PERFORMANCE ANALYSIS OF PV SYSTEMS ON THE WATER

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ABSTRACT: Floating PV systems are developed and installed on the water surface of the “Aichi ike” balancing reservoir in Aichi, Japan. Floating systems are fixed by anchors and DC cables are connected to the inverter which is mounted on the ground. Systems are grid connected and those outputs are monitored every minute. PV module cooling system with intermittent watering is installed in one of the floating systems and performance is compared with the other systems. As a result, loss ratio due to the module temperature rise is reduced from 17.0 [%] to 7.4 [%] in August 2007. The cooling effect becomes smaller in winter but still has approximately 3 [%] improvements. This paper describes the overview and analysis result of the PV systems on the water.
Keywords: System Performance, PV System, Floating System, Water Cooling

1 INTRODUCTION

The surface of the water is one of the potential areas for the PV system deployment. There are a lot of unused water surfaces such as of the hydroelectric dams, balancing reservoirs, water purification plants, lakes and ponds. To install the PV systems on the water, floating system is one of the key technologies to realize the robust and cost competitive PV system. A float needs to have enough buoyant force in order to maintain the PV modules on the water even with snow or typhoon. Long term corrosion resistance is also required for both float and frame. Suppression of the weed and prevention of the nest of the waterfowl need to be considered in design.

In terms of the PV system performance, module temperature is one of the biggest factors which affect the performance of the crystalline silicon PV modules. Water cooling of the PV module can be used for the floating PV system because of the availability of the cooling water around the systems.

This paper describes the overview of the floating PV system and summarizes the effect of the water cooling.

2 SYSTEM CONFIGURATION

2.1 Floating PV systems

Floating PV systems are developed and installed on the water surface of the “Aichi ike” balancing reservoir in Aichi, Japan. Figure 1 shows the photos of the developed floating PV systems. Approximately 2 [m^2] of foamed polystyrene board is covered and connected each other by plastic sheet and used as a float. The size of the float is around 15 [m] by 9 [m]. Steel pipes are connected around the periphery of the float. Module supports are mounted on the float and PV modules are fixed on the supports. Tilt angle is 1.3 [Deg] and the orientation is due south. Two set of the 10 [kW] floating PV systems are installed on the water, each floating system is fixed to the bottom of the water by anchors. DC cables are connected to the inverter which is mounted on the ground. Systems are grid connected and those outputs are monitored every minute.

PV module cooling system with intermittent watering is installed in one of the floating PV systems. The water of the reservoir is used as the cooling water. The water is pumped and sprayed on the PV module by using sprinkler for one minute per every ten minutes from 7:00 to 17:00. PV module temperature is monitored at the backside of the module by using thermocouple sensor.

Pyranometer is used to measure the irradiation at the PV array’s plane.

2.2 Ground mounted PV system

Another 10[kW] of ground mounted PV system is installed at the lakeside. Figure 2 shows the photo of the ground mounted PV system. Array inclination is 30[Deg] and the orientation is due south. An estimated optimal tilt angle for annual reference yield at this location is 30.9[Deg] with the south orientation. PV module

Figure 1: Photos of the floating PV systems

Figure 2: Photo of the ground mounted PV system

temperature and irradiation are measured in the same way of the floating systems.

Ten minutes average of the wind speed and the wind direcion are also measured near by the ground mounted PV system.

3 EVALUATION METHOD

3.1 Yield and Performance ratio

One-minute data are used for the analysis. Overall system performance is evaluated using system yield and performance ratio (P.R). P.R is calculated by using equation (1).

$$P.R = \frac{E_{PCS}}{P_{ACap}} \cdot \frac{G_S}{H_{Ag}} \quad (1)$$

where E_{PCS} [kWh] is a PCS (inverter) output energy, P_{ACap} [kW] is a system nominal power, G_S [kW/m^2] is the STC sunlight and H_{Ag} [kWh/m^2] is a total global irradiation at the PV array's plane. Sum of the nominal powers on the nameplates of the PV modules are used as the system rated power. Specification of the module is summarized in Table I.

Table I: Specification of the module

Type	mc-silicon
Nominal power (P_{max})	167 [W]
V_{Pmax}	22.98 [V]
I_{Pmax}	7.27 [A]
V_{OC}	29.04 [V]
I_{SC}	8.02 [A]

Module manufacturer tests each module output and attaches the test result to the module. Figure 3 shows the summary of the test results of the installed 180 modules. Although these values will not guarantee the module output, and thus these values are not used for the performance analysis, most of the modules showed higher output than the nominal power.

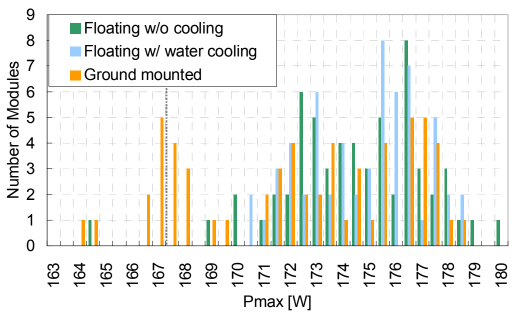

Figure 3: Manufacturer test result of the module output

3.2 Loss analysis

An output power loss due to the module temperature rise is calculated in order to evaluate the effect of the water cooling system. Equations (2) and (3) are used for the calculation of the loss due to the module temperature l_T [kWh].

$$l_T = E_{AT} - E_A \quad (2)$$

$$E_{AT} = \frac{E_A}{1 + (\alpha_{P\max} \cdot (T_{\mathrm{mod}} - 25))} \quad (3)$$

where E_{AT} is a temperature corrected PV array output [kWh], E_A [kWh] is a DC output energy of PV array, α_{Pmax} is a temperature coefficient of the PV module's maximum power [1/degC] and T_{mod} is a measured PV module temperature [degC]. Temperature coefficient of -0.485 [%/degC] is used for the loss calculation.

Other performance losses are also calculated using Sophisticated Verification (SV) method [1, 2]. Figure 4 illustrates the principle of the SV method. P.R (K) can be described as a multiplication of the loss factors (K_X). The output power losses l_X are quantitatively calculated using the K_X. The latest version of the SV method can separate the system performance loss into 12 loss factors which are;

1. Shading ($_S$)
2. System peak power loss ($_{SPL}$)
3. Reflection ($_I$)
4. Module Temperature ($_T$)
5. PCS capacity shortage ($_{PCC}$)
6. Grid voltage ($_{OR}$)
7. Operating point mismatch (high voltage) ($_{MHV}$)
8. Fluctuation ($_F$)
9. DC circuit resistance ($_{DC}$)
10. PCS (Inverter) ($_{PCS}$)
11. PCS Off / PCS Standby ($_{PCO}$)
12. Miscellaneous loss ($_O$).

The SV method calculates the shading loss for each sun's position in an increment of 5 [Deg] for both azimuth and height angle. In order to improve the accuracy of the calculation, clear day's data are required for each sun's position. Thus monthly analyses are conducted in this paper.

System peak power is calculated as the most frequently appeared system peak power during the evaluation period. Each system output data are divided by the corresponding irradiance data and the mode value of the results of the division is used as the system peak power loss factor K_{SPL}.

The system peak power loss l_{SPL} is calculated by using K_{SPL}. l_{SPL} will be in the negative value if K_{SPL} is greater than one. This means the calculated system peak power is higher than the nominal power. Under rating of the module nominal power and soil or degradation of the pyranometer are the typical reasons of the negative system peak power loss.

4 RESULTS AND DISCUSSIONS

4.1 System yield

Data from August 2007 to June 2008 are used for the

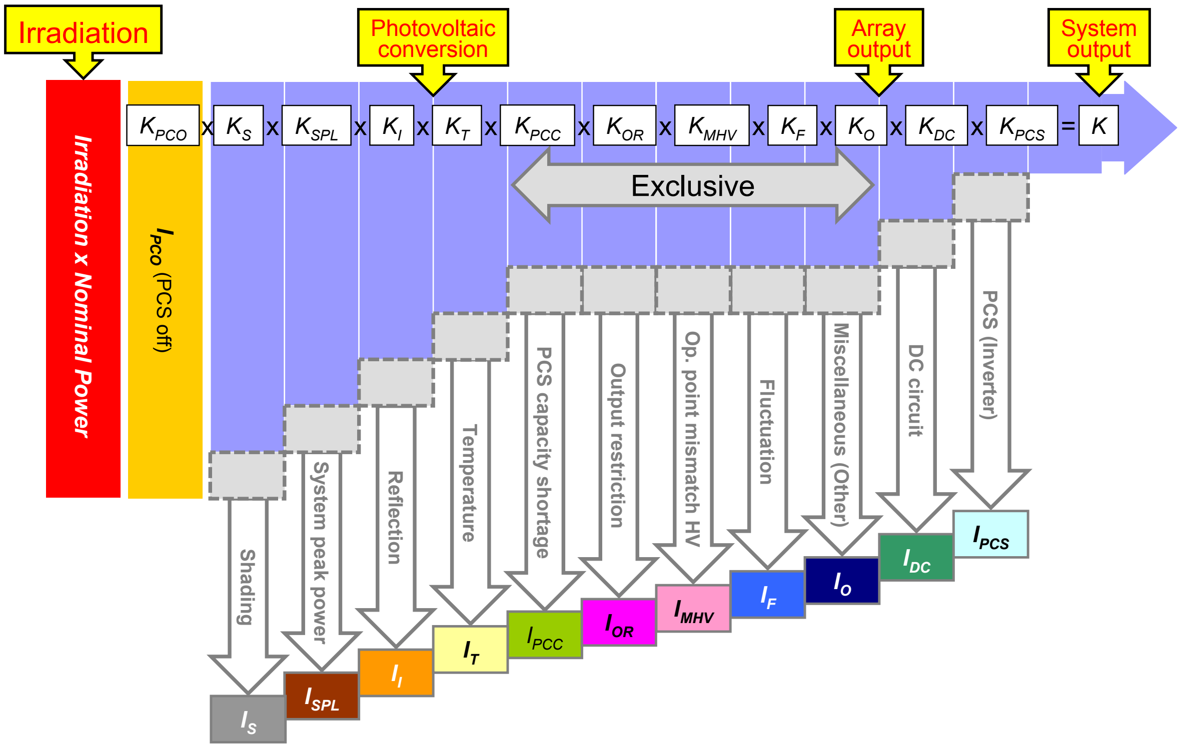

Figure 4: Illustration of the principle of the SV method

analysis. Monthly reference yields and system yields are summarized in Figure 5. Received total irradiation of the floating PV systems is approximately 15 [%] less than that of the ground mounted PV system. This is expected from the difference of the tilt angle. Monthly reference yields from May to August were almost the same in two planes. The differences of the reference yields became larger in winter season, ground mounted system had approximately 50 [%] more reference yield than that of the floating systems had in December 2007.

The maximum system yield was recorded by the floating PV systems with water cooling in August 2007. System yields of the ground mounted system became larger than those of the floating systems along with the increase of the differences of the reference yields. The ground mounted system also had approximately 50 [%] more system yield than those of the floating systems had in December 2007.

The system yields of the floating PV system with water cooling were higher than that of the floating system without cooling through the evaluation period except March and June 2008. System yields were almost the same in these two months.

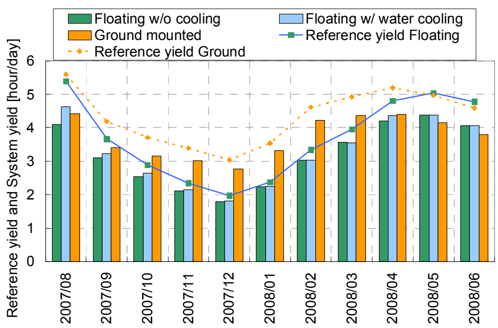

Figure 5: Summary of monthly reference yields and system yields

4.2 Water cooling effect

Figure 6 shows the daily module temperatures, in-plane irradiance and DC outputs of the floating PV systems with and without water cooling on August 20, 2007. Almost no difference between two module temperatures during the night, then the difference became lager along with the increase of the irradiance. Module temperature dropped from 70[degC] to 50[degC] around 11:00 and 13:30. Total generated electric power with water cooling was 61.4 [kWh] whereas the system without water cooling generated 54.6 [kWh]. The maximum temperature drop by the water cooling was about 25 [degC] in August 2007.

4.3 Performance ratio and Loss analysis

Monthly performance ratios of the three systems and those of loss ratios due to the module temperature rise are summarized in Figure 7 and 8 respectively. Loss ratios λ_X are calculated by using equation (4).

$$\lambda_X = \frac{l_X}{P_{ACap}} \cdot \frac{G_S}{H_{Ag}} \qquad (4).$$

Performance ratios of the floating PV system with water cooling are always higher than the other systems except in February 2008. The drop of the P.R in Feb. 2008 was because of the snow coverage. Due to the small inclination of the floating PV systems, snow had remained on the PV module during the following fine day of the snow day whereas the snow on the ground mounted PV modules already melt and drop.

Output energy loss due to the module temperature rise was significantly reduced in the system with water cooling in summer. Loss ratio due to the module temperature rise was reduced from 17.0 [%] to 7.4 [%] in August 2007. The cooling effect became smaller in winter but still had approximately 3 [%] improvements.

Not only the improvement of the system performance, additional losses due to the water cooling system such as the light reflection by the cooling water may exist in the water cooling system. Figure 9 shows the monthly system peak power loss ratios of the three systems. All the systems had negative loss ratio, which means the actual system peak power is higher than the nominal

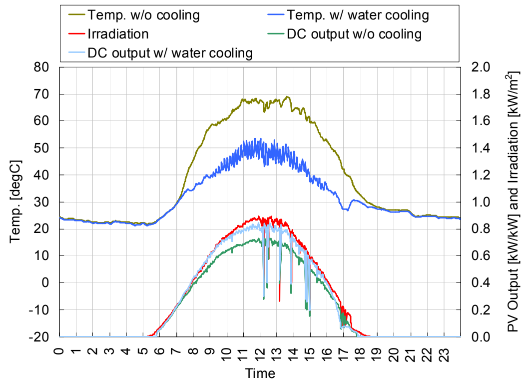

Figure 6: Daily module temperatures, irradiance and DC outputs of the floating PV systems with and without water cooling

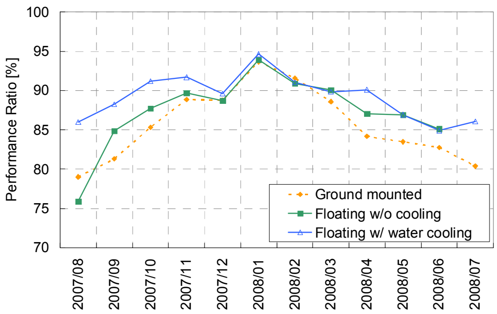

Figure 7: Monthly performance ratios

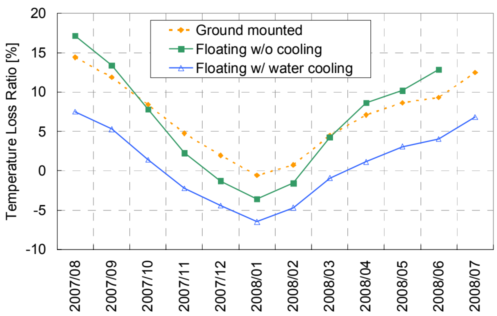

Figure 8: Monthly loss ratios due to the module temperature rise

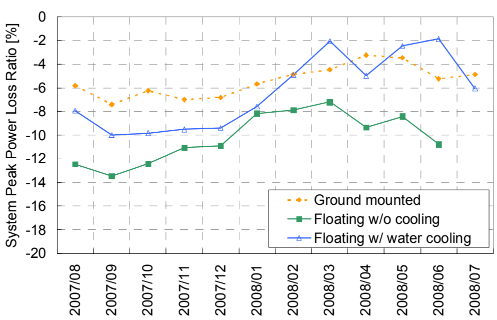

Figure 9: Monthly system peak power loss ratios

power as mentioned in the previous section. l_{SPL} of the floating system with water cooling is a few percent larger (smaller negative value) than that of the non-water-cooled system. Incoming light reflection and water stain are suspected as the cause of the difference. Calculated system peak power of the floating system is larger than that of the ground mounted system. Since the floating systems are continuously moving because of the wave and are changing their tilt angle and orientation, actual receiving irradiation may not be the same as the measured irradiation by the pyranometer. The pyranometer takes 10 to 20 [sec] to follow the fast fluctuation of the irradiance whereas the PV array reacts almost immediately. Further investigation will be continued.

Soil accumulation, water stain and bird dropping are commonly observed issues in the floating systems. The reason of the lowest P.R of the non-water-cooled floating system in Aug. 2007 was the bird droppings. After the cleaning of the PV module and the installation of the bird fence, the system did not have a serious performance loss due to the soil accumulation. The increase of the system peak power loss of water-cooled floating system from March to June 2008 may also be caused by the soil and water stain. After the cleaning in June, system peak power was recovered in July 2008.

Additional electric power consumption by the pump for the water cooling is estimated at approximately 12 [kWh/month]. Although the pump and water cooling system are not optimized yet, water cooling increased the total energy yield during the summer.

5 CONCLUSION

Floating PV systems are developed and their performance including the effect of water cooling is analyzed in this paper. Performance ratio of the systems on the water was better than that of the ground mounted system in average. Effect of the water cooling system was considerable through the evaluation period.

We have installed 60 [kW] water-cooled floating PV system and start monitoring from summer, 2008. PV array's slope is increased to 10 [Deg]. This research will be continued for the further optimization of the floating PV system.

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