EXPERIMENTAL PERFORMANCE OF WATER COOLED BUILDING INTEGRATED PHOTOVOLTAIC/THERMAL SOLAR COLLECTORS

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ABSTRACT

The idea of integrating water cooled photovoltaic/thermal collectors into building structures (BIPVT collectors) to provide electrical and heat energy is an area that has received only limited attention. BIPVT collectors are particularly attractive, as the integration of a single photovoltaic and thermal collector into the long-run roofing structure of a building could provide greater opportunity for the use of renewable solar energy technologies. In this study, the thermal efficiency of a novel low cost water cooled building integrated photovoltaic/thermal (BIPVT) solar collector was experimentally measured. The results show that despite being made of a typical roofing material, the thermal efficiency is not unreasonably affected. Furthermore, it is shown that the measured efficiency is similar to that predicted by the Hottel-Whillier equations.

INTRODUCTION

Traditionally, solar energy research has been divided into two separate but distinct fields of study: solar thermal and photovoltaics (PV). The two fields have, for the majority of their lives, remained as separate entities. In the late 1970’s however, a number of studies began to investigate the feasibility of incorporating photovoltaic and solar thermal into a single device, commonly referred to as Photovoltaic/Thermal (PVT) solar collectors. It was realised that there were two main benefits to PVT style solar collectors: firstly, the efficiency of PV cells can be increased by actively cooling them using the solar thermal system and secondly, by incorporating both systems into a single unit, a larger portion of the incident radiation could be captured. The realisation of these benefits has lead to a wide range of concepts being developed to incorporate photovoltaics and solar thermal systems into a single device. These can be loosely defined as PVT water or air heaters.

In its simplest form a PVT water heater could be fabricated to resemble a “standard” solar thermal collector with a PV module taking the place of the collector plate, or alternatively as PV cells laminated to the finned absorber of a solar water heater. Florschuetz (1979) provided perhaps the earliest theoretical analysis of a PVT solar collector through the use of a modified version of the Hottel-Whillier model, developed for predicting the performance of solar thermal collectors. However, an early study by Andrews (1981) showed that PVT collectors were, at the time, marginally suitable for low temperature heating operations such as pool heating.

Although there have been numerous other studies into water cooled PVT systems, a significant portion of studies have been aimed at producing “standalone” collectors similar to those already used for water heating. The downside to this is that aesthetics may not receive its necessary attention. Bazilian et. al. (2001), note that the integration of PV systems into the built environment can achieve “a cohesive design, construction and energy solution”. Furthermore, by capturing the “waste” heat from a building integrated photovoltaic (BIPV) system it is possible to create a building integrated PVT (BIPVT) that is architecturally acceptable. In essence, BIPVT is the use of PVT as building elements such as roofing or façade.

Unlike standalone collectors, building integrated PVT and more widely building integrated solar collectors have received far less attention. To date the majority of studies on BIPVT style collectors have examined the use of air cooling of PV panels. In this regard, studies such as those of Mosfegh and Sandberg (1998) and Brinkworth (2006) have concentrated on using natural and forced convection of air to cool the rear surface BIPV panels.

The use of water cooled solar collectors as building elements has largely been ignored. Although Chow et.al. (2007) examined a PVT system for integration into building walls in Hong Kong these systems were essentially standalone PVT panels integrated *onto* a building rather than *into* the building. Probst and Roecker (2007) note that although this method of integrating solar collectors is considered to be “acceptable” to architects, future building integrated solar collectors “should be conceived as part of a construction system”.

With this in mind, Anderson et. al. (2007) proposed a method for integrating water cooled PVT collectors into long-run sheet metal roofing, as a means of achieving an aesthetically pleasing BIPVT collector.

BIPVT Description

The system examined in this study is unique in a number of ways. Unlike many of the systems that have been proposed, this system is directly integrated into the roof of a building, in this case a standing seam or troughed sheet roof. During the roof manufacturing process in addition to the normal troughed shape, passageways are added to the trough for the thermal cooling medium to travel through. Subsequently a cover sheet having PV cells laminated to its surface is bonded into the trough. The passageways formed in the trough are enclosed by the cover; thus forming a tube to which heat can be transferred as shown in Figure 1. As the PV cells are exposed to sunlight they absorb radiation and generate electricity, however because silicon PV cells tend to convert only short wavelength radiation to electricity, the longer wavelengths result in heating of the laminate. As such, in the BIPVT collector there is heat transfer from the cells through the laminate to the fluid passing underneath. The heating of the fluid reduces the temperature of the PV cells, thereby increasing their efficiency under high temperature and radiation conditions.

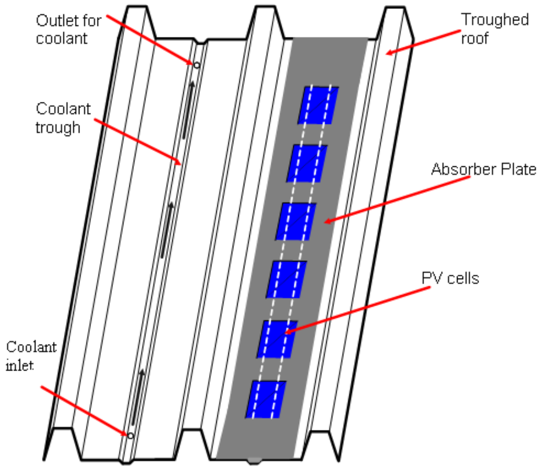

Figure 1: BIPVT Collector

BIPVT Fabrication

Before any testing could be conducted, it was necessary to fabricate a prototype BIPVT collector. Although the fabrication of finned copper tube style collectors is well understood, the unconventional design of the BIPVT and some of the desired design goals, in particular that it be made from pre-coated steel, presented a number of challenges. This is mainly due to the fact that the material is galvanised and dip coated in black paint and so could not be easily welded without removing both these coatings. In order to circumvent this issue, the top absorber sheet to which the PV cells were to be laminated, was bonded to the supporting troughed roof sheet with a high temperature Silicone adhesive and sealant.

Furthermore, due to the batch production nature of the prototype, the roof profile was folded using a CNC folder, holes were drilled to allow fluid into the underside of the coolant trough, nipples were soldered to the rear surface to allow a manifold to be attached, the ends were sealed with Silicone and the top absorber sheet was bonded into place with the same. Once sealed and watertight, PV cells were laminated to the top absorber sheet and encapsulated in a poly-vinyl resin. Finally, the ends of the roof trough profile were enclosed and a removable low-iron-glass cover was placed over the collector to prevent convection losses.

However, due to the practicalities associated with installing the BIPVT into an actual building roof, the rear surface of the collector panel was instead insulated with 100mm of mineral fibre insulation thereby forming a standalone collector but with a roof profile.

EXPERIMENTAL SETUP

Although there are a number of methods that can be used such to determine the thermal efficiency of solar water heaters, there is still no agreed standard method for the testing of PVT collectors. As such, for this study it was decided to use a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1-1999, as shown in Figure 2, with no electrical load being placed on the collector.

In order to test the prototype collector, an unimpeded north facing test location was found on the University of Waikato library roof. To quantify the performance of the collector the global incident solar radiation was measured using a calibrated WMO First Class pyranometer mounted inline with the collector, at an angle equal to the local latitude (37 degrees).

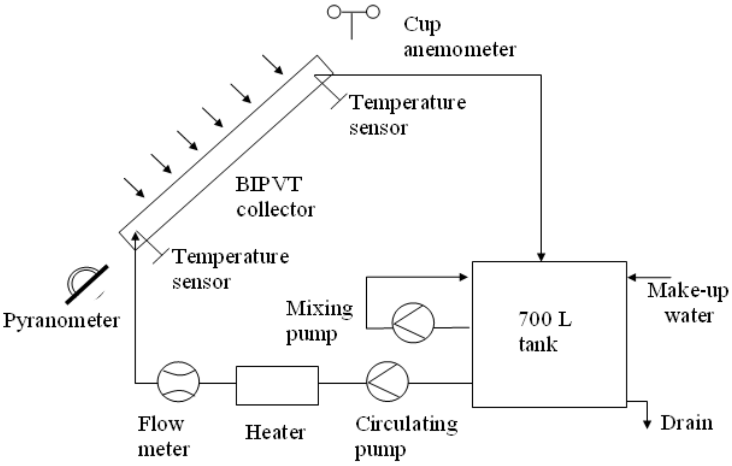

Figure 2: BIPVT collector test system

T-type thermocouples, calibrated to ±0.3K, were used to measure the inlet (T_i) and outlet temperatures to the collector, as well as the local ambient air temperature (T_a). Furthermore, a cup anemometer was used to monitor the wind speed in the test area and was mounted adjacent to the test stand for the collector. Finally, the flow rate through the collector was set at a constant rate and monitored throughout the testing periods by measuring the time taken for a known mass of coolant to pass through the collector.

In addition to the measurement apparatus, an instantaneous electric water heater with an inbuilt temperature controller was mounted on the inlet side of the collector so as to provide a controllable inlet water temperature. The outlet from the collector was returned to a 700 litre water tank where it was well mixed to ensure that large instantaneous temperature variations were not encountered by the heater.

Finally, the design parameters of the prototype collector tested are shown in Table 1. Although the prototype is far from an optimum design, it was fabricated in such a way as to ease manufacture and, more importantly, demonstrate the concept. In particular the prototype used a much narrower cooling trough than would be considered ideal, and therefore had a far from optimal tube diameter to spacing ratio. In addition, the encapsulation method was significantly different from that used by previous researchers, with the PV cells covered by a very fine film of resin. This method of encapsulation would not however be suitable for a commercial BIPVT, due to the poor longevity of the resin under high temperature operation.

Table 1: BIPVT prototype physical characteristics

Parameter	Symbol	Value	Unit
Number of covers	N	1 or 0	
Emittance of plate	ε_p	0.95	
Emittance of cover	ε_c	0.88	
Number of tubes	n	2	
Collector Length	L	1.96	m

Collector Breadth	b	0.5	m
Collector Area	$A_{collector}$	0.98	m^2
Absorber thickness	t	0.5	mm
PV thickness	L_{PV}	0.4	mm
PV conductivity (Krauter, 2006)	k_{pv}	130	W/mK
Tube Hydraulic Diameter	d_h	8	mm
Tube Spacing	W	0.23	m
Ratio of Tube width to spacing	d/W	0.087	
Heat transfer coefficient from cell to absorber (de Vries, 1998)	h_{PVA}	45	W/m^2K
Insulation Conductivity	k	0.045	W/mK
Back Insulation Thickness	L_b	0.1	m
Edge Insulation Thickness	L_{edge}	0.025	m
Absorber Conductivity	k_{abs}	50	W/mK
Packing Factor (Area covered by PV "module")	S	0.4 (or 40%)	
Mounting Angle	β	37	Degrees

EXPERIMENTAL METHOD AND ANALYSIS

As has been mentioned, the testing of the prototype BIVT was conducted in accordance with AS/NZS 2535.1-1999. This standard specifies a test method to determine the thermal performance of solar collectors. A prerequisite to accurately determining the performance of the collector is to conduct a number of outdoor tests under a range of ambient conditions. In this case both a glazed and unglazed BIPVT collector were tested, and benchmarked against test results from a commercially available flat plate collector, and the efficiency of a high performance glazed flat plate collector.

When analysing the collectors, the instantaneous collector efficiency can be reached directly from the experimental results as it is defined simply as the ratio of heat transfer in the collector to the product of the collector area and the global solar irradiance.

However, further analysis of the raw data is needed to determine the efficiency of the BIPVT solar collector. Furthermore to accurately determine the efficiency of the collector a number of readings were taken when the collector was operating under steady state conditions. As such, the thermal efficiency of the BIPVT solar collector can be represented by a first order equation as shown in Eqn. 1.

$$\eta_A = \eta_{0A} - a_1\left(\frac{T_i - T_a}{G''}\right) \quad (1)$$

EXPERIMENTAL RESULTS

From the experimental data collected during the testing it was possible to derive the performance of the both a glazed and unglazed BIPVT collector using a linear least squares regression analysis. The experimental data yields two equations that describe the glazed and unglazed collector efficiencies respectively, as shown in Eqn 2 and 3

$$\eta = 0.6 - 5.55\frac{T_i - T_a}{G''} \quad (2)$$

$$\eta = 0.36 - 9.22\frac{T_i - T_a}{G''} \quad (3)$$

Although this is a common way of presenting the efficiency of the collector it can be better understood from an inspection of Figures 3 and 4.

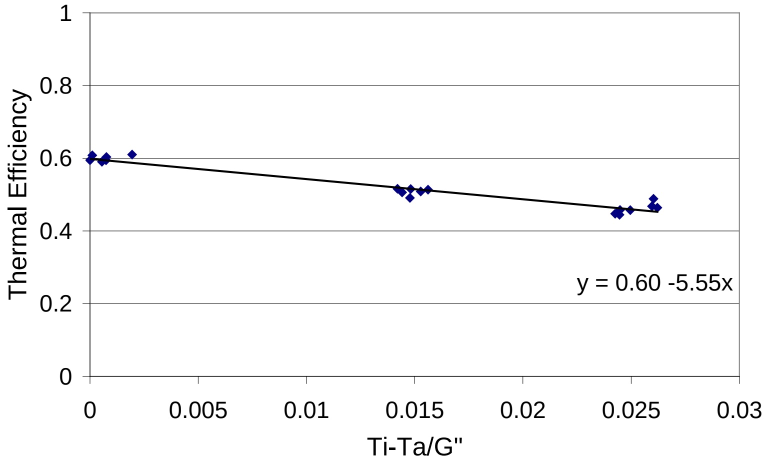

Figure 3: Thermal efficiency of glazed BIPVT collector

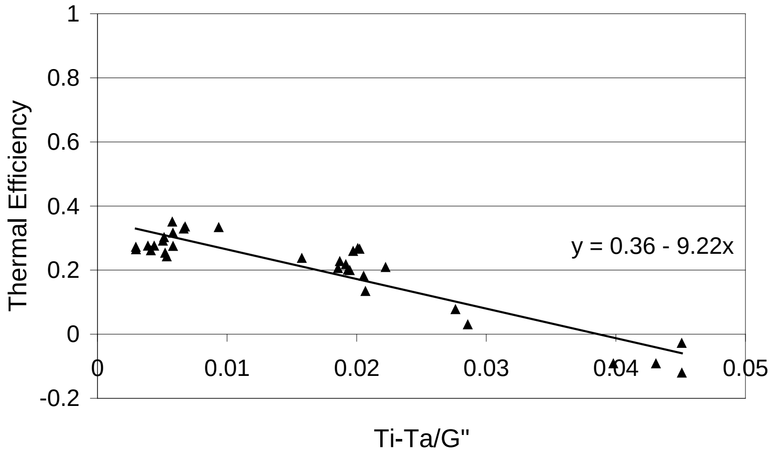

Figure 4: Thermal efficiency of prototype unglazed BIPVT collector

From the graphs of the prototype collector efficiency it can be seen that as the difference in temperature between the collector inlet and the ambient increases, at constant radiation intensity, that there is a decrease in collector efficiency due to increased thermal losses. Moreover, the gradient of the curves tells us the heat loss from the collector, in this case we can clearly see that the unglazed collector has a higher heat loss. In particular, it should be pointed out that there is significantly more scatter of the unglazed data. This is due to the increased significance of wind induced heat loss. Where a glazed collector has a pocket of air trapped between the cover and the collector plate, this is not the case in an unglazed collector and therefore they are prone to higher heat loss.

Furthermore, the point at which the curve intersects the y-axis is commonly referred to as the optical efficiency and in this case is lower for the unglazed collector. This is the result of the collectors low geometric fin efficiency in combination with high radiative losses from the collector to the "sky" (due to the high emissivity of the collector) and convective heat losses both by natural convection and wind induced forced convection.

When we compare the performance of the prototype BIPVT collectors with that of a commercially available glazed flat-plate collector, which was also tested, we find that there is not a significant difference in the heat loss, or slope, of the efficiency curves, as shown in Figure 5. However, there is a noticeable difference in the optical efficiency of the panels; for example, the tested glazed flat plate was closer to 65%. If we compare this to a high efficiency glazed flat plate collector these typically have an optical efficiency of approximately 80%. The reason for the low optical efficiency of the tested glazed flat plate was that it used a high-iron glass cover. The use of this type of cover tends to reduce the transmission of longer wavelength radiation. The glazed BIPVT however used a low iron cover and so was almost comparable with the tested flat plate collector. However, because the PV cells tend to reflect a large portion of the solar spectrum, the BIPVT optical efficiency is marginally lower. Furthermore, the influence of both the heat loss and optical efficiency are highlighted when considering the relative performance of the unglazed BIPVT. In comparison to the other collectors, there is significantly higher heat loss from the unglazed collector as well as a lower optical efficiency.

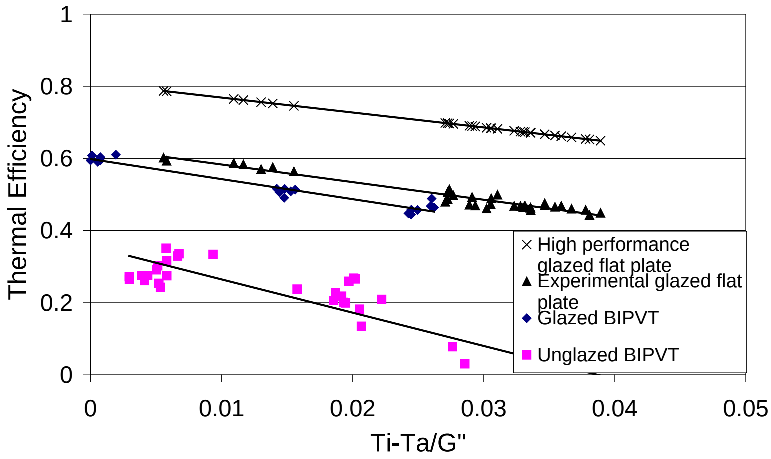

Figure 5: Comparative efficiency of glazed flat plate and BIPVT collectors

CHARACTERISING THE OPTICAL EFFICIENCY OF BIPVT PANELS

When comparing the efficiency of the BIPVT and glazed flat plate solar collectors, it was noted that there was a difference in the optical efficiencies. If we intend to improve the performance of the BIPVT, it is logical that we should be able to quantify the parameters that affect its performance. From a theoretical perspective the thermal efficiency of the BIPVT is represented by a relationship between the collectors heat removal factor (F_r), the collector heat loss coefficient (U_L), the inlet (T_i) and ambient temperatures (T_a), solar radiation (G'') and the collector transmittance-absorptance product ($\tau\alpha$) as shown in Eqn. 4.

$$\eta = F_r(\tau\alpha) - F_r U_L \left(\frac{T_t - T_a}{G''} \right) \quad (4)$$

Of these parameters, the transmittance-absorptance product is the only one that is based solely on the physical properties of the collector materials. The absorptance provides a measurement of the optical properties of the radiation absorbing surface, in this case either the PV cells or the black steel roof, while the transmission component measures the portion of the radiation transmitted by any glazing layer. Therefore in order to understand the optical characteristics of the BIPVT it was decided to determine the absorptance properties over the solar radiation spectrum.

To determine the absorption of the BIPVT, the reflectance of a resin encapsulated PV cell, as used on the prototype collector, and a sample of the black coated steel was measured at Industrial Research Limited (Wellington, NZ) using a spectrophotometer and a 6° integrating sphere. The diffuse reflectance was measured at 20 nm wavelength intervals for radiation in the range 300 nm to 2500 nm.

From the measurements of the reflectance shown in Figure 6 we can see that the black painted steel roofing material has relatively constant reflectance characteristics across the measured wavelengths of the Air Mass 1.5 (AM1.5) solar spectrum shown. The encapsulated PV cell however is far more sensitive to wavelength; in particular it absorbs a significantly larger portion of the shorter rather than longer wavelength radiation, this is due to the spectral characteristics of the silicon, the PV rear surface reflector and the anti-reflective coating on the cell.

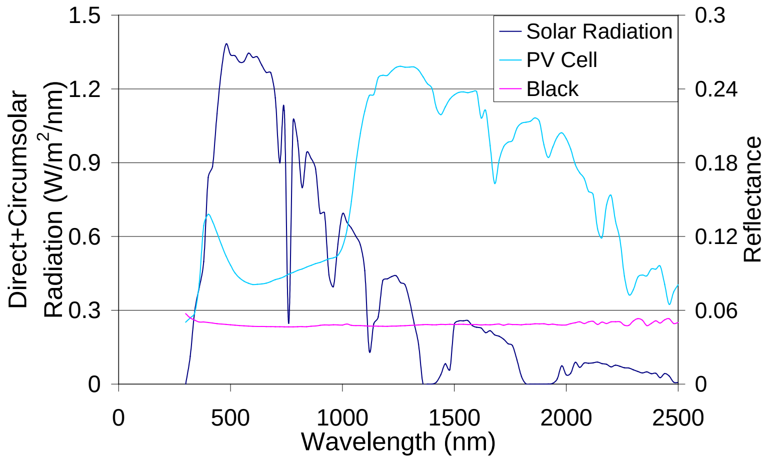

Figure 6: AM 1.5 spectrum and reflectance from PV cells and black coated steel

Now, if we integrate the absorptance of the PV cell and the black coated steel samples over the tested wavelength of the AM1.5 solar spectrum, we find that they have an absorptance of 0.875 and 0.952 respectively, or the "transmittance-absorptance" product for an unglazed BIPVT collector. However, to determine the transmittance-absoptance product for a glazed collector however we need to substitute the measured spectral absorption characteristics and the low iron glass transmittance characteristics of Dietz (1954) into Eqn. 5.

$$\tau\alpha = \frac{\int_{\lambda_1}^{\lambda_2} \tau_\lambda \alpha_\lambda I_{\lambda,i} d\lambda}{\int_{\lambda_1}^{\lambda_2} I_{\lambda,i} d\lambda} \quad (5)$$

By integrating these values over the AM1.5 spectrum we find that the transmittance absorptance product of the black steel surface and the PV cell in a glazed BIPVT collector are 0.871 and 0.801 respectively.

THEORETICAL PERFORMANCE

If we wish to analyse and improve the thermal and electrical performance of the BIPVT it is possible use a 1-dimensional steady state thermal model. Therefore a steady state model was developed to examine the performance of the BIPVT collectors. In this model it was assumed that the collector could be represented as a flat plate thermal collector. Hence, a modified from of the Hottel-Whillier-Bliss equations presented by Duffie and Beckman (2006) were used, as suggested by Florshuetz (1979).

Despite being a one-dimensional steady state model we see, in Figure 7, quite good correlation between the predicted thermal efficiencies for both the unglazed and glazed BIPVT and that from the experimental testing. This suggests that the use of this model is suitable for further optimising the design of future BIPVT collectors. In particular it can be seen that although the measured transmittance-absorptance products were relatively high, the optical efficiency is low, thus suggesting that the optical efficiency is being dominated by the collectors heat removal factor (F_r). As such this is an area that should be addressed in the future.

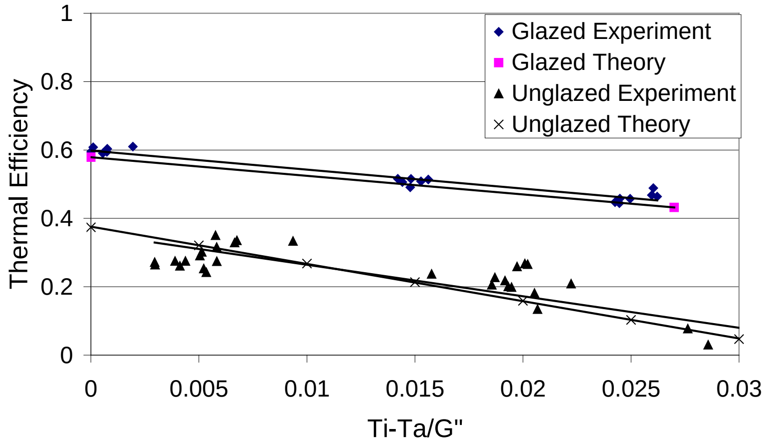

Figure 7: Measured and theoretically calculated thermal efficiencies of BIPVT

CONCLUSION

The idea of integrating water cooled photovoltaic/thermal collectors into building structures (BIPVT collectors) is an area that has received only limited attention. In this study, the thermal efficiency of a novel low cost water cooled building integrated photovoltaic/thermal (BIPVT) solar collector was experimentally measured. The results show that despite being made of a typical roofing material, the thermal efficiency is not unreasonably affected. Furthermore, it was shown that the measured efficiency is similar to that predicted by the Hottel-Whillier equations. Based on this finding, and the presented data, there is potential for the collector to be optimised using this model.

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BRIEF BIOGRAPHY OF PRESENTER

Tim Anderson studied Mechanical Engineering as an undergraduate and postgraduate research student at the University of New South Wales. He is currently completing his PhD at The University of Waikato for a thesis entitled "Thermal Aspects of Building Integrated Photovoltaic/Thermal Solar Collectors".