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Optimized Performance and Life Cycle Analysis of Cooled Solar PV

Mohammad R Herfatmanesh[1], Yiming Liu [1], Zhijun Peng [2+]

[1]School of Engineering and Technology, University of Hertfordshire, UK

[2]Faculty of Creative Arts, Science and Technology, University of Bedfordshire, UK

Abstract. This research is aiming to investigate practical effects of solar PV surface temperature on output performance, in particular output efficiency. Experimental works were carried out under different radiation condition for exploring variation of output voltage, current, output power and efficiency. After that, cooling test was conducted to find how much efficiency improvement can be achieved with cooling condition. As test results shows the efficiency of solar PV can be increased close to 50% with cooled condition, a cooling system is proposed for possible system setup of residential solar PV application. Life cycle assessment suggests that the cost payback time can be reduced to 12.5 years, compared to 15 years of the baseline of a similar system without cooling sub-system.

Keywords: solar PV, cooled condition, efficiency improvement, life cycle analysis.

1. Introduction

In recent years, relevant technologies and performances of solar PV (Photovoltaic) have been improved significantly. However, although some solar PV's efficiencies achieved in lab have been over 40%, commercial module efficiencies are much lower than those. Even for the same type solar PV, the commercial efficiency is generally much lower than the lab efficiency. For instance, while monocrystalline's lab efficiency can be around 24%, the practical efficiency is only around 11-17% [1], [2].

When scientists' efforts for optimising solar PV's performance to achieving possible improvement of electric output efficiency, it is necessary to examine why some efficiency was lost from commercial products and how to maintain those efficiencies during practical application. One reason which has been noticed for significantly influencing practical solar PV efficiency is working temperature, or solar panel surface temperature [3]-[6]. Some research has revealed that an increase in solar cell temperature of around 1 ℃ leads to a decrease in efficiency of about 0.45% [7], [8]. The problem is the ambient temperature is always high under high radiation condition. Meanwhile the solar panel surface temperature also keeps increase with increased radiation. This provides task for solar system development that how to obtain possible low temperature for solar panel, even with high radiation condition.

To general commercial application of solar panel, high efficiency will directly result in the payback time's reduction, including energy payback time and cost payback. In recent years, it was estimated the energy payback is from 1 to 4 years [9], [10] depending on the module type and location. With a typical lifetime of 20 to 30 years, this means that, modern solar cells would be net energy producers, i.e. they would generate more energy over their lifetime than the energy expended in producing them. Generally, thin-film technologies—despite having comparatively low conversion efficiencies—achieve significantly shorter energy payback times than conventional systems, usually less than 1 year [11], [12]. In the other hand, the cost payback time is not so optimistic, compared to the energy payback time. When end customers are directly concerned cost payback time, it will be helpful to have direct economic benefit when practical solar PV system is developed.

+ Corresponding author. Tel.: +44 1707 281098.
E-mail address: z.peng2@herts.ac.uk.

The research presented in this manuscript is aiming to investigate practical effects of solar PV surface temperature on output performance, in particular efficiency. Experimental works would be carried out under different radiation condition for exploring the output efficiency. After that, cooling test would be conducted to find how much efficiency improvement can be achieved with cooling condition. Considering the benefit of cooled solar PV, a cooling system would be proposed for residential solar PV system and the cost payback would be compared with non-cooled system.

2. Experimental Rig and Conditions

The schematic of experimental system is shown in Figure 1. The polycrystalline-Si solar PV module (produced by Eco-Worthy Company and made in China in November 2013) which has an area of 0.1872 m^2 and a max power output of 20 W was suspended for facing down to absorb radiation from underneath. From the supplier's information, it demonstrated that the panel can work under 1000 W/m^2 of maximum irradiance. Detailed specifications of the solar panel are demonstrated in Table 1. Solar radiation was simulated by an electric incandescent lamp with power of 160 W, 300 W and 400 W, respectively. By adjust the distance and angle of lamp to the solar panel, the average radiation on the solar panel were kept to 160 W/m^2, 300 W/m^2 and 400 W/m^2, which was measured by an ISM 400 solar power meter. The close circuit of solar panel was connected with a 12 Ω of resistance. Voltages and current outputs were measured by a multi-meter.

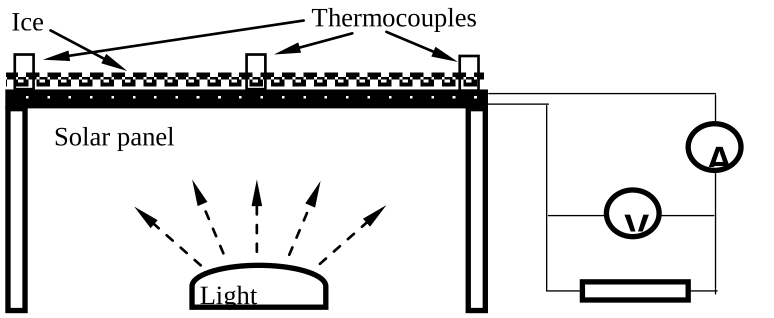

Fig. 1: Test rig for solar PV output under cooled condition.

For providing a cooled condition to the solar panel, ice was spread evenly on the back of solar panel during the test of cooled condition. During the test, limited melting of ice was observed. During all tests, the ambient temperature was between 24 and 25 ℃ of naturally weather condition.Before the close circuit test was started, an initial test for checking the PV module's open circuit voltage was made with 300 W/m^2 of radiation. As showed in Figure 2, it can be seen that the open circuit voltage kept decrease with the increase of surface temperature. From the practical test, it also showed the practical measurement value of open circuit voltage is difficult to reach the rated value provided by the manufacturer.

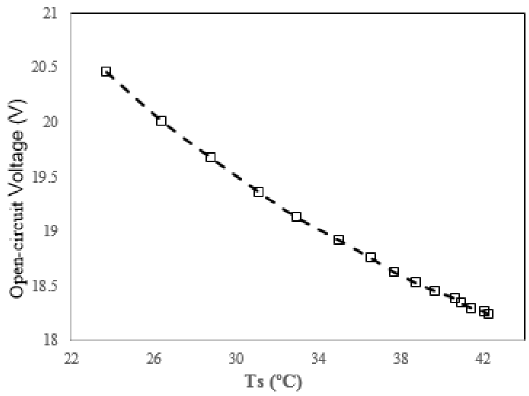

Fig. 2: Effects of surface temperature on open circuit voltage (300 W/m^2 of radiation)

3. Results and Discussion

3.1 Solar PV Output Performance under Different Radiation

The close circuit voltage and output current under 300 W/m^2 of radiation are shown in Figure 3. When the surface temperature increases, the current keeps increase until the maximum value of 0.15 A. This should be due to the reduction of voltage under increased surface temperature.

Based on the measured voltage and current output, the power output and efficiency are presented in Figure 4. It shows the maximum power and efficiency were obtained around 36 ℃ of surface temperature. Both higher and lower temperature than 36 ℃ would result in reductions of power output and efficiency. This suggests, under a certain condition of environment or weather, there exists an optimum working temperature for solar PV to reach its most efficient output.

Table 1: Specifications of solar panel used in the test

Parameter	Value
Max power	20 W
Max output voltage	17.7 V
Max output current	1.11 A
Open circuit voltage	21.6 V
Short circuit current	1.22 A
Dimensions	0.52 m x 0.36 m (0.1872 m^2)

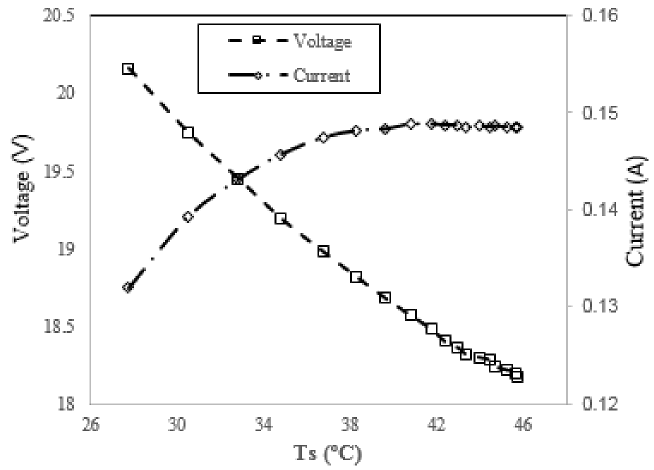

Fig. 3: Effects of surface temperature on voltage and current (300 W/m^2 of radiation)

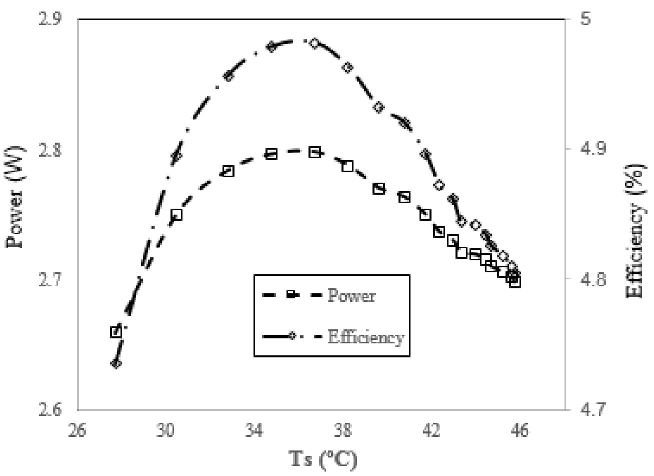

Fig. 4: Effects of surface temperature on power and efficiency (300 W/m^2 of radiation)

Under different condition of radiation, variations of current output as function of voltage are shows in Figure 5. From those results, it can be seen, although the trend of current is similar under different radiation, increased radiation can result in that the maximum current takes place at higher voltage value. This will be helpful to increase power output and in particular the efficiency, which are clearly demonstrated in Figure 6 and Figure 7.

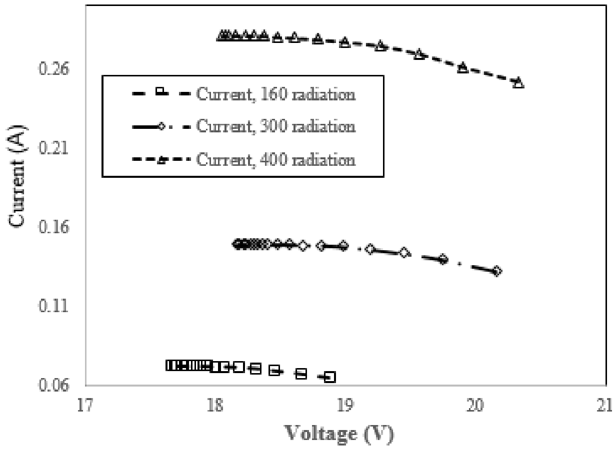

Fig. 5: Variations of current as function of voltage under different radiation

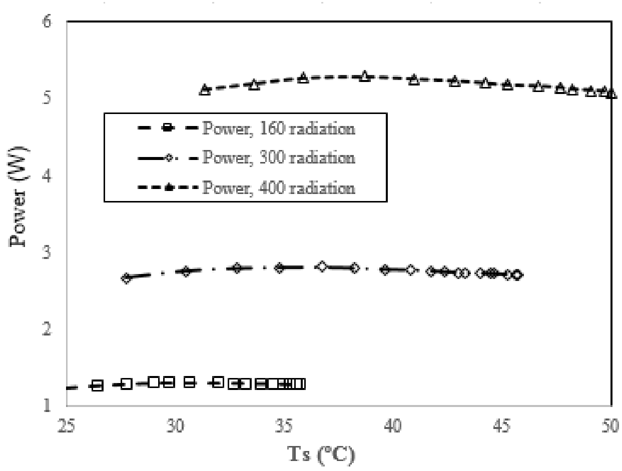

Fig. 6: Effects of surface temperature on power output under different radiation

In Figure 6 and Figure 7, it can be seen that power output and efficiency can have significant increased with the increased of radiation. Meanwhile, higher radiation can tolerate higher surface temperature. The surface temperature of maximum efficiency for three radiations of 160, 300 and 400 W/m2 are about 28, 34 and 38 ℃, respectively.

It can be seen from those figures that the surface temperature always keeps increase with radiation, and the stable surface temperature is always obviously higher than the maximum efficiency temperature. This provides the requirement for examining how a cooled solar PV will influence the output efficiency.

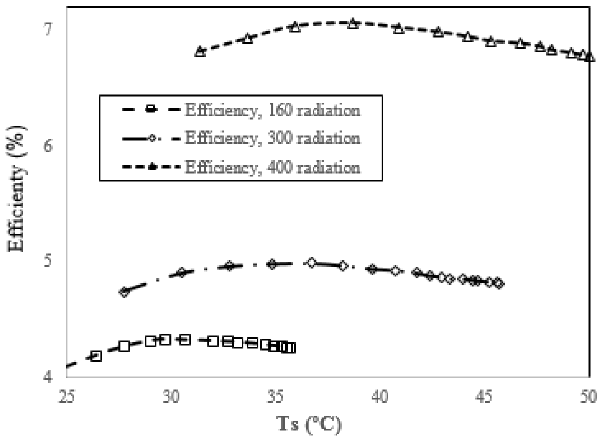

Fig. 7: Effects of surface temperature on efficiency under different radiation

3.2. Solar PV Performance under Cooled Condition

In the section of investigation, ice was spread on the back to cool down the surface temperature of solar PV. The radiation was kept at 300 W/m^2. From the variations of current, as shown in Figure 8, it can be seen both current and voltage had significant increase under cooled condition.

The results are reflected on Figure 9, for the variation of efficiency as function of surface temperature, it clearly suggests that cooled condition can increase the efficiency very obviously. Under non-cooled condition, the best efficiency is about 4.98% which took place at about 36 ℃ of surface temperature. With cooled solar PV, the highest efficiency is about 7.32%, which took place at around 21 ℃ (surface temperature). Comparing two conditions between cooled solar panel and non-cooled solar panel with both under about 24 ℃ of ambient temperature, the efficiency increase rate is about 47%.

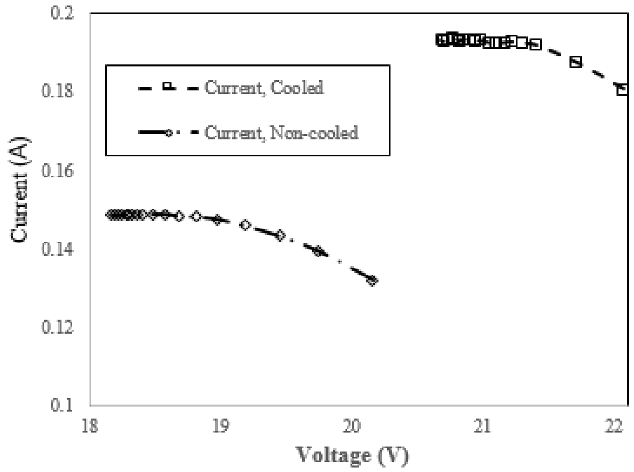

Fig. 8: Increase of current under cooled condition (300 W/m^2 of radiation)

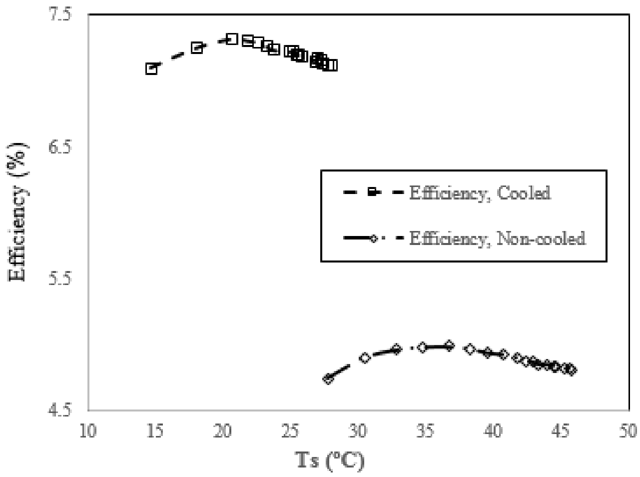

Fig. 9: Increase of efficiency under cooled condition (300 W/m^2 of radiation)

Under cooled and non-cooled conditions, the optimal surface temperature for highest efficiency of solar PV are very different, though with the same radiation and similar weather condition. Perhaps the reason is the cooled condition increases the temperature difference between the solar PV surface and the back. Although those surface temperatures mentioned above are named 'surface temperature', they were actually measured at the back of the solar PV. As the radiation can directly affect the thermocouple's output, those temperature measurements were conducted at the back of solar panel in order to remove the direct influence of radiation on thermocouple reading.

When the cooled condition had possible higher temperature difference between the front surface and back of solar PV, it may contribute to the efficiency increase. If a cooling system can be developed to have about the temperature decrease of 10 ℃, then about 50% efficiency increase rate can be expected and the system is worth to be explored.

3.3. Proposed Cooling System for Practical Application

Base on a typical solar PV system installed on a general resident house in England, a cooling system can be developed with the following arrangement shown in Figure 10. Basically necessary cooling channel with similar structure as general radiators of central heating (but with flat surface to touch the back of solar panel) can be fixed under solar panel. Cooling water is supplied by a water pump which is similar as used general central heating system. Through the heat exchange between the solar panel and the cooling channel, the cooling water with increased temperature can be partly or totally circulated in the water tank (for shower) and then flows into the helical heat exchanger.

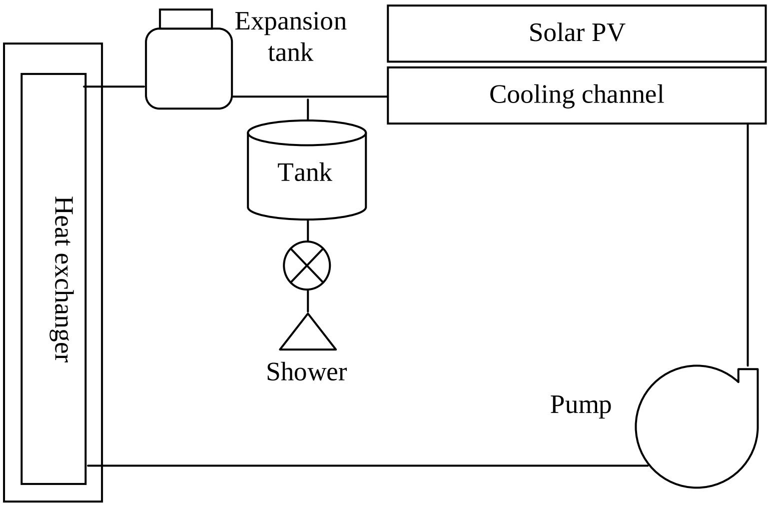

Fig. 10: Proposed cooling system for solar panel of residential application

The heat exchange takes place between the water and air by naturally convection or enforced convection. In accordance with initial estimate, the heat exchanger can ensure a temperature reduction of around 10 ℃ for the cooling water. Then it can be pumped back again to the cooling channel.

With a 4 KW solar system which has a system purchase cost of about 6000 pounds, based on typical average radiation condition in England with currently annual benefit of 400 pound, its payment back time of purchase cost can be 15 years. After a cooling system as shown in Figure 10 is fitted, assume the efficiency can have an increase of 47%, the income trend can be found in Figure 11.

Considering the cooling system will increase the manufacture or purchase cost to 7900 pounds, then the payback time of purchase cost can be reduced to 12.5 years. If taking 20 years as the system life time, by the end, the cooled solar PV can make profit about 4100 pounds, compared the non-cooled solar PV system's profit of 2000 pounds.

4. Conclusions

In this research, effects of solar PV surface temperature on output performance have been experimentally investigated, under different radiation condition for exploring variation of output voltage, current, output power and efficiency. Meanwhile cooled solar PV performance has been also tested by spreading ice on the back of solar panel. The final part of this research is to have the life cycle assessment to compare between non-cooled and cooled solar PV system, in terms of their payback time of system cost. With those parts of investigation, the following conclusions have been derived.

- Under different radiation condition there exists an optimal surface temperature for solar PV to produce the maximum efficiency. The higher the radiation is, the higher the optimal surface temperature is.
- When solar panel is cooled down, the efficiency can have significant increase. The optimal surface temperature for highest efficiency can have obvious increase for cooled condition, compared to non-cooled condition.
- In this research with ice for providing cooling function, the efficiency of solar PV can be increased up to 50% with cooled condition.

- A cooling system was proposed for possible system setup of residential application to cool down the solar panel. Life cycle assessment suggests that the cost payback time can be reduced to 12.5 years, compared to 15 years of the baseline of a similar system without cooling sub-system.

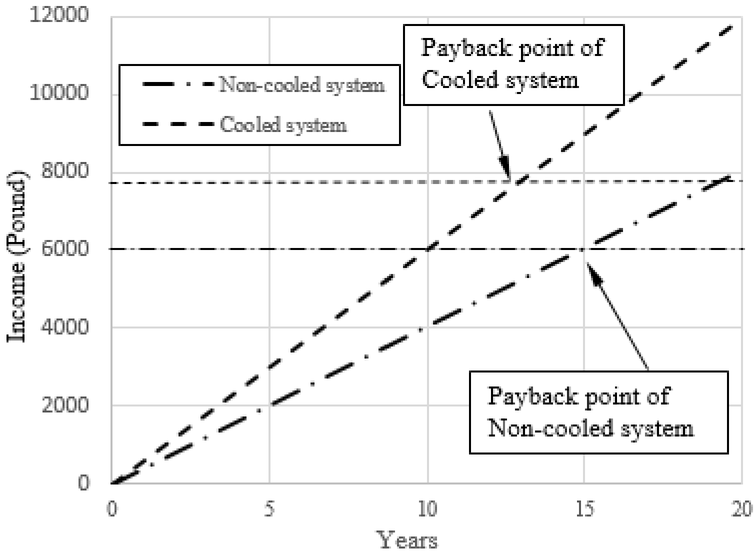

Fig. 11: Possible payback time and long term benefit of cooled solar panel system (based on a 4 kW system)

5. Acknowledgements

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