids provide an economical thermal storage system for either a hybrid or stand-alone unit. Also, the receiver itself is less affected by transient clouds. The resulting effect on the circulating system and steam generators is minimal because of the thermal buffer or storage system. While the use of sodium, for example, is strange to the power industry, the technology and experience has been developing over many years in a number of liquid metal cooled breeder reactor programs throughout the world.

Conclusions and future trends

Babcock & Wilcox believes, therefore, the development of solar power will proceed in three stages:

1. The earliest practical demonstration of solar power in a utility application will be the 10 MWe Barstow Plant applying a water/steam receiver and thermocline thermal storage system. This is a stand-alone system that will give an early demonstration of a solar power system and provide experience with the operation of heliostats, the receiver thermal storage system, and associated turbine generator. The schedule for completion is late 1981.
2. The next logical step is to repower existing oil- and/or gas-fired fossil boilers serving those turbine generators with an expected extended service life and an economic cycle, and where the availability of fuel is to be restricted by government direction or cost considerations. The Department of Energy has underway at least six study projects for repowering utility boilers, with six teams involving electric utilities, consulting engineers, and system and component suppliers. One team is made up of Public Service Co. of Oklahoma, Black and Veatch, and Babcock & Wilcox. A similar program is underway for repowering of industrial and process industries. By July of next year at least one project will be selected for a phase II contract. If the emphasis is to be on early demonstration, then we believe a steam/water receiver with or without a solar reheater is the best choice.
3. If solar power from stand-alone or hybrid utility-size units is ever to become economical and widely applied, the receivers most likely will be cooled by either liquid metal or fused salts. The application of such systems will result in smaller and lighter receivers that can accept higher rates of insolation, are less affected by



SOLAR CENTRAL RECEIVER HYBRID POWER SYSTEM

WITH SUNSHINE

Follow The Yellow Arrow Below

Mirrors Reflect And Concentrate The Sun's Rays Onto The Receiver

The Receiver Collects The Heat From The Rays

Liquid Sodium Running Through The Receiver Absorbs The Heat

Hot Liquid Sodium Then Heats Water Which Turns To Steam In The Steam Generator

Steam Runs The Turbine Generator

And The Result: ELECTRICITY

WITHOUT SUNSHINE

Follow The Red Arrow Below

The Liquid Sodium Is Now Heated By The Conventional Fossil-Fuel-Fired Plant

Hot Liquid Sodium Then Heats Water Which Turns To Steam In The Steam Generator

Steam Runs The Turbine Generator

And The Result: ELECTRICITY

Hard at work to bring Low Cost Energy to your home

79-D3-3-0

Fig. 12 Solar central receiver hybrid power system

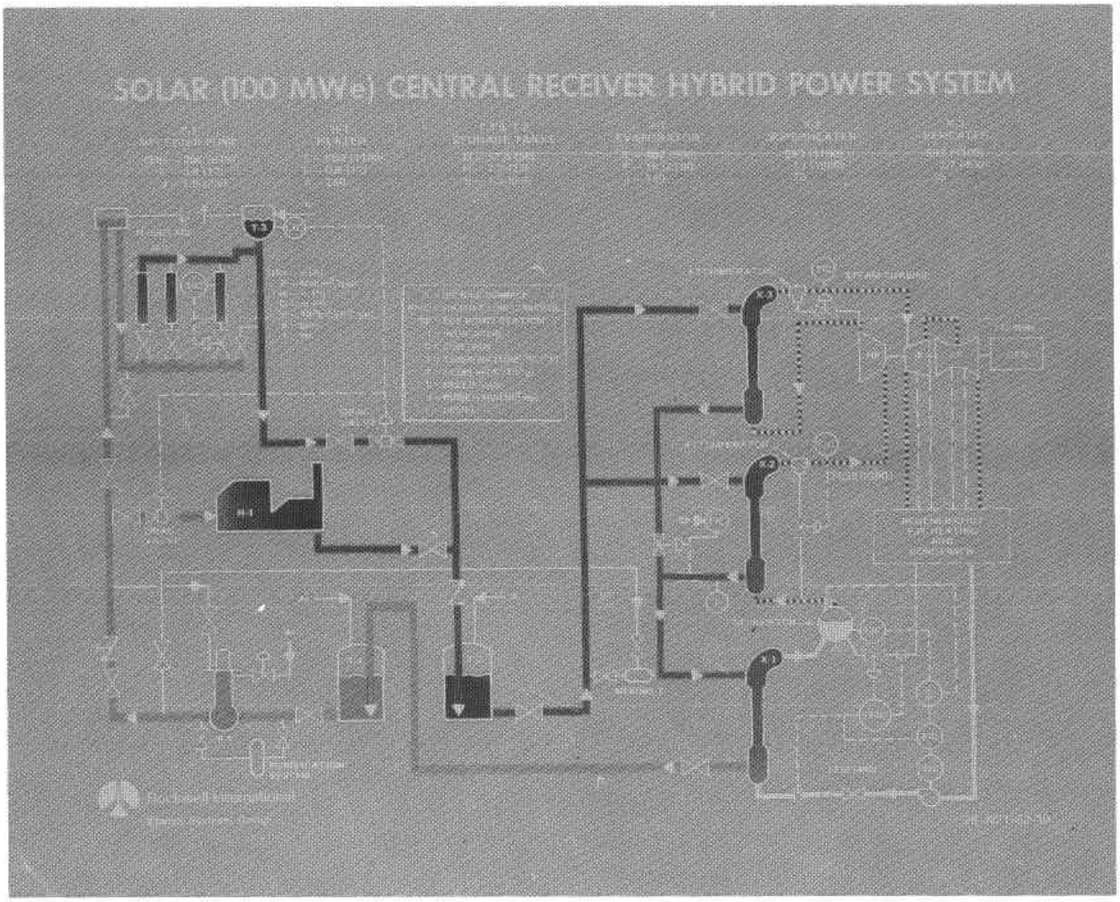


Fig. 13 Schematic of solar (100 MWe) central receiver hybrid power system

transient cloud cover, and allow the application of thermal storage without the serious degradation of cycle efficiency and turbine output for steam/water systems.

Before any solar system can be commercially accepted as an economical addition to utility power systems, the cost of the components and system must be reduced sharply. The primary objective of the Department of Energy R&D and demonstration programs is to reduce the cost of the heliostats, receivers, and thermal storage systems to meet the necessary economic targets.

As the development and application of high temperature thermal storage systems proceeds, the utility industry should consider their use for fossil or nuclear applications. The daily load swing and the significant fuel cost differential between peak and base load power will provide the economic incentive for a periodic evaluation of high efficiency, thermal energy storage systems.

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