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Cooled Solar PV Panels for Output Energy Efficiency Optimisation

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Abstract

As working temperature plays a critical role in influencing solar PV's electrical output and efficacy, it is necessary to examine possible way for maintaining the appropriate temperature for solar panels. This research is aiming to investigate practical effects of solar PV surface temperature on output performance, in particular efficiency. Experimental works were carried out under different radiation condition for exploring the variation of the output voltage, current, output power and efficiency. After that, the cooling test was conducted to find how much efficiency improvement can be achieved with the cooling condition. As test results show the efficiency of solar PV can have an increasing rate of 47% with the cooled condition, a cooling system is proposed for possible system setup of residential solar PV application. The system performance and life cycle assessment suggest that the annual PV electric output efficiencies can increase up to 35%, and the annual total system energy efficiency including electric output and hot water energy output can increase up to 107%. The cost payback time can be reduced to 12.1 years, compared to 15 years of the baseline of a similar system without cooling sub-system.

Keywords: Solar PV; Cooled condition; Efficiency improvement

1 Introduction

With the continuous development of solar Photovoltaic (PV) technology, their performance has been improved significantly. However, although some solar PV's efficiencies achieved in the lab have been over 40%, economic module efficiencies are much lower than those. Even for the same type solar PV, the commercial efficiency is much lower than the lab efficiency. For instance, while monocrystalline PV'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 °C leads to a decrease in efficiency of about 0.45% [7, 8]. The problem is the ambient temperature is always keeping high level under high radiation condition. Meanwhile the solar panel surface temperature also keeps increase with increased radiation. Therefore, in order to achieve high energy efficiency, it is necessary to investigate possible technology for obtaining a possibly low temperature for solar panel, in particular with high radiation condition.

For reducing the working temperature of solar PV panels, some researches have been reported with possible solutions. For instance, Kasaeian *et al* applied air flow for providing enforced convection to cool down solar panels' temperature and resulted in an efficiency increase of 12% [9]. Both Bahaidarah [10] and Nizetic *et al* [11] employed high cost water spray technology to cool down solar panels. Perhaps because their test locations and other test conditions were different, Bahaidarah achieved over 60% increase in electric output while Nizetic *et al* got only 17%. Flat plate cooling channels had also been used for providing cooling function to solar PV panels by some researchers. Jouhara et al's results show that 15% increase in energy efficiency was obtained [12]. Other technologies for exploring the performance of cooled PV include using nano hot pipes [13, 14] which achieved a temperature reduction of solar PV panel over 10 ºC and efficiency increase of 59%. Using a simple clay pot for providing evaporative cooling water for cooling down solar panels, Ramkumar *et al* made an efficiency increase of 60% [15]. Spertino *et al* developed a numerical model for investigating the cooled PV performance and demonstrated the increase of electric power could be over 30% [16].

From those different researches, it can be found that 12% to 60% of electric efficiency improvement could be expected while solar PV panels were cooled with possible cooling system. Meanwhile, a research made by Su *et al* [17] which experimentally compared different fluid in the cooling system suggested that water cooled PV-Thermal system is most efficient for improving both electric and thermal performances. A review from Guo *et al* [18] for various cooled PV systems has also provided a similar conclusion. However, although those researches have confirmed that cooled solar PV, in particular with water as cooling liquid, can effectively improve the electric output efficiency, so far no practical application has been published.

For general commercial application of solar panel, high energy efficiency can directly result in the payback time's reduction, including the energy payback time and the cost payback time. Regarding the energy payback time, it is normally defined as the recovery time required for generating the energy spent for manufacturing the photovoltaic module. In recent years, the energy payback time of solar PV system is generally from 1 to 4 years, depending on the module type and location [19, 20]. With a typical lifetime of 20 to 30 years for general solar PV system, this means that, modern solar cells would be definitely net energy producers. Generally, thin-film technologies—despite having comparatively low conversion efficiencies—achieve significantly shorter energy payback times than conventional systems, usually less than 1 year [21, 22]. Compared to the energy payback time, the cost payback time is not so optimistic. When end customers are concerned more about cost payback time, it is important to have high economic benefit when a practical solar PV system is developed.

The research presented in this manuscript is aiming to investigate practical effects of solar PV surface temperature on output performance, in particular efficiency. As experimental works were carried out under different radiation condition for exploring the output efficiency, cooling test was performed to find how much efficiency improvement can be achieved with cooling condition. By analysing the variation of electric output as function of solar panel surface temperature under different conditions, effects of temperature on output efficiency were demonstrated quantitatively. Finally, a practical cooling system was proposed for residential solar PV system and the cost payback time was analysed and compared with non-cooled system, in order to assess its energy and economic benefits.

2 Experimental Rig and Conditions

The schematic of the 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 could 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 adjusting the distance and angle of lamp to the solar panel, the average radiation on the solar panel was 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. Output voltages and current were measured by a multi-meter.

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 ºC of naturally weather condition. In addition to a thermocouple for recording the ambient temperature, six thermocouples were fixed at the central point, two corners and other three points for achieving the average surface temperature.

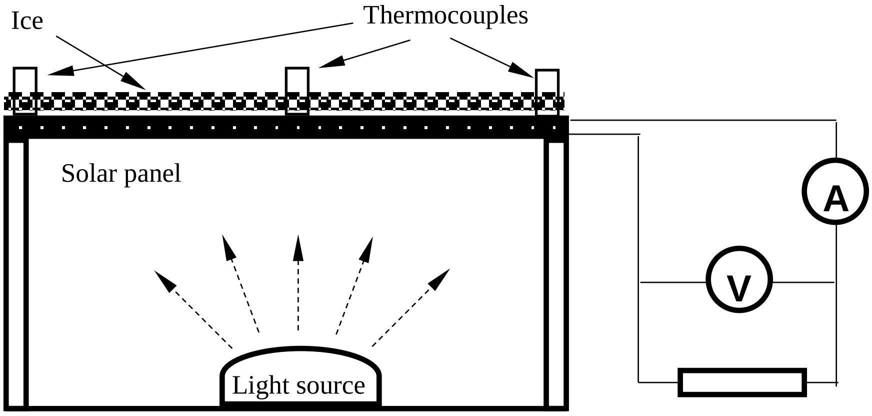

Figure 1: Test rig for solar PV output under cooled condition

Table 1 Specifications of solar panel used in the test

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

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. Results show that the open circuit voltage kept decrease with the increase of surface temperature. Also from actual results, it also showed the practical measurement value of open circuit voltage is difficult to reach the rated value provided by the manufacturer.

3 Experimental Results and Discussion

3.1 Solar PV Output Performance under Different Radiation

Initial measurement of the close circuit voltage and output current under 300 W/m^2 of radiation show, as the surface temperature increases, the current keeps increasing 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 2, Figure 3 and Figure 4 for three different radiation levels with similar ambient temperature (24-25 ºC). From those results, it can be seen, although the trend of current is similar under different radiation, increased radiation can result in the maximum current taking place at higher voltage value. This will be helpful to increase power output and in particular the efficiency, which is clearly demonstrated in Figure 3 and Figure 4.

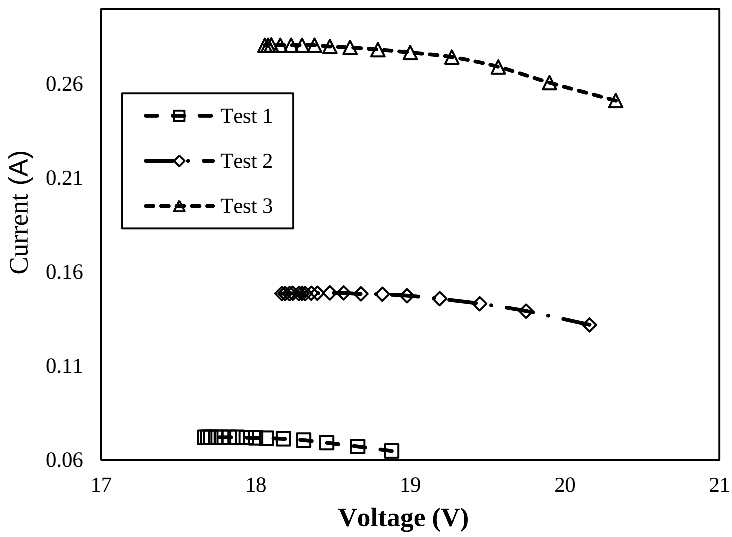

Figure 2: Variations of current as function of voltage under different radiation

(Test 1 – 160 W/m^2 of radiation, Test 2 – 300 W/m^2 of radiation, Test 3 – 400 W/m^2 of radiation)

In Figure 3 and Figure 4, 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/m^2 are about 28, 34 and 38 ºC, respectively.

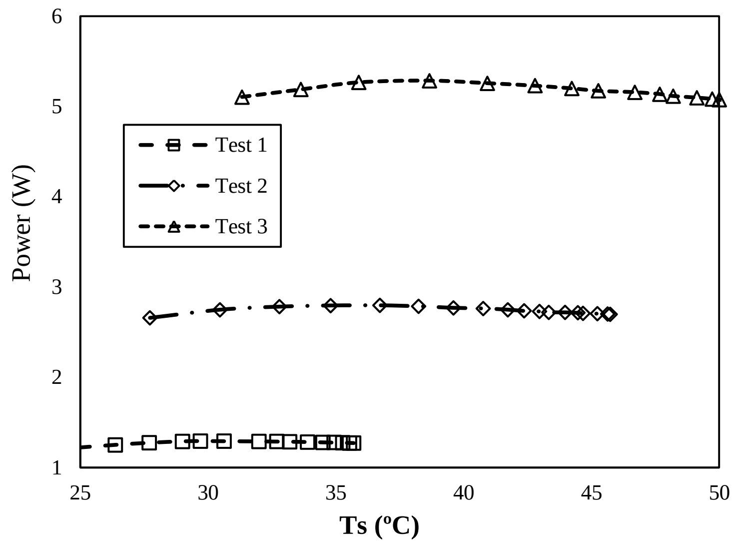

Figure 3: Effects of surface temperature (Ts) on power output under different radiation
(Test 1 – 160 W/m^2 of radiation, Test 2 – 300 W/m^2 of radiation, Test 3 – 400 W/m^2 of radiation)

It can also 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. For instance, under 160, 300 and 400 W/m^2 of radiation conditions, the surface stable temperatures are 35.7, 45.6 and 49.3 °C, respectively, compared to the maximum efficiency temperatures 28, 34, 38 °C of those test conditions. This provides the requirement for examining how a cooled solar PV with lower surface temperaturae will influence the output efficiency.

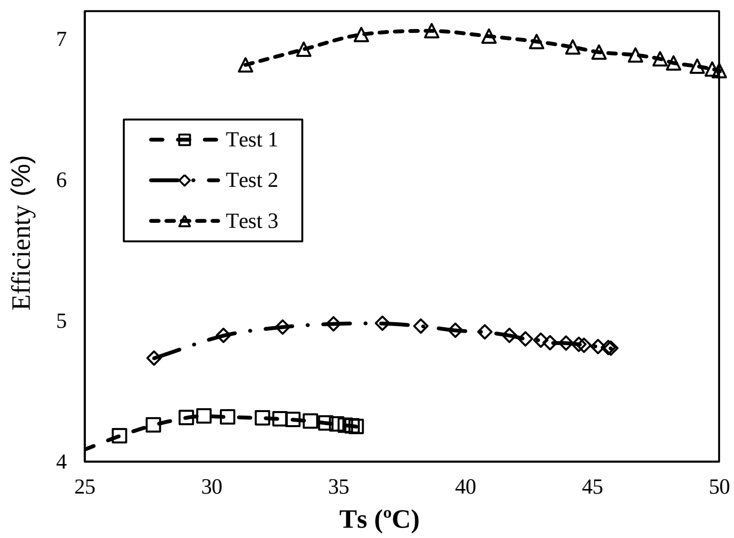

Figure 4: Effects of surface temperature (Ts) on efficiency under different radiation
(Test 1 – 160 W/m^2 of radiation, Test 2 – 300 W/m^2 of radiation, Test 3 – 400 W/m^2 of radiation)

3.2 Solar PV Performance under Cooled Condition

In this section of investigation, ice was spread on the back to cool down the surface of solar PV for a stable temperature. The radiation was kept at 300 W/m^2. From the variations of current, as shown in Figure 5, it can be seen both current and voltage had significant increase under cooled condition.

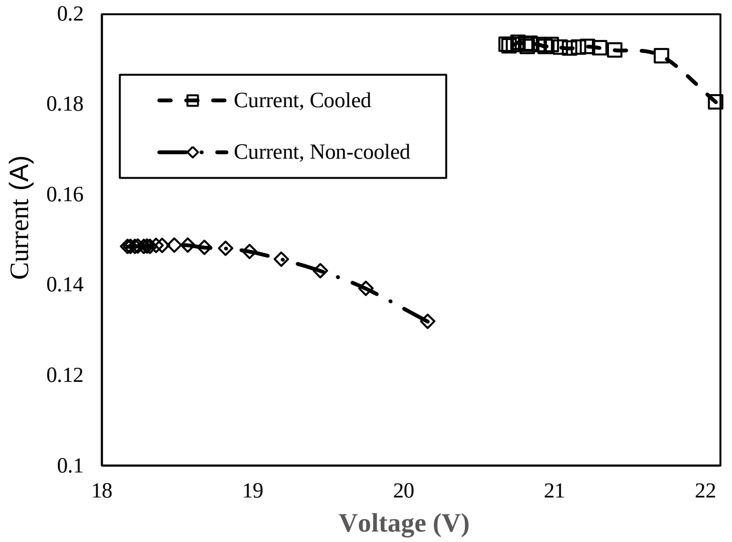

Figure 5: Increase of current under cooled condition (300 W/m^2 of radiation)

The results as reflected in Figure 6, for the variation of efficiency as function of surface temperature Ts, clearly suggest that cooled condition can increase the efficiency obviously. Under non-cooled condition, the best efficiency is about 4.98% which took place at about 36 ºC of surface temperature. With cooled solar PV, the highest efficiency is about 7.32%, which took place at around 21 ºC (surface temperature). Comparing two conditions between cooled solar panel and non-cooled solar panel with both under about 24 ºC of ambient temperature, the efficiency increase rate is (7.32%-4.98%)/4.98% = 47%. Compared to those published results from other researchers which are between 12% and 60%, as shown in Figure 7, this value should be reasonable.

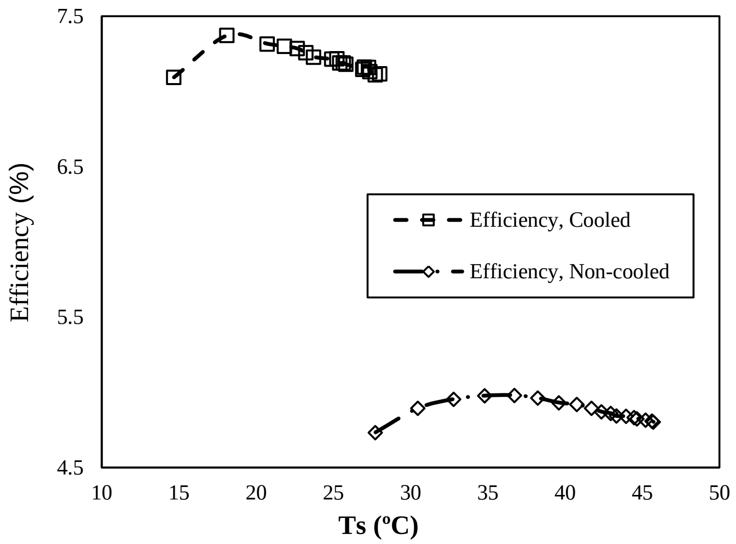

Figure 6: Increase of efficiency under cooled condition (300 W/m^2 of radiation)

In Figure 7, the comparison with other researchers' results is about effects of PV surface temperature on electric output efficiency. Most of solar PV types used by cited those researches are monocrystalline or polycrystalline, while some researchers did not mentioned their solar PV types, such as [12] and [17].

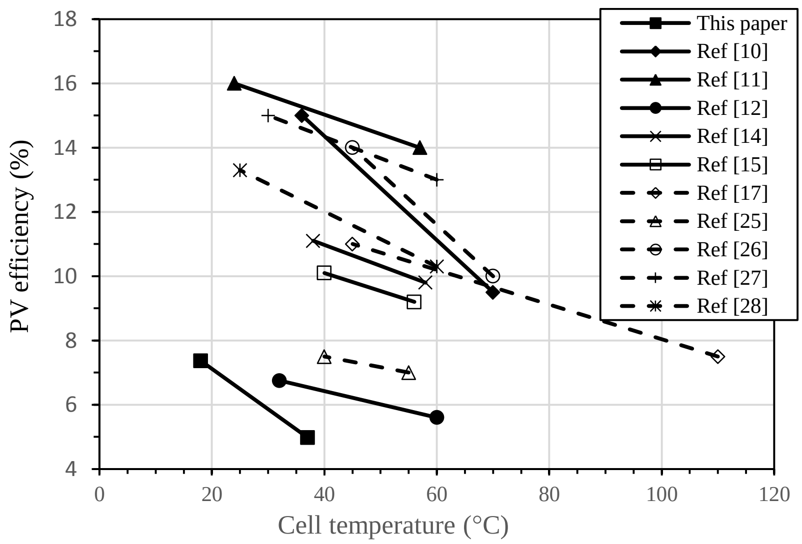

Figure 7: Comparison with other researchers' results about effects of PV surface temperature on output efficiency

From the comparison, it can be found that two published results of [10] and [26] have higher increase rate while solar PV surface temperature were reduced. In [10], water spray was employed and in [26] a complicated water cooling system with cooling channel was used for providing cooling. Most of others which developed different water or air cooling systems measured lower efficiency improvement rate. Perhaps one reason is different temperature ranges and other test conditions.

Regarding effects of working temperature on solar PV performance, it is suggested, under the same radiation consideration, the electric output efficiency is mainly influenced by solar PV surface temperature or PN junction temperature. In accordance with the formula published in reference [23], relation between ambient temperature, PV surface temperature and radiation level can be expressed as:

$$T_s - T_a = aR$$

Where, T_s is surface temperature of solar PV, T_a is ambient temperature, R is the solar radiation, *a* is a constant.

As shown in Figure 8, without cooling, the values of *a* are around 0.07 for three different radiation conditions. If taking the surface temperature of the cooled case as 0 ºC, the *a* value is about 0.093. This is much different from other three cases. For achieving a similar value for the constant of '*a*', the average ambient temperature should be around 7 ºC. The reason for the ambient temperature of this case not being the ice temperature may be the different temperature on two sides, while ice temperature in one side is low and air temperature on another side is high.

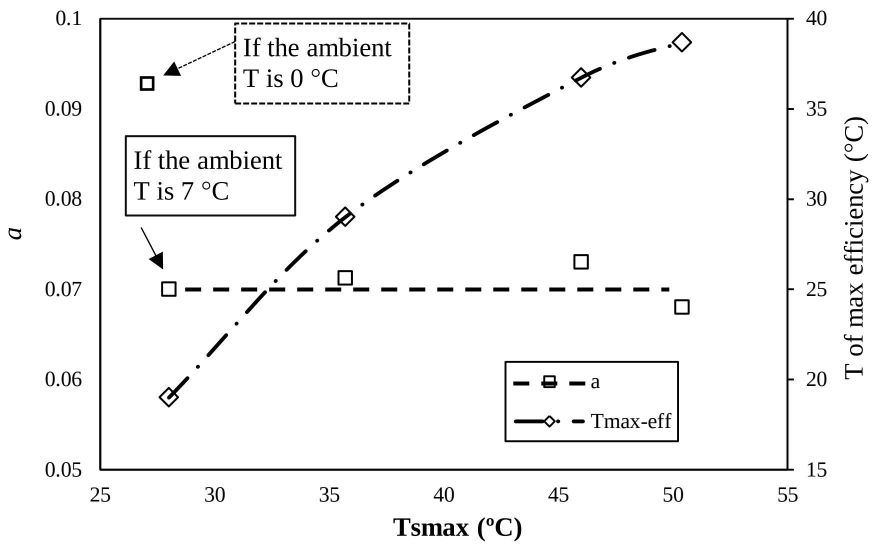

Figure 8: '*a*' value and max efficiency temperature (Tsmax) under different ambient temperature

If the average ambient temperature for this condition is 7 ºC, the temperature difference between the cooled case and uncooled case of 300 W/m^2 radiation is 24.1 – 7 = 17.1 ºC. Then the average efficiency increase per degree of temperature reduction is about (7.32% - 4.98%)/17.1 = 0.14%/ ºC. Also shown in Figure 7, it suggests an almost linear relation between maximum surface temperature and maximum efficiency temperature.

With above analyses for experimental results, it demonstrates that to reduce solar panel working temperature with reasonable cost can improve the total system electric output efficiency, then increase net energy output and benefit customers for shorter payback time of cost. As the weather condition is complicated in different region and in different seasons, practical profits will be analysed and dicussed in next section with a practical case.

4 Proposed Cooling System for Practical Application

4.1 System Performance

Based on a typical 4 kW solar PV system installed on a general resident house in England, a cooling system can be developed with the following arrangement shown in Figure 9. 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 other house water application) and then flows into the cooling tower fixed in the loft.

In the loft where normally has a much lower temperature than outside ambient temperate, the cooling water can be cooled down through the cooling tower which is mainly operated by naturally convection or enforced convection due to ventilation flows. Then cool water can be pumped back again to the cooling channel. By initial estimate, the cooling tower can ensure a temperature reduction of over 10 ºC for the cooling water during summer.

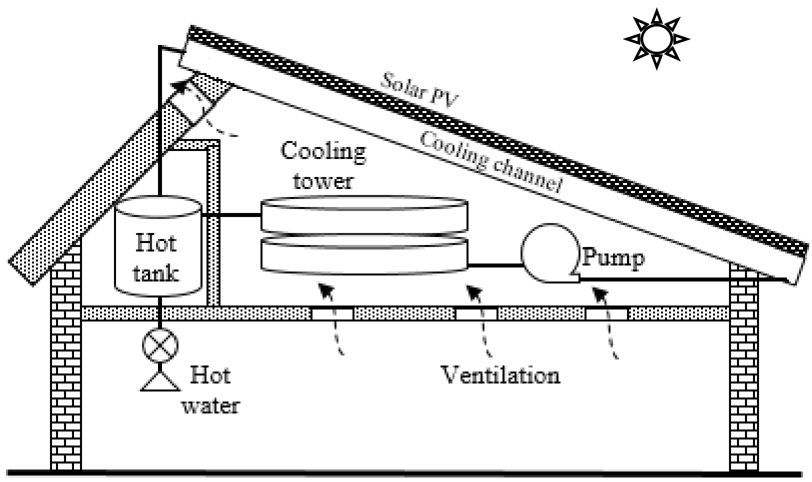

Figure 9: Proposed cooling system for solar panel of residential application

For the system performance, the following analysis will mainly base on the above 4 kW system and assumes the system is based in South England. The monthly average air temperature and solar radiation in England [24] are shown in Figure 10. Those conditions are used as input to analyse energy outputs.

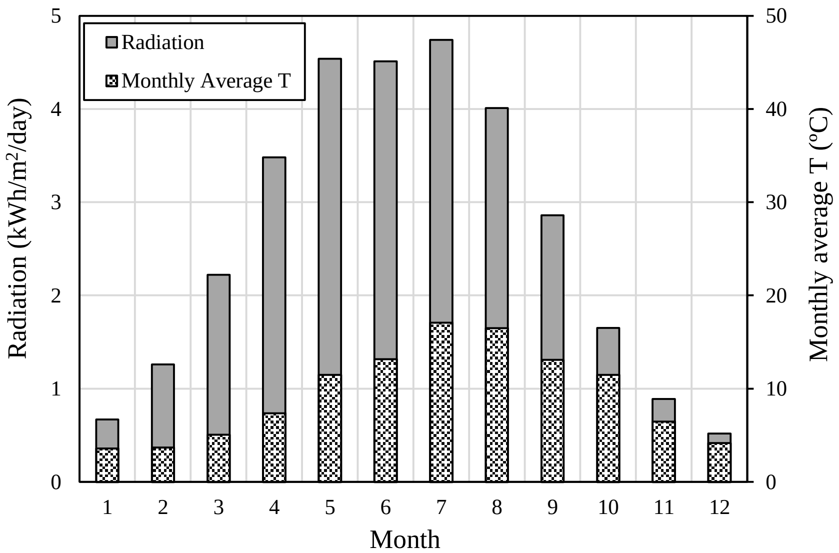

Figure 10: Average monthly solar radiation and average monthly temperature in South England

Based on the above conditions, the electric output from solar PV panels are estimated and results are listed in Figure 11. Without the cooling system for solar PV, the annual electric output of solar PV panels is 1805.76 kWh. With the cooling system working on, the annual electric output of solar PV panels increases to 2430.05 kWh. This results in an increase of 34.6%. If including the energy output of hot water which is about 1311.95 kWh annually, the energy output increase is 107%.

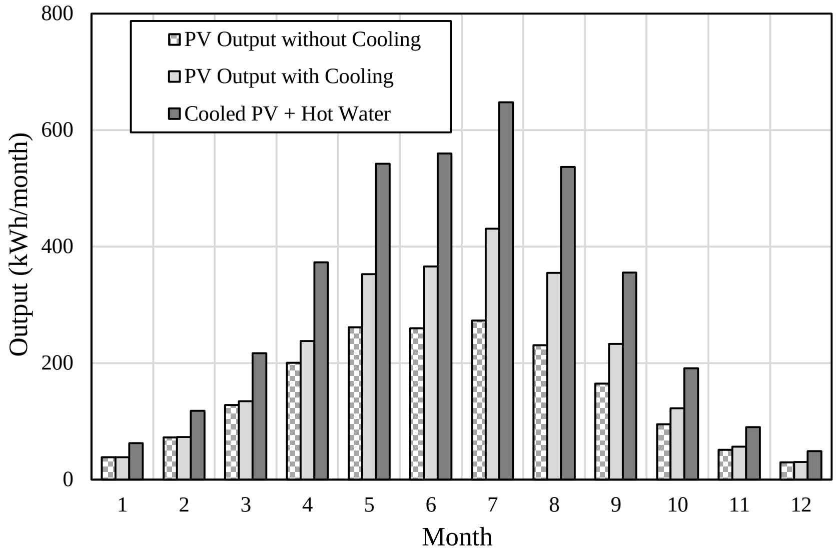

Figure 11: Monthly energy outputs of uncooled PV, cooled PV and cooled PV plus hot water

4.2 Life Cycle Analysis

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 is fitted as shown in Figure 9 is fitted, assuming the electric output has the same price per kWh, the increased economic benefit of electric output will increase 34.6%. The trend can be found in Figure 12.

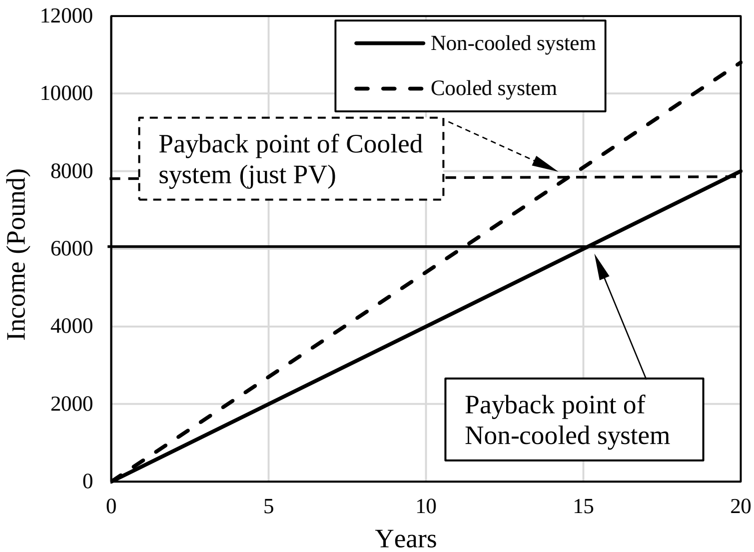

Figure 12: Possible payback time of cooled solar PV system, including hot water benefit (based on a 4 kW system)

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 14.8 years, by just considering the increase from electric output. If taking 20 years as the system life time, by the end, the cooled solar PV can make profit about 2800 pounds, compared the non-cooled solar PV system's profit of 2000 pounds.

Currently in England, natural gas price is 30% of electricity price for residential customers. As the efficiency of general central heating boilers for producing hot water is about 75%, the energy output of per kWh hot water has 40% worth of per kWh electric output. Then if both electric output and hot water output are taken in to account, the payback time of cooled PV system purchase cost can be reduced to 12.1 years, as shown in Figure 13. For a solar PV which has 20 years of the system life time [19, 20], the cooled solar PV can make profit about 5200 pounds, compared the non-cooled solar PV system's profit of 2000 pounds. Considering the solar radiation level in England is not high, the cooled PV system should has a much better performance and much shorter payback time if it is installed in some high radiation region.

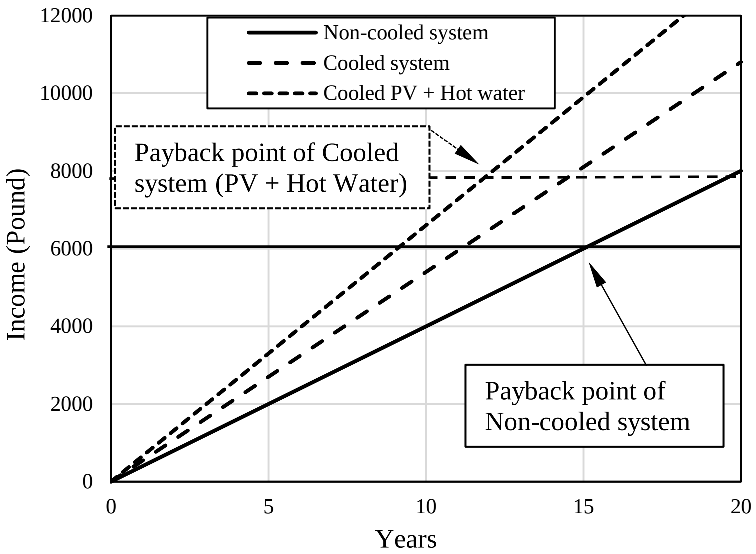

Figure 13: Possible payback time of cooled solar PV system including hot water benefit

In terms of the relationship between system performance increase and system cost, a comparison with other researchers' results is presented in Figure 14. Except [27] which used air cooling, all other cooling systems in Figure 14 are based on water cooling, though very different designs were employed by those researchers.

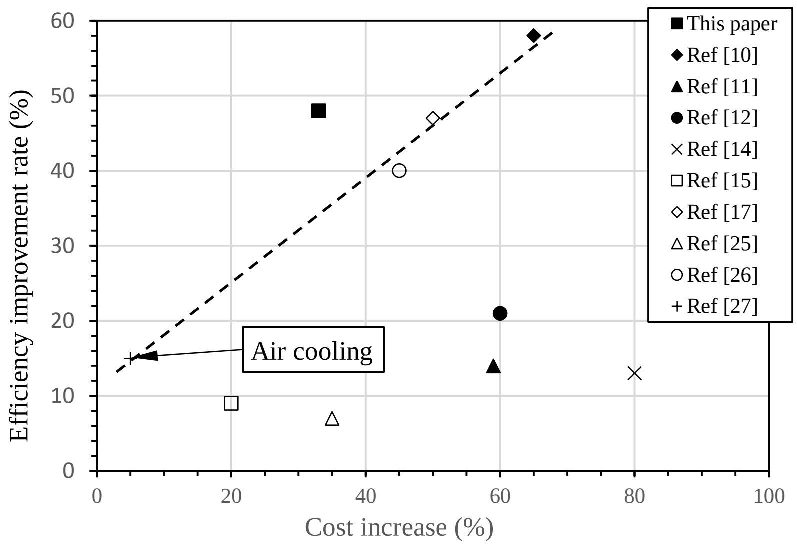

Figure 14: Comparison with other researchers' results about the electric efficiency improvement as function of cost

The lowest cost of water cooling system came from [15] which used a clay pot for providing evaporative cooling water for supplying a slow flow on PV panel surface. In [25], a very similar cooling channel design as used in the current research was reported, though a much lower efficiency improvement was produced. Other methods include water spray [10, 11], double side cooling channels [17], complicated circulation cooling system [26], metal cooling channel [12] and nano heat pipe [14].

Although results from different researchers are very different, as shown in Figure 14, a reasonable trend for linear increase of cost with increased efficiency can be seen by following the dash line in Figure 14. Then a higher ratio of efficiency increase to cost for the current research has been demonstrated than other researchers' systems. In addition to those low cost materials, such as plastic cooling channels which are available from existing market, the novel system design provides the main advantage for the low cost but high efficiency improvement.

5 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. A cooled case for solar PV performance has been also performed by spreading ice on the back of solar panel. Based on those results, a cooled solar PV system has been proposed for resident application. By analysing the electric and hot water output, the life cycle assessment for comparing non-cooled and cooled solar PV systems, in terms of their payback time of system cost, was conducted. With those investigations, 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 on the back of solar PV panel, the efficiency of solar PV can have an increasing rate of 47% with cooled condition.

- A cooling system has been 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 12.1 years, compared to 15 years of the baseline of a similar system without cooling sub-system.

Acknowledgements

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References

[1] Hankins, H., Stand-alone solar electric systems, London: Earthscan, 2010.

[2] Wong, J., Sridharan, R. and Shanmugam, V., Quantifying Edge and Peripheral Recombination Losses in Industrial Silicon Solar Cells, *IEEE Transactions on Electron Devices*, Vol.62(11), Article No.7289429, PP.3750-3755, 2015.

[3] Teo, H. G., Lee, P. S., Hawlader, M. N. A, An active cooling system for photovoltaic modules, *Applied Energy*, Vol.90: 309-315, 2012.

[4] Popovici, C. G., Hudisteanu, S. V., Mateescu, T. D., Chereches, N. C., Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks, *Energy Procedia*, Vol.85:425-432, 2016.

[5] Skoplaki, E, Palyvos, J. A., On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations, *Solar Energy*, Vol.83:614-624, 2009.

[6] Du, B., Hu, E., Kolhe, M., Performance analysis of water cooled concentrated photovoltaic (CPV) system, *Renewable and Sustainable Energy Reviews*, Vol.16: 6732-6736, 2012.

[7] Zhu, L., Raman, A. P., Fan, S., Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody, *Proceedings of the National Academy of Sciences*, Vol.**112** (40):12282–12287, 2015.

[8] Debra, H., An investigation on energy performance assessment of a photovoltaic solar wall under buoyancy-induced and fan-assisted ventilation system, *Applied Energy*, Vol.191, PP.55-74, 2017.

[9] Kasaeian, A., Khanjari, Y., Golzari, S., Mahian, O. and Wongwises, S., Effects of forced convection on the performance of a photovoltaic thermal system: An experimental study, *Experimental Thermal and Fluid Science*, Vol.85, PP.13-21, 2017.

[10] Bahaidarah, H. M. S., Experimental performance evaluation and modeling of jet impingement cooling for thermal management of photovoltaics, *Solar Energy*, Vol.135, PP.605–617, 2016.

[11] Nizetic, S., Coko, D., Yadav, A. and Grubisic-Cabo, F, Water spray cooling technique applied on a photovoltaic panel: The performance response, *Energy Conversion and Management*, Vol.108, PP.287–296, 2016.

[12] Jouhara, H., Milko, J., Danielewicz, J., Sayegh, M. A., Szulgowska-Zgrzywa, M., Ramos, J. B. and Lester, S. P., The performance of a novel flat heat pipe based thermal and PV/T (photovoltaic and thermal systems) solar collector that can be used as an energy-active building envelope material, *Energy*, Vol.108, PP.148-154, 2016.

[13] Du, Y., Advanced thermal management of a solar cell by a nano-coated heat pipe plate: A thermal assessment, *Energy Conversion and Management*, Vol.134, PP.70-76, 2017.

[14] Zhang, Y., Du, Y., Shum, C., Cai, B., Le, N. C. H, Chen, X., Duck, B., Fell, C., Zhu, Y. and Gu, M., Efficiently-cooled plasmonic amorphous silicon solar cells integrated with a nano-coated heat-pipe plate, *Scientific Reports*, Vol.6:24972, 2016, DOI: 10.1038/srep24972.

[15] Ramkumar, R., Kesavan, M., Raguraman, C. M. and Ragupathy, A., Enhancing the Performance of Photovoltaic Module Using Clay Pot Evaporative Cooling Water, *IEEE* 978-1-4673-9925-8/16, 2016.

[16] Spertino, F., D'Angola, A., Enescu, D., Di Leo, P., Fracastoro, G. V. and Zaffina, R., Thermal–electrical model for energy estimation of a water cooled photovoltaic module, *Solar Energy*, Vol.133, PP.119–140, 2016.

[17] Su, D., Jia, Y., Huang, X., Alva, G., Tang, Y., and Fang, G., Dynamic performance analysis of photovoltaic–thermal solar collector with dual channels for different fluids, *Energy Conversion and Management*, Vol.120, PP.13-24, 2016.

[18] Guo, J., Lin, S., Bilbao, J. I., White, S. D., and Sproul, A. B., A review of photovoltaic thermal (PV/T) heat utilisation with low temperature desiccant cooling and dehumidification, *Renewable and Sustainable Energy Reviews*, Vol.67, PP.1-14, 2017.

[19] Ito, M., Kato, K., Komoto, K., et al. A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules, *Progress in Photovoltaics: Research and Applications*. Vol.**16**:17–30, 2008.

[20] Allouhi, A., Saadani, R., Kousksou, T., Saidur, R., Jamil, A. and Rahmoune, M., Grid-connected PV systems installed on institutional buildings: Technology comparison, energy analysis and economic performance, *Energy and Buildings*, Vol.130, PP.188-201, 2016.

[21] Chopra, K. L., Paulson, P. D., Dutta, V., Thin-film solar cells: An overview Progress in Photovoltaics, *Research and Applications*. Vol.**12**:69–92, 2004.

[22] Louwen, A, Van Sark, W. G. J. H. M., Schropp, R. E. I., Turkenburg, W. C. and Faaij, A. P. C., Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs, *Progress in Photovoltaics: Research and Applications*, Vol.23(10), PP.1406-1428, 2015.

[23] Ross, R. G., Flat-Plate Photovoltaic Array Design Optimization, *14th IEEE Photovoltaic Specialists Conference*. San Diego, CA, PP.1126-1132, 1980.

[24] Wilshaw, A. R., Pearsall, N. M. and Hill, R., Installation and Operation of the First City Centre PV Monitoring Station in the United Kingdom, *Solar Energy*, Vol.59(1-3), PP.19-29, 1997.

[25] Arias, H., Cabrera, J. and Hernandez, J., Performance Evaluation of a Mono-Crystalline PV Module Cooled By a Flat Plate Solar Collector in Thermosyphon Mode, IEEE 42nd Photovoltaic Specialist Conference, New Orleans, LA, USA, 14-19 June 2015.

[26] Bahaidarah, H.M, Gandhidasan, P., Baloch, A.A.B., Tanweer, B. and Mahmood, M., A comparative study on the effect of glazing and cooling for compound parabolic concentrator PV systems – Experimental and analytical investigations, *Energy Conversion and Management*, Vol.129, PP.227-239, 2016.

[27] Kaldellis, J. K., Kapsali, M. and Kavadias, K. A., Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece, *Renewable Energy*, Vol.66, PP.612-624, 2014.

[28] Radziemska, E., The effect of temperature on the power drop in crystalline silicon solar cells, *Renewable Energy*, Vol.28, PP.1-12, 2003.