First CSP hybrid system test facility in Awaji, Japan

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Abstract
This paper presents the results of the operation and performance evaluation obtained from the first stage of the experiments that have been performed with the hybrid power test plant built in Awaji Island, which consists of a Concentrated Solar Power (CSP) system, biomass boilers and wind turbine. This pilot plant is the first CSP based power station in Japan and followed the requirements of Japanese Electric Utility Industrial Law. The results clearly showed that the changes in thermal performance of the pilot plant are strongly depending on solar intensity and climatic conditions specific for the site location. In addition, adjusting the amount of the biomass fuel supplied to the boilers is found effective to stabilize power output.

Key words: Renewable energy, Solar power, CSP, Biomass boiler, Hybrid system

1. Introduction

As an alternative to fossil fuels, usage of renewable energy sources is receiving increasing attention worldwide. Among other renewable energy technologies, solar based technology is a promising candidate to replace fossil fuels. However, fluctuation in power output is the main limitation of solar technologies.

In order to promote the introduction of renewable energy in Japan and to verify a new concept of hybrid power plant integrating three types of renewable energy, Toshiba Corporation together with Kobe Steel Corporation developed a demonstration project. This project was partially subsidized by Ministry of the Environment of Japan. The plant was developed and constructed in Hyogo Prefecture’s Awaji Island (Lat.: 34°12’ N). The demonstration tests and system verification were started in year 2014.

The main objective of this study was performance assessment of the solar hybrid pilot plant operated under local weather conditions. The results presented in this paper are focused on the evaluation of the CSP and biomass boilers. Wind power based experiments will be reported in a future presentation.

2. Hybrid plant configuration

The Awaji hybrid test plant is composed of three independent renewable energy technologies: the CSP system, a 1.5 MW wind turbine and two biomass boilers with a 70kW binary generation unit as shown in Fig.1. The CSP facility is based on parabolic troughs, which is one of the most widely installed CSP technologies. North-south oriented parabolic collectors with a single axis sun tracking system concentrate sun radiation onto heat collecting elements (HCE) to transfer the thermal energy to a working fluid, which circulates inside the HCE. Synthetic oil with an operating temperature range of 200~300°C is used as a heat transfer fluid (HTF). The Solar field (SF) has one loop and consists of two types of collectors – Large trough and Micro (small) trough as shown in Fig.2. It has a total aperture area of about 1300 m² and a gross length of the loop about 140 m. Heat generated by the SF is enough to produce saturated steam (150~170°C) which is used to drive a binary turbine for electricity generation. The set of two biomass...
combustion boilers has a total capacity similar to the SF with identical amount of steam generated. Both systems can operate independently or in a combined mode, due to their having the same feed-water source and similar steam characteristics. In addition to thermal energy generated by the SF or biomass boilers, the hybrid system is able to absorb rapid fluctuations (short-term variations) removed from the output of the existing 1.5MW wind turbine.

Fig.1  Simplified schematic of the hybrid pilot plant
Fig.2  Layout of the solar field (SF)

3. Methodology

Technical performance of the CSP plant is evaluated through an energy analysis, using total thermal output \( Q_{\text{out}} \) (kW) and collector efficiency \( \eta_{\text{th}} \) as evaluation criteria. Total thermal output \( Q_{\text{out}} \) is defined as a difference between solar energy \( Q_{\text{abs}} \) (kW) delivered to the SF and heat losses \( Q_{\text{loss}} \) (kW) of the heat collection elements (HCE). The hourly performance of the SF is evaluated based on the typical parameters, such as HCE inlet \( (T_{\text{in}}, ^\circ \text{C}) \) and outlet \( (T_{\text{out}}, ^\circ \text{C}) \) temperature, constant flow rate \( (\dot{G}, \text{t/h}) \), direct normal irradiation \( (\text{DNI}, \text{W/m}^2) \), average \( \text{DNI}' \) (the average measured value over the travel time of the HTF between inlet/outlet), SF aperture area \( (A, \text{m}^2) \), incident angle \( (\theta, \text{deg}) \), incident angle modifier \( (M) \), measured reflectivity \( (R) \), collector’s end loss \( (E) \), effective collector efficiency \( (\eta_{\text{abs}}) \) and optical efficiency \( (\eta_{\text{opt}}) \) (Forristall, 2003). HTF fluid flowing time between receiver’s inlet and outlet was also taken into account. HCE inlet temperature \( T_{\text{in}} \) is controlled by electrical heater. The value for \( Q_{\text{loss}} \) was obtained experimentally, through a series of night tests. In order to evaluate relationship between the incident angle \( \theta \), and the incident angle modifier \( M \), an evaluation criteria \( M' \) represented by the equation (6) has been introduced. Performance evaluation has been made according to the following equations:

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\begin{align*}
Q_{\text{out}} &= Q_{\text{abs}} - Q_{\text{loss}} \quad (1) \\
Q_{\text{out}} &= \dot{G} \times \bar{C}_p \times (T_{\text{out}} - T_{\text{in}}) \quad (2) \\
\eta_{\text{th}} &= Q_{\text{out}} / (\text{DNI}' \times A) \quad (3) \\
\eta_{\text{abs}} &= Q_{\text{abs}} / (\text{DNI}' \times A) \quad (4) \\
Q_{\text{abs}} &= \text{DNI}' \times A \times \cos \theta \times \eta_{\text{opt}} \times E \times M \quad (5) \\
M' &= (\eta_{\text{opt}}/R) \times M = \eta_{\text{abs}} / (\cos \theta \times E)/R \quad (6)
\end{align*}
\]

4. Results
4.1 Heat collection experiment

This section presents the results obtained from actual experimental data received during operation of the pilot plant. Weather data specific for the site such as, ambient temperature, barometric pressure, wind speed, wind direction, humidity and DNI, were collected using a weather station and a pyrheliometer. Reflectivity of the mirrors was analyzed using a reflectometer. A typical example of the large trough’s actual operation data during autumn and spring is presented below. Figure 3 and 4 show the influence of \( \text{DNI}, \cos \theta \) and \( E \) on the plant performance during sunlight hours. In Fig.4, the \( \text{DNI} \) data shows rapid fluctuations around mid-morning due to small clouds, which are common for
the site location. In comparison, the thermal output $Q_{\text{out}}$ shows much less fluctuation, which is attributed to the natural smoothing of the heat collection due to the long travel time of the HTF trough the SF loop. Figure 5 shows that the incident angle modifier is influenced by the incident angle and reflectivity of the mirrors at the time on each test. Lower reflectivity cases show a much greater decrease in incident angle modifier with increasing incident angle.

Fig.3  The example of large trough’s daily performance in May

Fig.4  The example of large trough’s daily performance in October

Fig.5  The relationship between incident angle and incident angle modifier for large trough
4.2 CSP combined with biomass boilers

The performance analysis of the hybrid system including the CSP system and two biomass boilers was conducted under changeable local conditions. Bamboo chips widely available in Awaji Island, wood chips and pellets produced from waste wood were used as a fuel for the biomass boilers. Observed daily performance is presented in Fig.6. From the experimental results, it can be seen that continuously adjusting the amount of biomass fuel supplied to the boiler can minimize the influence of fluctuating DNI on the power output, providing balanced supply of the generated steam, and as result stabilized energy production. It was also confirmed that during day time operation with constant and high DNI, total steam generation rate from the hybrid system is increased. As result, the steam from the CSP facilities can substitute the steam produced from biomass boilers with significant reduction of biofuel supply.

The operation in the hybrid mode has several benefits, such as a stable power output, and reduced quantity of fuel consumed by the biomass boilers.

Fig.6  The performance characteristics of the system

5. Conclusion

The hybrid pilot plant was operated under specific local weather conditions. Plant performance was assessed based on actual detailed experimental and hourly weather data. During operation of the plant, changes in local conditions and its influence on power output were observed.

The results indicate that the operation of the CSP plant combined with the biomass boilers produced more stable energy supply than in CSP only operation mode without requiring heat storage. This hybrid operation has a better performance, due to the stable electricity generation and the low impact of the DNI fluctuation. The results obtained from the Awaji project indicate that the integration of biomass boilers into a CSP system is an effective option in terms of stable energy supply. However, such integration is a subject to availability of the biomass resources. For this reason, CSP technology combined with biomass boilers can be more effective in regions where biomass resources are widely available in form of forest biomass or woody wastes.

References

Acknowledgement
This work is supported by Ministry of the Environment of Japan for Research and Development against Global Climate Change.