

# Improved Electrical Efficiency by Active Cooling of Building Integrated Photovoltaic Panels

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**Abstract:** The electrical efficiency of photovoltaic devices can be directly related to the temperature of the photovoltaic cells. The ability to actively cool building integrated photovoltaic solar panels allows their electrical efficiency to be maintained during periods of high solar radiation. Furthermore, the ability to capture and store heat from building integrated photovoltaic panels presents the opportunity for building integrated photovoltaic thermal (BIPVT) solar collectors. In this study a BIPVT solar collector was analysed and key parameters affecting its electrical efficiency were identified.

**Keywords** photovoltaics, electrical efficiency, temperature, heat transfer

## 1. INTRODUCTION

In recent times there has been growing interest in, and significant concern expressed, over environmental issues such as climate change and energy use. These concerns, combined with economic realities of rising energy costs, have begun to raise awareness of what have typically been “niche” energy technologies. In particular, the use of solar energy has been presented as a way of reducing dependence on energy derived from non-renewable sources.

Traditionally, solar energy has been divided into two distinct but separate fields of study: solar thermal, where incoming radiation is converted into heat, and photovoltaics (PV), where solar energy is converted to electricity. Solar thermal systems have long been used for applications such as water heating, space heating and power generation. Photovoltaics, although a comparatively recent development, have also been applied to a large number of electricity generating applications, including watches, calculators and large power systems such as those used at the Sydney Olympic Village.

One of the key shortcomings of photovoltaics however is their relatively low efficiency. Typically, commercially available PV modules are only able to convert 6-18% of the incident radiation falling on them to electrical energy with the remainder lost by reflection or as heat [1]. However, a small portion of the heat is “sunk” into the cells which results in a reduction in their efficiency.

Green [2] states that the short circuit current of PV cells is not strongly temperature dependent, however he does note that it tends to increase slightly due to the increased light absorption which he attributes to the temperature dependant decrease in band gap in the semiconductor materials.

Moreover, the relationship between the short circuit current ( $I_{sc}$ ) and open circuit voltage ( $V_{oc}$ ) given in Equation 1 can be reduced to an expression for the change in open circuit voltage with respect to temperature ( $T$ ), Equation 2 [2], where  $I_0$  is the diode saturation current,  $k$  is the Boltzmann constant,  $q$  is the element charge and  $\gamma$  is a parameter used to accommodate other temperature dependencies. This results in a decrease of efficiency of approximately 0.5%/°C for typical silicon based PV cells.

$$I_{SC} = I_0 \left( e^{qV_{oc}/kT} - 1 \right) \quad (1)$$

$$\frac{dV_{oc}}{dT} = - \frac{V_{g0} - V_{oc} + \gamma \left( \frac{kT}{q} \right)}{T} \quad (2)$$

In order to reduce the impact of temperature on PV cells, a cooling system can be implemented to take heat out of them. However rather than just dumping this heat to the environment, it is possible to capture and store it. As such, a number of studies in the late 1970's, and more recently, began to investigate the use of the heat generated by photovoltaics in what have become known as Photovoltaic/Thermal (PVT) solar collectors.

In addition, there has been a growing trend towards the integration of PV into the built environment, BIPV. As such this has opened up the possibility of combining PVT and BIPV to form a BIPVT system.

A BIPVT style collector is currently under development at the University of Waikato (UoW) and this study examines how some design parameters influence the electrical efficiency of the collector

## 2. BIPVT OVERVIEW

The BIPVT collector under development at (UoW) incorporates a number of novel elements. Unlike many of the PVT systems that have been developed, the BIPVT has been designed to integrate directly into standing seam or troughed sheet roofs that are commonly used in large industrial or commercial buildings.

These roofs are commonly made from aluminium or coated steel, although copper or stainless steel are sometimes used. Typically these roofing products are roll formed such that the formed profile gives the roof stiffness, strength and is weather proof. Being metallic also means that roofs are inherently good heat conductors, thus making them ideal to act as a heat sink for photovoltaic cells.

As such during the manufacturing process in addition to the normal roof profile, passageways are added to the trough to allow a cooling medium to be circulated, thus cooling the PV cells, as shown in Figure 1.

In essence, a PV module is laminated into the "normal" trough of the roof, thus covering the additional trough and forming an enclosed tube. The system has been design such that these tubes have an inlet and outlet at opposite ends of the roof panel to allow them to be connected to a manifold system. In addition the design of the BIPVT allows a glass or polymer glazing to be added to the collector to improve its thermal efficiency.

Now, as the PV cells are exposed to sunlight they absorb radiation and generate electricity. However, silicon PV cells tend to convert short wavelength radiation to electricity better, while the longer wavelengths result in heating of the module.

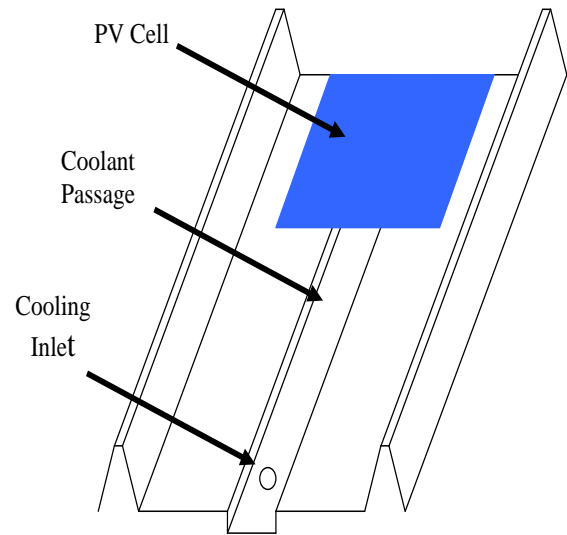


Figure 1: BIPVT Collector

Therefore the presence of the cooling medium in the BIPVT tubes enhances heat transfer from the cells. In this manner, the heat transfer to the fluid reduces the temperature of the PV cells, thereby increasing their efficiency under high temperature and radiation conditions while concurrently capturing the thermal energy.

## 3. ANALYSIS

In order to analyse the electrical efficiency of the BIPVT it was decided to use a 1 dimensional steady state model. In this model the temperature of the PV cells could be calculated using equations typically applied to the determination of the efficiency of a flat plate thermal collector. This is based on a modified form of the Hottel-Whillier-Bliss equations [3].

Under these conditions the heat transfer from the BIPVT can be calculated using Equation 3.

$$Q = AF_R [(\tau\alpha)_{PV} \cdot G - U_{loss} (T_i - T_a)] \quad (3)$$

In this equation the heat transfer from the BIPVT ( $Q$ ) is given as a function of the collector area ( $A$ ), the heat removal efficiency factor ( $F_R$ ), the transmittance-absorbance product of the PV module ( $(\tau\alpha)_{PV}$ ), the solar radiation ( $G$ ), the collector heat loss coefficient ( $U_{loss}$ ) and the temperature difference between the cooling fluids inlet temperature ( $T_i$ ) and the ambient temperature ( $T_a$ ).

By calculating the heat transfer from the panel we are able to determine the mean temperature ( $T_{pm}$ ) of the BIPVT using Equation 4.

$$T_{pm} = T_i + \frac{Q/A}{F_R U_{loss}} (1 - F_R) \quad (4)$$

Where ( $F_R$ ) in Equation 4, is a function that accounts for the cooling medium flow rate in the collector ( $m$ ) and the specific heat of the collector cooling medium ( $C_p$ ) as shown in Equation 5.

$$F_R = \frac{mC_p}{AU_{loss}} \left[ 1 - e^{-\frac{AU_{loss}F'}{mC_p}} \right] \quad (5)$$

To obtain the heat removal efficiency factor however, it is necessary to calculate a value for the corrected fin efficiency ( $F'$ ) that is used in Equation 5. This is done by first calculating the fin efficiency ( $F$ ) as shown in Equation 6.

$$F = \frac{\tanh\left(M \frac{W-d}{2}\right)}{\left(M \frac{W-d}{2}\right)} \quad (6)$$

This equation determines the ability of the finned area between the adjacent tubes to remove the heat from the PV cells by taking into account the influence of the tube spacing ( $W$ ) and the tube hydraulic diameter ( $d$ ).

The coefficient ( $M$ ) is a term that accounts for the thermal resistance of the PV module and is represented by Equation 7; where  $K_{abs}$  and  $K_{pv}$  are the thermal conductivity of the absorber and the photovoltaic cells and  $L_{abs}$  and  $L_{pv}$  are their respective thicknesses.

$$M = \sqrt{\frac{U_{loss}}{K_{abs}L_{abs} + K_{pv}L_{pv}}} \quad (7)$$

This allows, the corrected fin efficiency ( $F'$ ) used in Equation 4 to be calculated using Equation 8.

$$F' = \frac{1}{U_{loss} \left[ \frac{1}{U_{loss}(d + (W-d)F)} + \frac{1}{Wh_{pVA}} + \frac{1}{\pi dh_{fluid}} \right]} \quad (8)$$

In Equation 8, the overall heat loss coefficient of the BIPVT ( $U_{loss}$ ) is merely the summation of the heat transfer coefficients at edge ( $U_{edge}$ ), top ( $U_{top}$ ) and rear surfaces of the BIPVT panel. For a BIPVT that is insulated the edge losses are given by Equation 9, where  $p$  is the collector perimeter,  $t$  is the absorber thickness,  $K_{edge}$ , the thermal conductivity of the edge insulation,  $L_{edge}$  the edge length and  $A_{collector}$  is the collectors area. Furthermore, the heat transfer coefficient of the pv-absorber interface is given by  $h_{pVA}$  and  $h_{fluid}$  is the heat transfer coefficient for the water in the cooling passage.

$$U_{edge} = \frac{K_{edge}pt}{L_{edge}A_{collector}} \quad (9)$$

Now if the BIPVT is glazed to improve its thermal efficiency, the top loss coefficient, due to reflections and wind, can be calculated using an empirical equation (Equation 10) given by [2].

$$U_{top} = \left\{ \frac{N}{\frac{c}{T_{pm}} \left( \frac{T_{pm} - T_a}{N - f} \right)^e + \frac{1}{h_w}} \right\}^{-1} + \frac{\sigma(T_{pm} + T_a)(T_{pm}^2 + T_a^2)}{(\varepsilon_p + 0.00591Nh_w)^{-1} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \quad (10)$$

Where  $N$  is the number of covers or glazing layers,  $\varepsilon_p$  and  $\varepsilon_g$  are the emissivities of the roofing material and the glazing and  $c$ ,  $e$  and  $f$  are given by:

$$c = (520 - 0.000051\beta^2)$$

where  $\beta$  is the BIPVT mounting angle

$$e = 0.430 \left( 1 - \frac{100}{T_{pm}} \right)$$

$$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$$

and the heat transfer coefficient for the top surface due to the wind ( $h_w$ ), as a function wind speed ( $v$ ), is given by an empirical expression from [2].

$$h_w = 2.8 + 3v \quad (11)$$

Alternatively for an unglazed collector solely the heat transfer coefficient due to the wind ( $h_w$ ) can be used (Equation 11).

Now, because the collector would be integrated into the roof of a building, the calculation of the heat loss through the rear surface of the BIPVT is less straight forward. Typically, when using the equations above in the analysis of a solar thermal collector, the rear surface heat loss coefficient is given by the inverse of the insulation's R-value (ie.  $K_b/L_b$ ). However, in New Zealand it is common for houses to be insulated at ceiling rather than roof level and as such the correlation for free convection in a triangular enclosure developed by Ridouane and Campo [4] was used to calculate the Nusselt Number ( $Nu$ ) at the rear surface, as shown in Equation 12, and subsequently the heat transfer coefficient.

$$Nu = 0.286A^{-0.286}Gr^{1/4} \quad (12)$$

Where  $A$  is the ratio of the vertical height to the horizontal width of the attic and the Grashof number ( $Gr$ ) was calculated based on the mean temperature of the BIPVT..

From these equations it is possible to calculate the heat removed from the BIPVT and as such, the mean temperature of the BIPVT ( $T_{pm}$ ). Finally, the electrical efficiency can be calculated based on the difference between the mean temperature of the BIPVT and the Nominal Operating Cell Temperature (NOCT), which is typically taken as 298K.

For this study it was assumed that the cell had an efficiency of 15% (being within the typical range of 10 to 20%) at NOCT, and that the temperature dependent efficiency could be represented by Equation 13; similar to that used by Bergene and Lovvik [5].

$$\eta = 0.15(1 - 0.0041(T_{pm} - NOCT)) \quad (13)$$

Having established the methodology for calculating the electrical efficiency of a BIPVT, some typical design values were chosen, as shown in Table 1, in order to examine the performance of the BIPVT under a range of conditions.

TABLE 1: BIPVT physical characteristics

Parameter	Symbol	Value	Unit
Number of covers	$N$	1	
Ambient Temperature	$T_a$	293	K
Emittance of plate	$\varepsilon_p$	0.95	
Emittance of cover	$\varepsilon_c$	0.88	
Number of tubes	$n$	66	
System flow rate	$m$	2	l/s
Collector Area	$A_{collector}$	100	m <sup>2</sup>
PV Trans/Abs	$\tau\alpha_{pv}$	0.74	
Absorber thickness	$t$	0.5	mm
PV thickness	$L_{pv}$	0.4	mm
PV conductivity	$K_{pv}$	84	W/mK
Tube Hydraulic Diameter	$d$	9.7	mm
Tube Spacing	$W$	0.1	m
Heat transfer coefficient from cell to absorber	$h_{pVA}$	45	W/m <sup>2</sup> K
Insulation Conductivity	$K$	0.045	W/mK
Edge Insulation Thickness	$L_{edge}$	0.025	m
Absorber Conductivity	$K_{abs}$	50	W/mK

## 4. RESULTS

After examining the design properties given in Table 1, it was apparent that there were a number of variables that could be altered to improve the electrical efficiency of the BIPVT. Given that varying these parameters experimentally would be a long and costly operation it was decided to examine their effect through a numerical experiment based on the theoretical thermal model derived in the analysis.

Perhaps the most obvious of these is the flow rate of the cooling medium. By increasing the flow, the Reynolds number also increases, thus improving the rate of the heat transfer to the coolant and as a consequence the mean temperature of the cells is lower, meaning the efficiency is higher. In Figure 2, it can be seen that this does indeed result in a small improvement to the electrical efficiency.

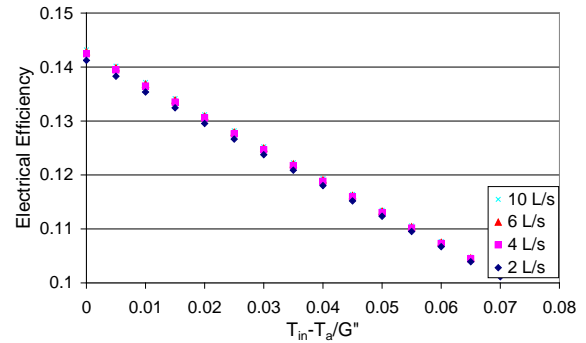


Figure 2: Electrical efficiency for varying coolant flow rate

However, an increase in the coolant flow-rate would result in a greater amount of energy being used by a circulating pump thus possibly offsetting the gains in efficiency. An alternative to increasing the coolant flow rate is to change the roof material. Electronic components typically use copper and aluminium as heat sink materials and so these were compared to the steel system presented in Table 1.

In Figure 3 it can be seen that there is a small increase in the electrical efficiency by using copper or aluminium.

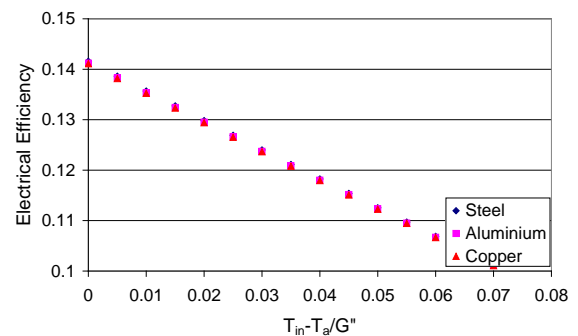


Figure 3: Electrical efficiency for varying roof materials

An alternative to modifying the roofing material or coolant flow rate is to modify the width of the cooling passage relative to the trough. This can be done in such a way that the hydraulic diameter remains constant but the tube spacing decreases. In Figure 4 it can be seen that by making the cooling trough wider, the efficiency increases. This is because the cells are being cooled more effectively; essentially, the entire back surface area of the PV cell would be in contact with the cooling channel. This means less heat needs to be transferred by conduction.

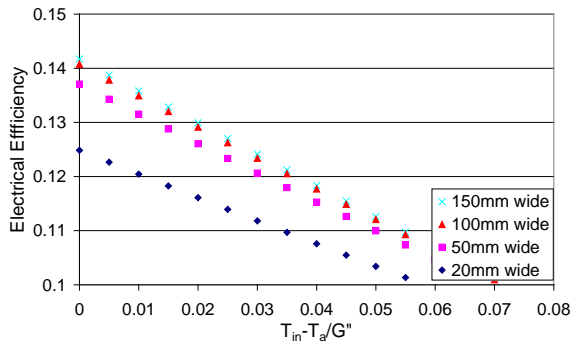


Figure 4: Electrical efficiency for varying tube widths

The use of thermally conductive adhesives is commonplace in the assembly of heat sinks to electrical components. In Table 1 a value of 45 W/mK was used, as reported by [6], however this could be improved by the use of thermally conductive adhesives to join the cells to the roof material. In Figure 5 it can be seen that by increasing the thermal conductivity between the cells and the roof the electrical efficiency can be improved quite dramatically.

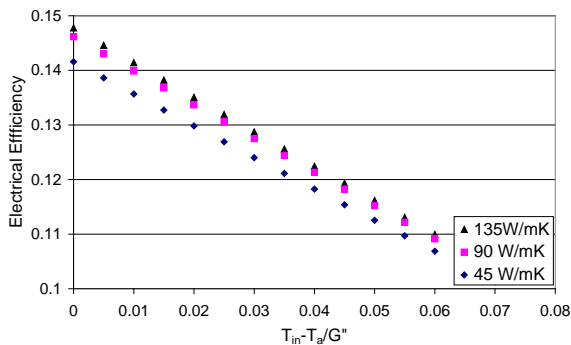


Figure 5: Electrical efficiency for varying PV thermal conductivities

Furthermore, by altering the inclination of PV panels it is possible to bias their performance to obtain greater electrical output. Typically this is at an angle approximately equal to the local latitude. However, in Figure 6 it can be seen that mounting the BIPVT at a lower angle, could actually improve its electrical efficiency.

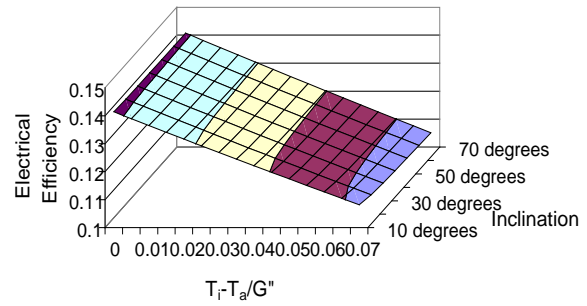


Figure 6: Electrical efficiency at varying roof inclinations

Finally, the preceding analysis has examined the BIPVT on the basis of it having a glazing layer to improve its thermal efficiency; however this layer inhibits the electrical efficiency of the BIPVT by diverting some of the electrical output to heating. By removing the glazing the electrical efficiency can be improved. In Figure 7 it can be seen that the efficiency becomes strongly dependent on wind speed. Conversely, the removal of the glazing means that the thermal efficiency is reduced due to the increase in the top heat transfer coefficient.

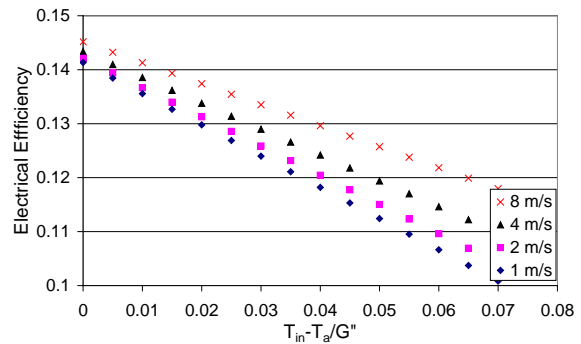


Figure 7: Electrical efficiency for unglazed BIPVT

## 5. CONCLUSIONS

From the analysis of the UoW BIPVT, it was found that there were a number of parameters in the design that could be changed to improve the electrical efficiency.

The parameter with the most significant influence was found to be the cover or glazing. By removing this it is possible to significantly improve the electrical efficiency. However, as noted the thermal efficiency would be reduced by doing this.

More easily, the electrical efficiency can be improved by widening the cooling tubes in relation to their spacing. This would also improve the thermal efficiency.

Similarly, the use of thermally conductive adhesives to attach the PV cells to the roof would improve the electrical efficiency.

However, changing the coolant flow rate through the BIPVT or the material from which it is constructed would have very little influence over the electrical efficiency.

Based on these findings, the use of BIPVT as a future building energy system appears promising. Further, the ability to capture the heat from the PV cells means that a greater portion of the incident radiation is being harnessed rather than lost, as it would be in a typical PV power system.

Finally, the influence of the mounting angle on the PV performance was shown to have an influence on the electrical efficiency when integrated in a roof style situation. As such, there is a need to examine this further to ensure that changing the mounting angle does not unnecessarily reduce the thermal efficiency of the BIPVT system.

## 6. REFERENCES

- [1] M Bazilian, H Kamalanathan and D Prasad, "Thermographic analysis of a building integrated photovoltaic system", *Renewable Energy*, v 26, n 3, pp. 449-461, July, 2002
- [2] M Green, *Solar Cells: Operating Principles, Technology and System Applications*, Kensington, Australia, The University of New South Wales, 1998
- [3] J Duffie and W Beckman, *Solar engineering of thermal processes*, Hoboken, NJ, Wiley, 2006
- [4] E Ridouane and A Campo, "Experimental-based correlations for the characterization of free convection of air inside isosceles triangular cavities with variable apex angles", *Experimental Heat Transfer*, v 18, n 2, pp. 81-86, April-June, 2005
- [5] T Bergene and M Lovvik, "Model calculations on a flat-plate solar heat collector with integrated solar cells", *Solar Energy*, v 55, n 6, pp. 453-462, December, 1995
- [6] D de Vries, *Design of a photovoltaic/thermal combi-panel*, Eindhoven University, PhD Thesis