

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

37 commercial products and how to maintain those efficiencies during practical application. One
38 reason which has been noticed for significantly influencing practical solar PV efficiency is working
39 temperature, or solar panel surface temperature [3-6]. Some research has revealed that an increase
40 in solar cell temperature of around 1 °C leads to a decrease in efficiency of about 0.45% [7, 8]. The
41 problem is the ambient temperature is always keeping high level under high radiation condition.
42 Meanwhile the solar panel surface temperature also keeps increase with increased radiation.
43 Therefore, in order to achieve high energy efficiency, it is necessary to investigate possible
44 technology for obtaining a possibly low temperature for solar panel, in particular with high
45 radiation condition.

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47 For reducing the working temperature of solar PV panels, some researches have been reported with
48 possible solutions. For instance, Kasaeian *et al* applied air flow for providing enforced convection
49 to cool down solar panels' temperature and resulted in an efficiency increase of 12% [9]. Both
50 Bahaidarah [10] and Nizetic *et al* [11] employed high cost water spray technology to cool down
51 solar panels. Perhaps because their test locations and other test conditions were different,
52 Bahaidarah achieved over 60% increase in electric output while Nizetic *et al* got only 17%. Flat
53 plate cooling channels had also been used for providing cooling function to solar PV panels by
54 some researchers. Jouhara *et al*'s results show that 15% increase in energy efficiency was obtained
55 [12]. Other technologies for exploring the performance of cooled PV include using nano hot pipes
56 [13, 14] which achieved a temperature reduction of solar PV panel over 10 °C and efficiency
57 increase of 59%. Using a simple clay pot for providing evaporative cooling water for cooling down
58 solar panels, Ramkumar *et al* made an efficiency increase of 60% [15]. Spertino *et al* developed a
59 numerical model for investigating the cooled PV performance and demonstrated the increase of
60 electric power could be over 30% [16].

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

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71 For general commercial application of solar panel, high energy efficiency can directly result in the
72 payback time's reduction, including the energy payback time and the cost payback time. Regarding
73 the energy payback time, it is normally defined as the recovery time required for generating the
74 energy spent for manufacturing the photovoltaic module. In recent years, the energy payback time
75 of solar PV system is generally from 1 to 4 years, depending on the module type and location [19,
76 20]. With a typical lifetime of 20 to 30 years for general solar PV system, this means that, modern
77 solar cells would be definitely net energy producers. Generally, thin-film technologies—despite
78 having comparatively low conversion efficiencies—achieve significantly shorter energy payback
79 times than conventional systems, usually less than 1 year [21, 22]. Compared to the energy payback
80 time, the cost payback time is not so optimistic. When end customers are concerned more about cost
81 payback time, it is important to have high economic benefit when a practical solar PV system is
82 developed.

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

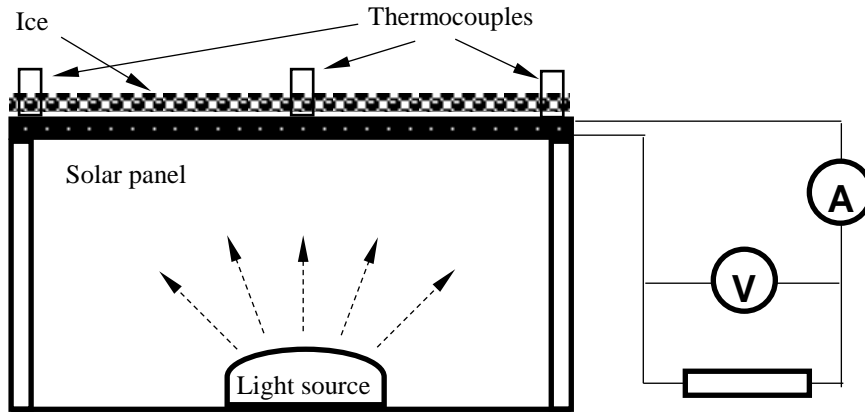
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94 **2 Experimental Rig and Conditions**

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

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106 For providing a cooled condition to the solar panel, ice was spread evenly on the back of solar panel
 107 during the test of cooled condition. During the test, limited melting of ice was observed. During all
 108 tests, the ambient temperature was between 24 and 25 °C of naturally weather condition. In addition
 109 to a thermocouple for recording the ambient temperature, six thermocouples were fixed at the
 110 central point, two corners and other three points for achieving the average surface temperature.



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

124 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)

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 127 Before the close circuit test was started, an initial test for checking the PV module's open circuit
 128 voltage was made with 300 W/m² of radiation. Results show that the open circuit voltage kept
 129 decrease with the increase of surface temperature. Also from actual results, it also showed the
 130 practical measurement value of open circuit voltage is difficult to reach the rated value provided by
 131 the manufacturer.

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133 **3 Experimental Results and Discussion**

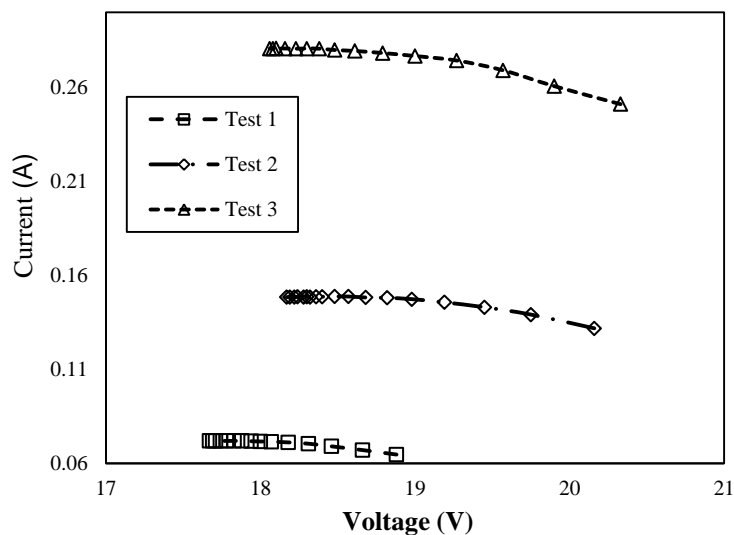
134 **3.1 Solar PV Output Performance under Different Radiation**

135 Initial measurement of the close circuit voltage and output current under 300 W/m^2 of radiation
136 show, as the surface temperature increases, the current keeps increasing until the maximum value of
137 0.15 A . This should be due to the reduction of voltage under increased surface temperature.

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139 Based on the measured voltage and current output, the power output and efficiency are presented in
140 Figure 2, Figure 3 and Figure 4 for three different radiation levels with similar ambient temperature
141 ($24\text{-}25 \text{ }^\circ\text{C}$). From those results, it can be seen, although the trend of current is similar under different
142 radiation, increased radiation can result in the maximum current taking place at higher voltage value.
143 This will be helpful to increase power output and in particular the efficiency, which is clearly
144 demonstrated in Figure 3 and Figure 4.

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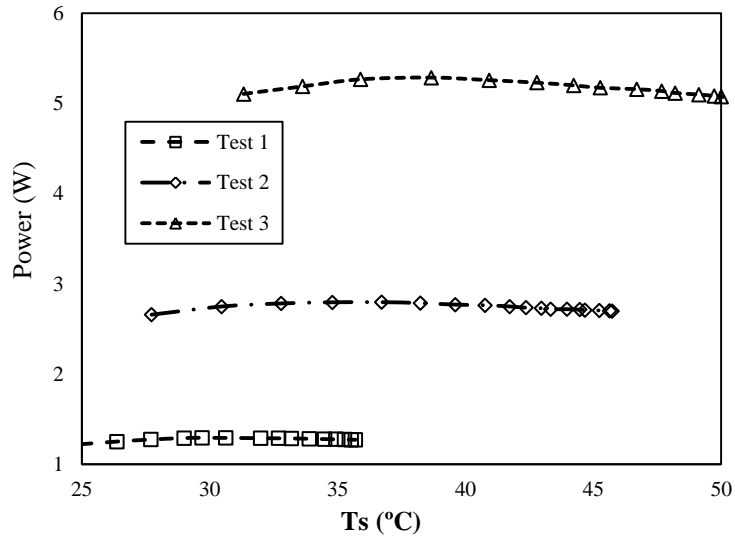
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148 Figure 2: Variations of current as function of voltage under different radiation

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

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151 In Figure 3 and Figure 4, it can be seen that power output and efficiency can have significant
152 increased with the increased of radiation. Meanwhile, higher radiation can tolerate higher surface
153 temperature. The surface temperature of maximum efficiency for three radiations of 160 , 300 and
154 400 W/m^2 are about 28 , 34 and $38 \text{ }^\circ\text{C}$, respectively.



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Figure 3: Effects of surface temperature (Ts) on power output under different radiation

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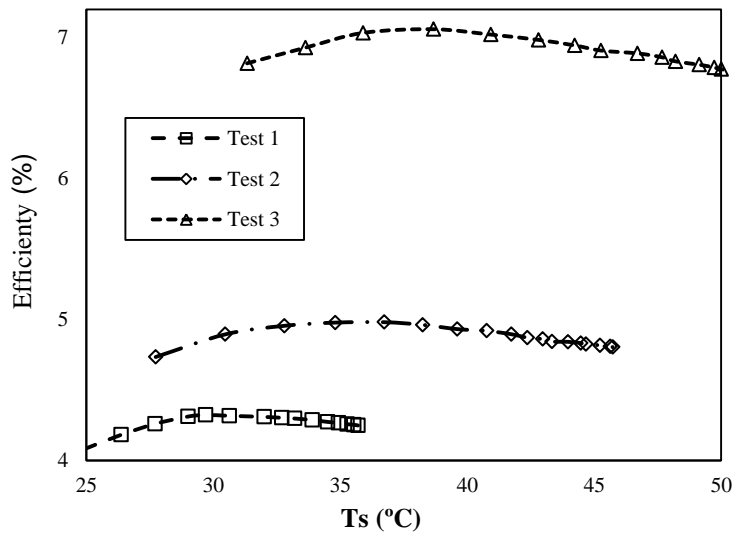
(Test 1 – 160 W/m² of radiation, Test 2 – 300 W/m² of radiation, Test 3 – 400 W/m² of radiation)

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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/m² 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.

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Figure 4: Effects of surface temperature (Ts) on efficiency under different radiation

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(Test 1 – 160 W/m² of radiation, Test 2 – 300 W/m² of radiation, Test 3 – 400 W/m² of radiation)

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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.

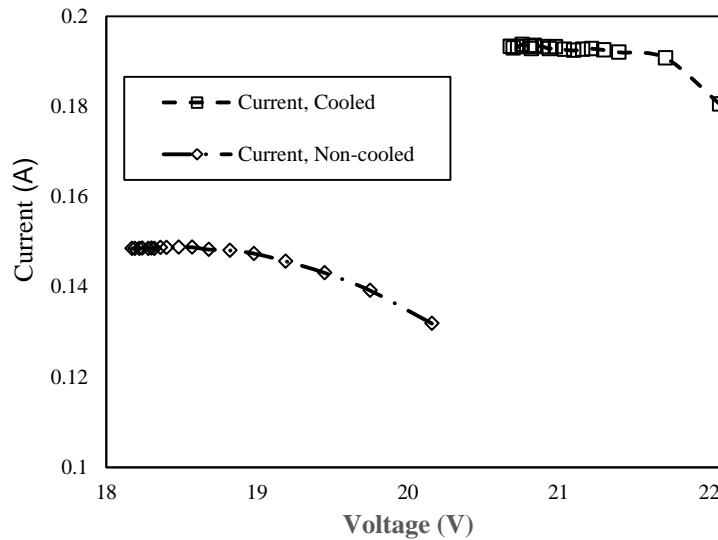


Figure 5: Increase of current under cooled condition (300 W/m^2 of radiation)

The results as reflected in Figure 6, for the variation of efficiency as function of surface temperature T_s , 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 $36 \text{ }^\circ\text{C}$ of surface temperature. With cooled solar PV, the highest efficiency is about 7.32%, which took place at around $21 \text{ }^\circ\text{C}$ (surface temperature). Comparing two conditions between cooled solar panel and non-cooled solar panel with both under about $24 \text{ }^\circ\text{C}$ 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.

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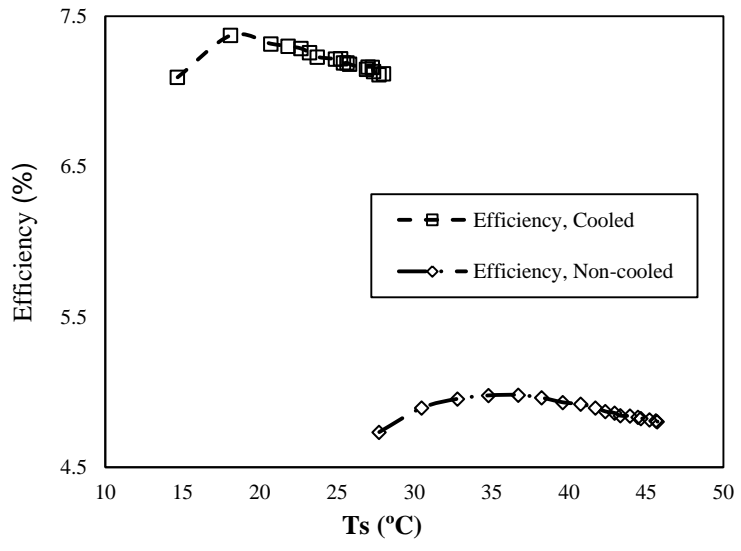


Figure 6: Increase of efficiency under cooled condition (300 W/m^2 of radiation)

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].

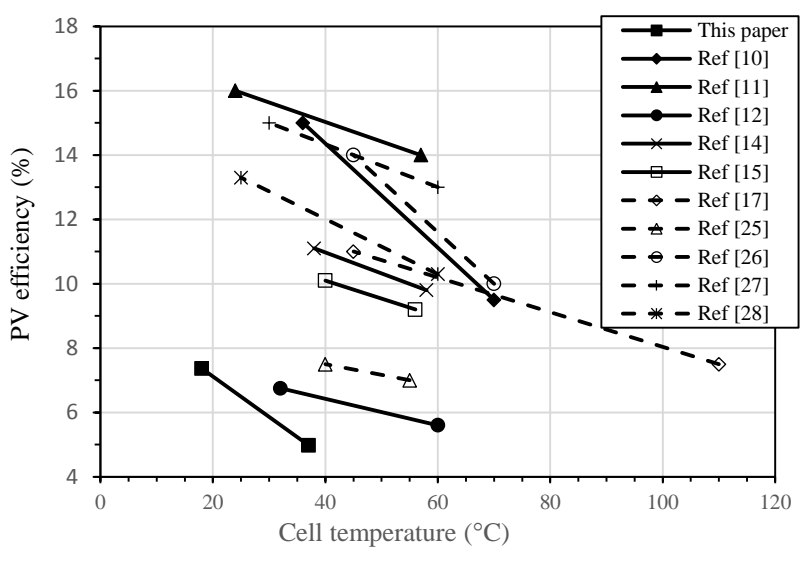


Figure 7: Comparison with other researchers' results about effects of PV surface temperature on output efficiency

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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

231 cooling. Most of others which developed different water or air cooling systems measured lower
 232 efficiency improvement rate. Perhaps one reason is different temperature ranges and other test
 233 conditions.

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

$$240 \quad T_s - T_a = aR$$

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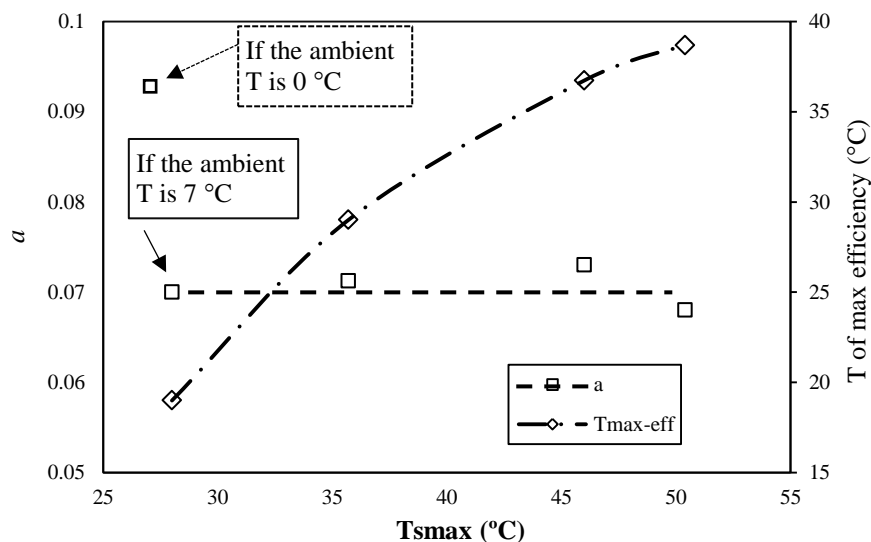
242 Where, T_s is surface temperature of solar PV, T_a is ambient temperature, R is the solar radiation, a is
 243 a constant.

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

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263 Figure 8: ' a ' value and max efficiency temperature (Tmax) under different ambient temperature

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265 If the average ambient temperature for this condition is 7 °C, the temperature difference between the
266 cooled case and uncooled case of 300 W/m² radiation is 24.1 – 7 = 17.1 °C. Then the average
267 efficiency increase per degree of temperature reduction is about (7.32% - 4.98%)/17.1 = 0.14%/ °C.
268 Also shown in Figure 7, it suggests an almost linear relation between maximum surface temperature
269 and maximum efficiency temperature.

270

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

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278 **4 Proposed Cooling System for Practical Application**

279 **4.1 System Performance**

280 Based on a typical 4 kW solar PV system installed on a general resident house in England, a cooling
281 system can be developed with the following arrangement shown in Figure 9. Basically necessary
282 cooling channel with similar structure as general radiators of central heating (but with flat surface to
283 touch the back of solar panel) can be fixed under solar panel. Cooling water is supplied by a water
284 pump which is similar as used general central heating system. Through the heat exchange between
285 the solar panel and the cooling channel, the cooling water with increased temperature can be partly
286 or totally circulated in the water tank (for shower and other house water application) and then flows
287 into the cooling tower fixed in the loft.

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

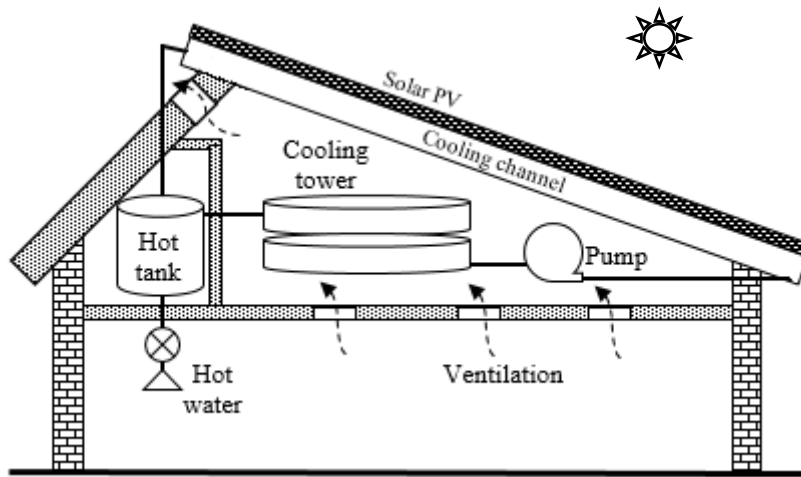


Figure 9: Proposed cooling system for solar panel of residential application

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.

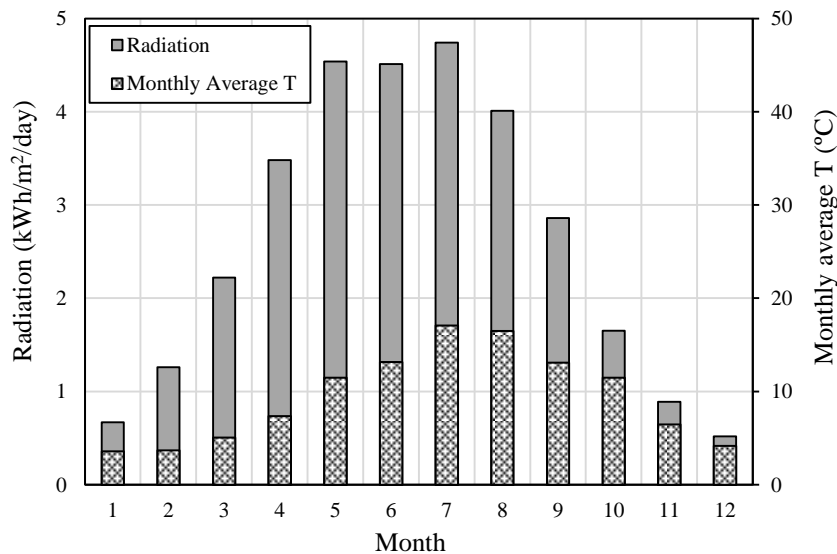


Figure 10: Average monthly solar radiation and average monthly temperature in South England

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%.

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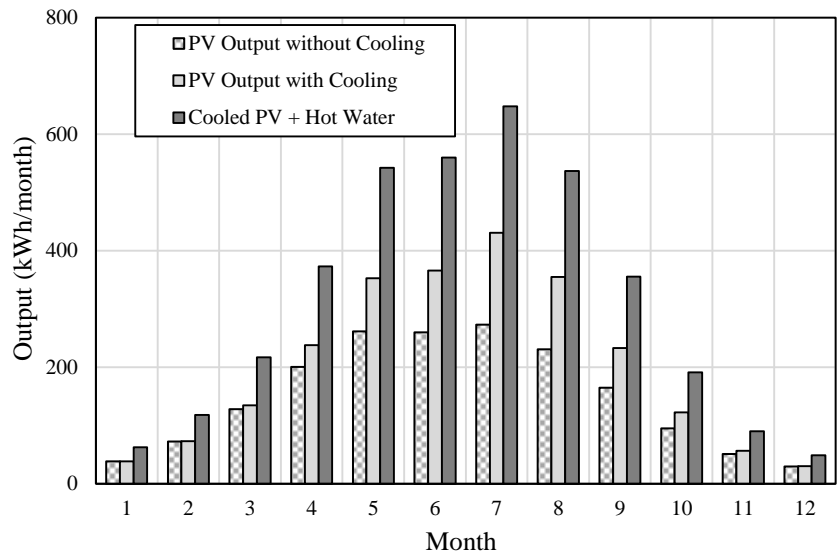


Figure 11: Monthly energy outputs of uncooled PV, cooled PV and cooled PV plus hot water

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.

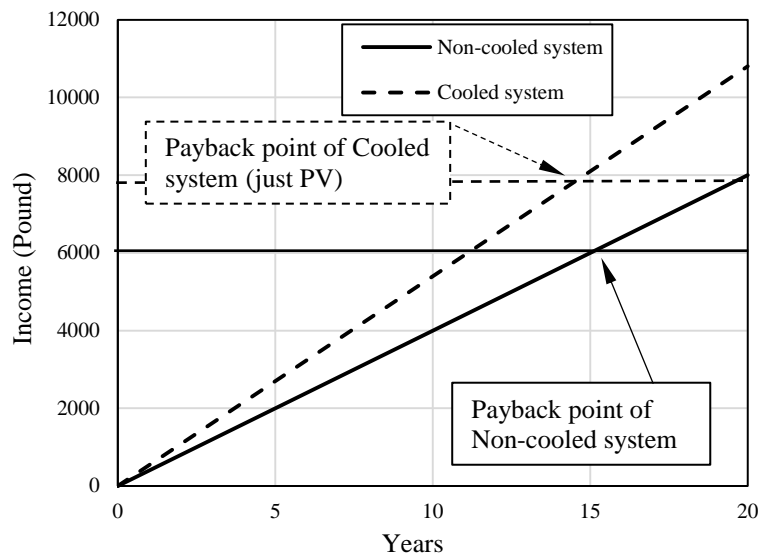
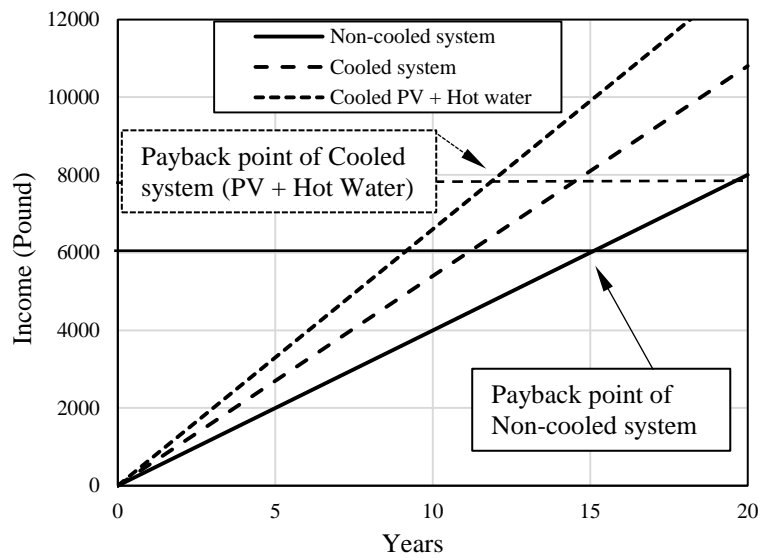


Figure 12: Possible payback time of cooled solar PV system, including hot water benefit (based on a 4 kW system)

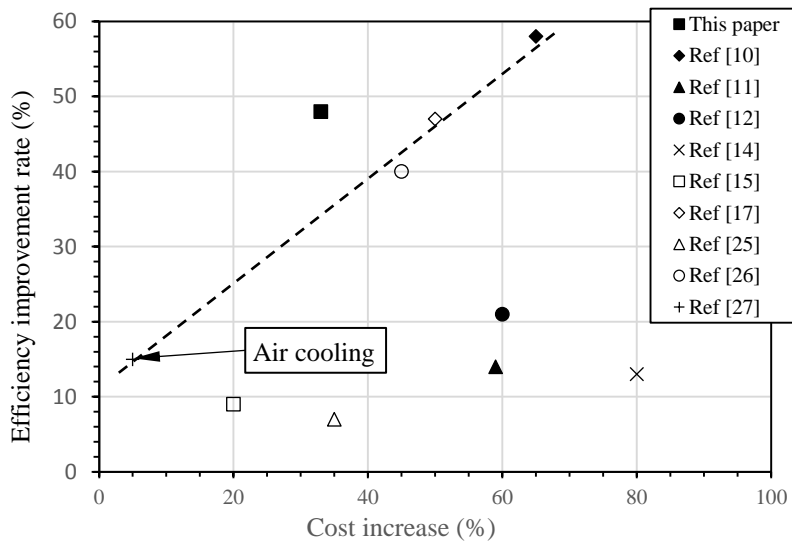
355 Considering the cooling system will increase the manufacture or purchase cost to 7900 pounds, then
 356 the payback time of purchase cost can be reduced to 14.8 years, by just considering the increase
 357 from electric output. If taking 20 years as the system life time, by the end, the cooled solar PV can
 358 make profit about 2800 pounds, compared the non-cooled solar PV system's profit of 2000 pounds.
 359

360 Currently in England, natural gas price is 30% of electricity price for residential customers. As the
 361 efficiency of general central heating boilers for producing hot water is about 75%, the energy output
 362 of per kWh hot water has 40% worth of per kWh electric output. Then if both electric output and
 363 hot water output are taken in to account, the payback time of cooled PV system purchase cost can
 364 be reduced to 12.1 years, as shown in Figure 13. For a solar PV which has 20 years of the system
 365 life time [19, 20], the cooled solar PV can make profit about 5200 pounds, compared the non-
 366 cooled solar PV system's profit of 2000 pounds. Considering the solar radiation level in England is
 367 not high, the cooled PV system should has a much better performance and much shorter payback
 368 time if it is installed in some high radiation region.
 369



381 Figure 13: Possible payback time of cooled solar PV system including hot water benefit
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383 In terms of the relationship between system performance increase and system cost, a comparison
 384 with other researchers' results is presented in Figure 14. Except [27] which used air cooling, all
 385 other cooling systems in Figure 14 are based on water cooling, though very different designs were
 386 employed by those researchers.
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390 Figure 14: Comparison with other researchers' results about the electric efficiency improvement as
 391 function of cost

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

399

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

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408 5 Conclusions

409 In this research, effects of solar PV surface temperature on output performance have been
 410 experimentally investigated under different radiation condition for exploring variation of output
 411 voltage, current, output power and efficiency. A cooled case for solar PV performance has been also
 412 performed by spreading ice on the back of solar panel. Based on those results, a cooled solar PV
 413 system has been proposed for resident application. By analysing the electric and hot water output,

414 the life cycle assessment for comparing non-cooled and cooled solar PV systems, in terms of their
415 payback time of system cost, was conducted. With those investigations, the following conclusions
416 have been derived.

417

418 • Under different radiation condition there exists an optimal surface temperature for solar PV
419 to produce the maximum efficiency. The higher the radiation is, the higher the optimal
420 surface temperature is.

421

422 • When solar panel is cooled down, the efficiency can have significant increase. The optimal
423 surface temperature for highest efficiency can have obvious increase for cooled condition,
424 compared to non-cooled condition.

425

426 • In this research with ice for providing cooling function on the back of solar PV panel, the
427 efficiency of solar PV can have an increasing rate of 47% with cooled condition.

428

429 • A cooling system has been proposed for possible system setup of residential application to
430 cool down the solar panel. Life cycle assessment suggests that the cost payback time can be
431 reduced to 12.1 years, compared to 15 years of the baseline of a similar system without
432 cooling sub-system.

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435 **Acknowledgements**

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