# Development of a Concentrated Solar Power Generation System with a Hot-Air Turbine

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*As part of the overall utilization of solar thermal energy, the application of concentrated solar power generation systems is highly anticipated in the Sunbelt. Mitsubishi Heavy Industries, Ltd. (MHI) is the world's leading developer of high-temperature air-turbine power generation systems, which concentrate insolation with heliostats to raise the air temperature to 850°C with a solar receiver, and generate electric power via an air turbine. The system offers advantages such as high conversion efficiency, and no need of water for power generation. This report describes the results of the pilot test of the solar receiver, which is one of the key components of the system, as well as some other items that govern system performance, including the design of the high-temperature turbine and solar field.*

## 1. Introduction

The need for alternative energy sources and environmental concerns are growing due to various reasons. In this regard, the utilization of solar energy has become increasingly important.

Photovoltaics systems convert insolation directly to electricity, although the effective wavelength is restricted. They have been widely installed even in Japan, where direct insolation is not abundant because diffusion light can also be utilized and can generate power at a reasonable cost.

On the other hand, as concentrated solar power systems have high conversion efficiency and do not lose efficiency due to temperature increase unlike photovoltaics, the market for such systems that can utilize only direct insolation is expected to expand in the so-called Sunbelt region.

It is generally believed that existing commercialized technology, based on a parabolic trough with a line focus collector and low light concentration, is difficult to improve in terms of efficiency/cost. Hence, attention is currently being focused on tower systems, in which the light concentration and efficiency can be increased by the use of a point focus collector, thereby reducing construction costs. This report describes the development of a tower concentrated solar power generation system based on the Brayton cycle. It does not require water cooling for power generation, which is very attractive for regions where water resources are quite limited.

## 2. Market and technical trends for concentrated solar power generation

In regions where sunny weather is not abundant and the insolation intensity is relatively low, photovoltaics systems, which can generate power from diffusion light, are more appropriate than concentrated solar power generation, which requires direct insolation. However, in regions where the weather is stable and the insolation intensity is high, concentrated solar power generation offers

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higher efficiency and capacity factor. **Figure 1** shows a map of the regions where concentrated solar power generation is suitable. In particular, the Sunbelt, where direct insolation is abundant and the climate is dry, is appropriate for this type of power generation. The Sunbelt includes various areas such as the U.S., Southern Europe, Australia, Africa, the Middle East and India.

As **Figure 2** indicates, the market size is forecast to be 25 to 45 GW of world installed capacity in 2020. The annual construction capacity is expected to be 2 to 5 GW. In addition to the installation plans of individual countries, huge global cooperative projects are in progress. One of these is called DESERTEC[1], in which the electricity generated in North Africa will be supplied to Europe through a submarine cable, and will cover approximately 15% of European consumption. The market size is expected to expand beyond the above forecast if the project is fully realized.

A comparison of concentrated solar power generation systems is presented in **Figure 3**. The current mainstream generation system utilizes a steam turbine rotated by the thermal energy converted from collected sunlight. In particular, the trough type (Figure 3 (1)) has a standardized receiver, and is widely used. The collected heat temperature is on the order of 400°C. A tower type (Figure 3 (2)) has recently been introduced as a means of increasing the collected heat temperature for improved plant efficiency.[3] A steam turbine (Rankine cycle) is used in both types of systems.

A hot-air turbine system (Figure 3 (3) tower type, Brayton cycle), which will lead to further efficiency enhancements by operating at higher temperatures than those of steam turbine systems, is currently under development. This system enables power generation without water cooling, and is attracting attention because of its applicability to dry areas suitable for concentrated solar power generation.

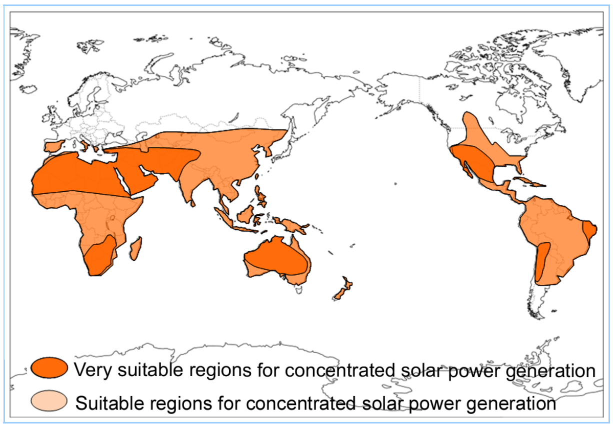


**Figure 1 Distribution of global solar radiation intensity**

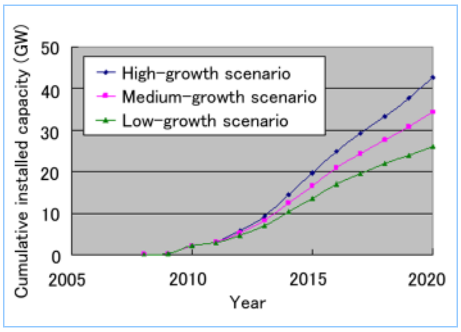


**Figure 2 Market size forecast of concentrated solar power generation**[2]

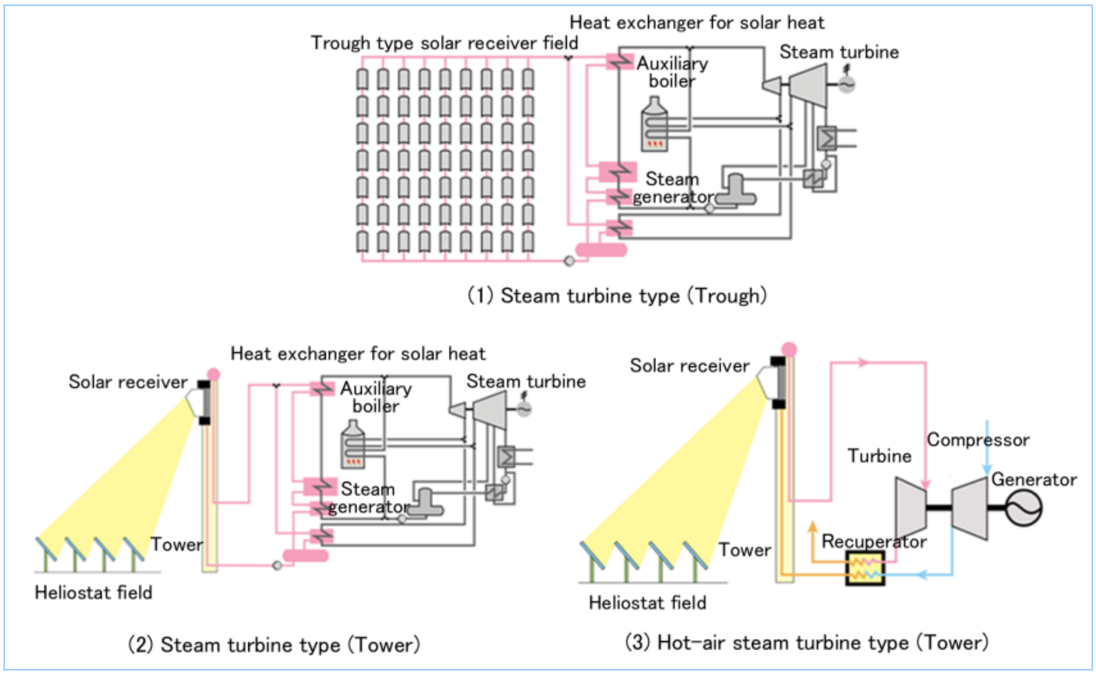


**Figure 3 Comparison of concentrated solar power generation systems**

# 3. Development of the new concentrated solar power generation system

## 3.1 Features of the system

We are developing an unprecedented hot-air turbine solar power generation system (Figure 3 (3)) utilizing our accumulated expertise and experiences in gas turbine, boiler, heat exchanger and other technologies. Air extracted from the atmosphere is compressed and heated in the solar receiver. The hot air drives the turbine to generate electric power. The heat of the exhaust air is transferred to the receiver inlet air via a recuperator, and the exhaust air is discharged into the atmosphere to form an open-cycle system. As high-temperature design is relatively easy even under low-pressure conditions in the case of an air based cycle, higher plant efficiency is attainable with the new system compared to a conventional steam turbine system. Also, auxiliary equipment such as a condenser and water supply pump is not required, and the simple structure facilitates maintenance. The system offers the advantages of easy handling and waterless operation, and thus is suitable for dry areas where abundant solar energy can be utilized.

## 3.2 Solar receiver

The solar receiver, which is one of the key components of a hot-air turbine power generating system, is a heat exchanger that draws thermal energy from the solar energy collected by an array of heliostats. The solar energy enters the receiver through an aperture of the casing and reaches the tubes inside the receiver. This energy heats the air passing through the tubes[4], and hot air at 850$^{o}$C is efficiently generated to drive the turbine. Since the metal temperature of the receiver exceeds 900$^{o}$C, heat-resistant nickel alloy is used. The design is suited for high-temperature operation, taking into account thermal fatigue, creep strength, and other factors, and the length, diameter, thickness, and pitch of the tubes are optimized. Since the operating temperature is high, and radiation loss significantly affects the performance, a cavity type receiver is adopted, with only a single aperture to admit the solar energy. This design permits the thermal radiation generated in the high-temperature casing to be effectively used to raise the temperature of the operating air, and radiation loss from the aperture is minimized. The aperture is located at the focal point of the heliostat-reflected light, and the size of the opening is minimal.

To validate the design, the three-dimensional heat radiation and heat transfer of the flow in a pipe were simultaneously analyzed using general-purpose thermal-fluid analysis software. The boundary conditions were the air inflow rate and temperature. The intensity distribution of the solar heat inlet, which was separately calculated, was applied to the heat-receiving surface. **Figure 4** shows the air temperature distribution as an example of the analysis results. The low-temperature airflow at the heat receiver inlet is heated by solar energy as it passes through the tubes, reaches a high temperature of 850$^{o}$C at the outlet of the receiver, and then flows into the turbine.

To verify the receiver performance predicted by the above analysis, a prototype of a 200 kWe-class receiver was built, and a verification test was conducted in May 2011 in collaboration with the Commonwealth Scientific and Industrial Research Organization (CSIRO[5]) in Australia (**Figure 5**). The results show that the receiver outlet temperature was raised to the target 850$^{o}$C by solar heat alone, and conform well to the radiation analysis predictions. The same considerations and analysis procedures will be applicable to future designs.

## 3.3 Hot-air turbine

We are currently developing a hot-air turbine applicable to the system. The heat source is the solar energy collected by the heliostats. Improved efficiency of the hot-air turbine system is important, since reducing the required number of heliostats will reduce the overall cost of the system. Although the system is operated at a relatively low temperature compared to the gas turbines on which it is based, the technology used in our most advanced high-efficiency J-class gas turbines is being applied to each element, with the aim of designing a high-circumferential-velocity compressor and turbine, capable of attaining high efficiency even at the 850$^{o}$C air temperature at the receiver outlet.

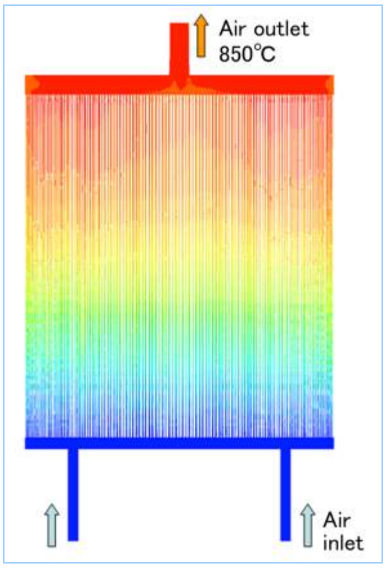


**Figure 4 Results of three-dimensional heat radiation analysis (air temperature distribution)**

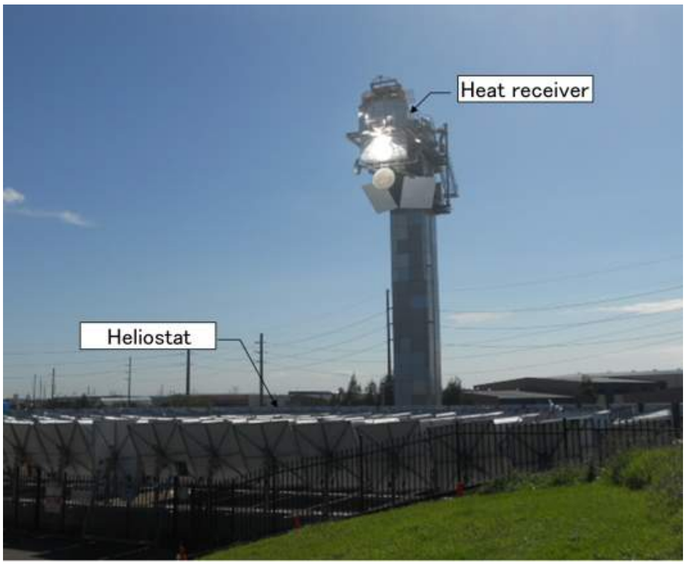


**Figure 5 Verification test of the heat receiver at CSIRO**

## 3.4 Solar field

(1) Heliostats

A heliostat is a device that reflects light to the receiver by coordinating mirror movements with solar diurnal movements, using two control axes. The devices are used exclusively in large-scale solar power plants. Various mirror sizes and drive systems are being developed by a number of manufacturers. The settings of the two axes vary, but the most commonly used configurations are the altazimuth mount which consists of a vertical pivot and a tilt axis rotating around the pivot, and the equatorial mount which consists of a polar axis and an orthogonal declination axis (**Figure 6**). Various mirror sizes are currently available, the smallest of which is 1 $m^2$, while the largest exceeds 100 $m^2$. The number of heliostats used in a typical system is enormous, and the cost impact is significant. Hence, the development of a low-cost, high-accuracy heliostat is a necessity.

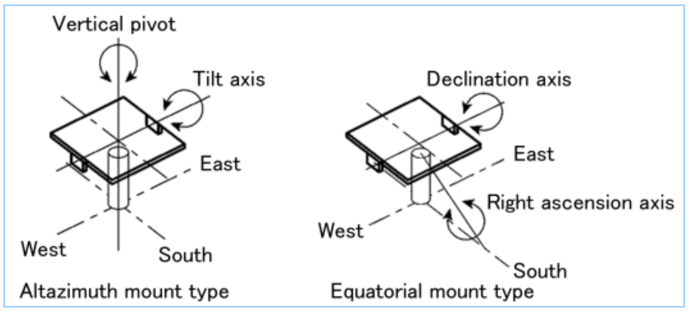


**Figure 6 Examples of heliostat construction**

(2) Optical path calculation

Optical path calculation is a tool to analyze the passage of light reflected by the heliostat, and it is used to study design factors such as the target angle and the heat input to the receiver. Optical path calculation is therefore necessary for plant design, including heliostat arrangement and tower height. Many manufacturers and research institutes develop unique light path calculation software exclusively for solar power plants.

**Figure 7** shows the efficiency of each of the heliostats arranged around a tower at the culmination of the spring equinox. The efficiency includes the effects of cosine loss (effective area reduction due to the slanted incidence angle) and blocking and shadowing loss by adjacent heliostats. The heliostat arrangement is very important, since it affects the output power differently even in cases where the same number of heliostats is used. **Figure 8** shows a plant image of the heliostat arrangement.

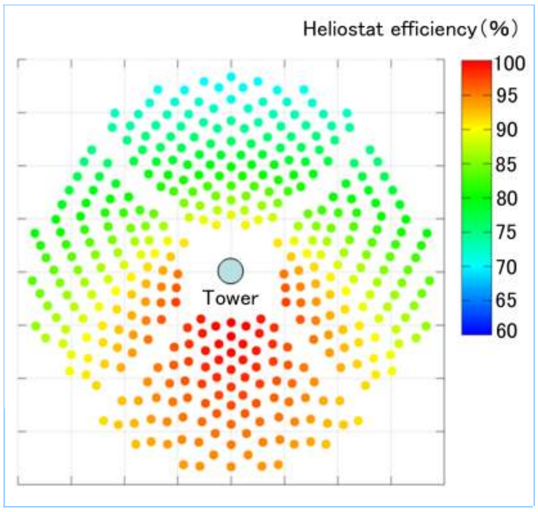


**Figure 7 Example of a heliostat efficiency evaluation**

**Figure 8 Plant image showing heliostat arrangement**

The light reflected by the heliostats is supposed to be focused at the receiver aperture. However, the focused light cannot be reduced to a dimensionless point, but must occupy some space, due to the apparent size of the sun and the reflection inaccuracy. For this reason, the receiver aperture must be of an appropriate size. However, the larger the opening, the larger will be the loss due to radiation and convection of the high-temperature air inside the receiver. Conversely, the smaller the opening, the greater will be the loss due to spillage. The shape and size are determined in accordance with the optimum angle and size, based on the above considerations. The incoming heat intensity distribution is calculated at the heat-receiving surface in the receiver, based on the optical path calculation. The thermal analysis of the receiver is then conducted.

## 4. Conclusion

To largely commercialize a renewable energy system, it is necessary to generate electricity with low operating, construction and maintenance costs. The concentrated solar power generating system introduced in this report has a very simple configuration with a hot-air turbine, is well matched with market demand and practical implementation is already anticipated in many countries.

A power generation test of a 200 kWe-class system will be conducted in collaboration with Australia/CSIRO, and after the demonstration project has been completed, commercialization is planned. We hope to contribute a new solution for global environmental and energy issues with our concentrated solar power system.

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