Development of a Low Cost Photovoltaic/Thermal Solar Concentrator for Building Integration (BIPVTC)

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ABSTRACT

The idea of concentrating solar energy to increase the output of photovoltaic and solar thermal collectors is an area that has received significant attention. However, the use of solar concentrators that form part of a building's fabric is an area that has received little attention to date. In this study, the design of a novel building integrated photovoltaic/thermal solar concentrator (BIPVTC) is discussed. The design is theoretically analysed and the model validated with experimental data.

The results show that BIPVTC offers improved electrical yields from both concentrating radiation onto the photovoltaic cells and also by actively cooling them. Also, it was shown that the BIPVT could be made of a durable (long life) stainless steel, rather than the more reflective aluminium, while still offering a noticeable increase in annual output.

Keywords* : *building integrated, concentrator, photovoltaic/thermal

INTRODUCTION

In recent times there has been an increased interest in the development of Photovoltaic/Thermal (PVT) solar energy systems that generate both thermal and electrical energy (Van Helden et al 2004, Tripanagnostopoulos et al, 2002, Huang et al, 2001). These studies have shown that PVT collectors can have high overall combined efficiencies and can be more cost effective than stand alone PV and solar thermal systems.

A significant number of the studies into PVT systems have produced "standalone" collectors similar to those already used for water heating. The downside to this is that such systems are often poorly integrated with the buildings to which they are supplying energy. Bazilian et al (2001) noted that the integration of PV systems into the built environment can achieve "a cohesive design, construction and energy solution".

Moreover the capture of "waste" heat from a building integrated photovoltaic (BIPV) systems allows the opportunity to create a building integrated PVT (BIPVT) that is architecturally acceptable. In essence, BIPVT is the embodiment of PVT in building elements such as roofing or façades. Considering the vast majority of solar panels are used in an urban environment using BIPVTs for cogeneration is a means of achieving higher energy generation density (kWh/m^2). Additionally, integration minimises the detrimental visual impact of conventional solar systems in the built environment. Perhaps most importantly the energy output of the photovoltaic cells could be improved with cooling while supplying thermal energy for hot water and or space heating.

There are however shortcomings in existing BIPVT systems: in particular a comparatively high cost by virtue of the use of photovoltaics. A potential solution to this shortcoming is to develop BIPVT collectors which incorporate concentrators to increase the output from the photovoltaics using lower cost material.

Tripanagnostopoulos et al (2002) discussed perhaps the simplest incarnation of a concentrating PVT concentrator. In their system they used a reflector plate to direct extra solar radiation onto a PVT collector giving a concentration ratio of approximately 1.3. They found that the use of this simple concentrator increased the thermal efficiency of their PVT collector from 38% to approximately 60%.

Similarly, concentration of solar radiation can also be achieved with compound parabolic concentrators (CPC), linear or circular Fresnel lenses or reflectors or with parabolic dishes. Garg and Adhikari (1999) demonstrated the use of several truncated CPCs in a single PVT module. They found that their collector for air heating, with a concentration ratio of 3, resulted in better efficiencies when integrated into a system. A similar system was also demonstrated by Othman et al (2003). However, where Garg and Adhikari used a single pass to heat air, they utilised a double pass with a rear finned surface in their system. The aim of the finned surface was to improve heat transfer on the rear face of the PV module.

As mentioned, concentration by linear Fresnel reflectors is also possible. Rosell et al (2005) demonstrated a system based on this method that had a concentrating ratio of 11. They were able to obtain a maximum thermal efficiency of approximately 60% from their system with no electrical load.

Another variation on line focusing PVT collectors was the CHAPS (concentrating heat and power system) discussed by Coventry (2005), which used a parabolic trough reflector with a PVT module mounted at its focus. The system had a concentration ratio of 37 and had a maximum reported combined efficiency of 69%. Coventry noted that although the system had a lower thermal efficiency than those reported in other studies, the heat losses from the CHAPS system where much lower, due to its smaller heated area. Coventry also noted that imperfections in the concentrator shape resulted in non-uniform illumination thus affecting the electrical performance.

The principle shortcoming of all these studies however was that none considered how such systems might be integrated into buildings to form a BIPVT-concentrator (BIPVTC). A solution to this may be to develop simple V-trough style concentrators that lend themselves to easy fabrication. This would represent a natural extension to BIPVT systems such as that demonstrated by Anderson et al (2009). Such systems have been shown to provide an opportunity to improved output from photovoltaic and thermal systems. An early study by Bannerot and Howell (1979) had suggested that static V-trough collectors could achieve an annual average concentration ratio of over 1.2 for locations with a high diffuse solar fraction, and might be suited to applications where the reflectors were offsetting the cost of expensive solar absorbers such as photovoltaics.

Therefore in this study a BIPVT concentrator system was developed that incorporated a V-trough concentrator to determine if such a system could produce a worthwhile increase in electrical and thermal energy for a BIPVT style collector.

THEORETICAL ASSESSMENT OF A BIPVTC

The solar concentrator proposed for this study was to be integrated into buildings and as such had to be robust enough to last over 30 years while maintaining its mechanical integrity and not corroding. Previously Anderson et al (2009) had demonstrated the use of BIPVT collectors based on trapezoidal profiled long run metal roofs. It was proposed that this concept be extended by increasing the depth of the troughs, such that the inclined sides acted as reflective elements, the result being a Building Integrated Photovoltaic Thermal Concentrator (BIPVTC) as shown in Figure 1. Additionally, to meet the design life it was suggested that the concentrator be constructed from mirror finished stainless steel sheet (Nostell et al, 1998) to cope with New Zealand's corrosive maritime climate.

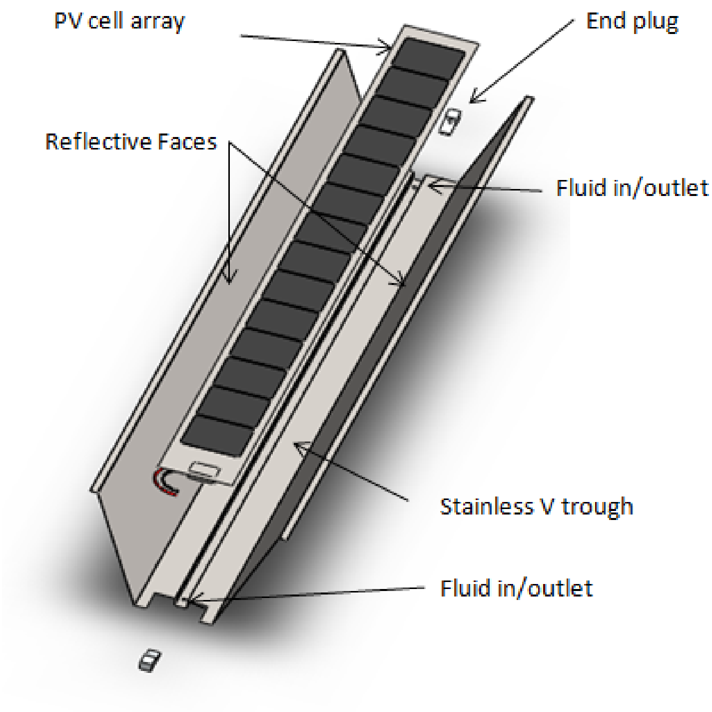

Fig. 1: V-Trough BIPVTC

It is well known that a flat plate solar collector mounted at an angle close to latitude will give the maximum annual output. Therefore it was decided that, when installed, the photovoltaic absorber in the V-Trough should be inclined to the horizontal at an angle equal to the local latitude (37.5 degrees) with the troughs being oriented East-West. Additionally, the V-Trough angle (φ) was set at 25 degrees, to account for the annual variation in declination, with the ratio of aperture area (A) to trough area (a) being 2.36 (Figure 2).

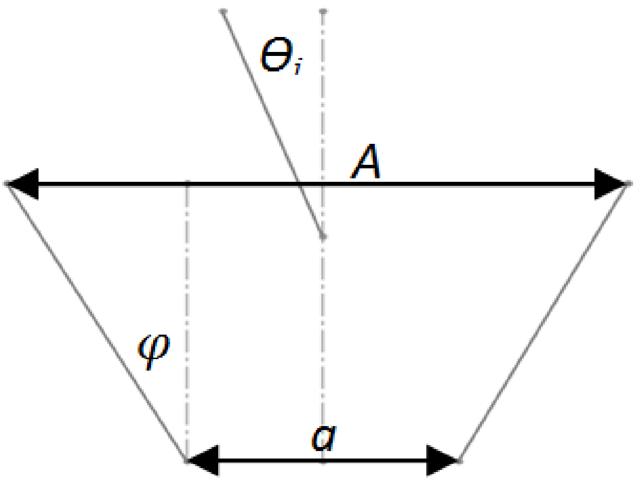

Fig. 2: V-Trough cross-section

Before undertaking the fabrication of a BIPVTC, the performance of the concentrator was simulated using the analytical solution presented by Fraidenraich (1992 and 1998) for a V-Trough concentrator. The total solar reflectance of the polished steel was taken to be ρ = 0.67, (Karlsson and Ribbing, 1982). The optical efficiency of the concentrator (η_F) was calculated as a function of incident angle (θi), concentration ratio (C), trough half-angle (φ), and material reflectivity (ρ): η_F (θ_i, C, φ, ρ) (Fraidenraich, 1992 and 1998).

Now in determining the performance of the BIPVTC at any particular instance within the year, the incident angle of the incoming radiation was determined from Reda and Andreas' (2008) solar position algorithm. Further, the local beam irradiance was estimated using Šúri and Hofierka's (2004) method based on the Linke turbidity factor (T_L). By combining the knowledge of concentrator' optical performance with the solar position and the estimated magnitude of the beam radiation it was possible to determine the irradiance occurring both on a flat inclined plane and on the absorber surface of the BIPVTC.

As such, considering a cool, dry, clear sky mid-winters day, where the Linke turbidity factor would be approximately 1.8 (Pedros et al, 1999), the modelled irradiance on the V-trough absorber and a flat panel inclined at an angle equal to latitude were compared to the radiation measured by a pyranometer as illustrated in Figure 3.

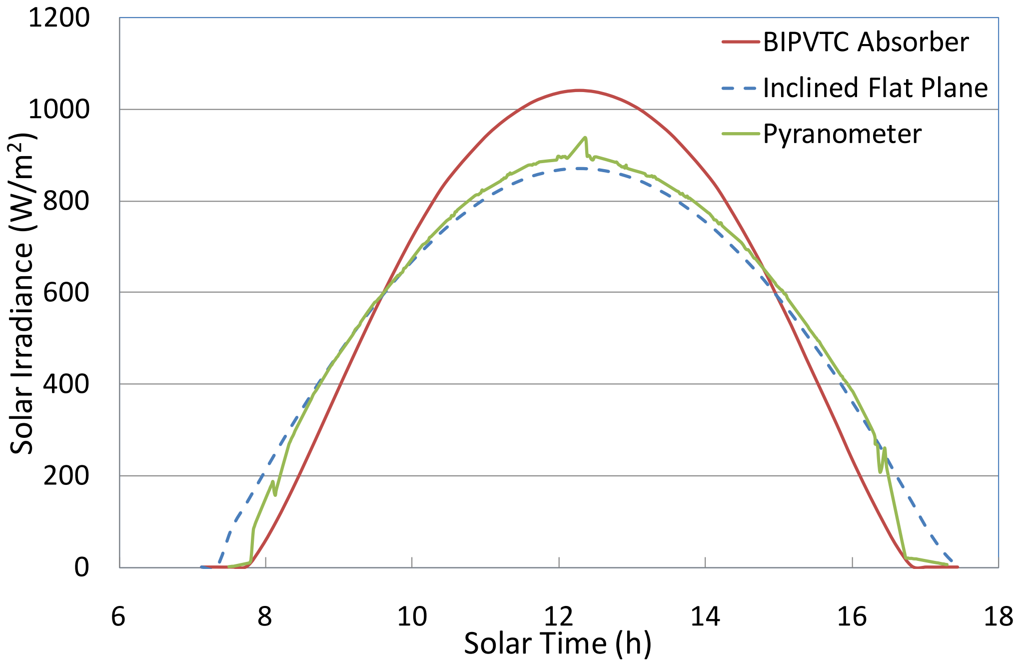

Fig. 3: Theoretical model of V-Trough

From Figure 3 it can be seen that there is a cross-over of the radiation on a flat plane with the radiation falling on the BIPVTC absorber surface. This cross-over illustrates that at times during the year the reflective sides of the V-trough shade the absorber surface. In the early morning the peak power output of the collector would be reduced but during the middle of the day the performance would be improved. In this instance it can be seen that the peak irradiance on the BIPVTC absorber is over 20% higher than the flat plate, however the overall energy yield is only 10% when evaluated over the whole winter's day.

It was assumed that polished stainless steel with a reflectivity of 0.67 would be used to fabricate the BIPVTC, however in order to improve the yield from the collector, it is possible that aluminium could be used. The use of aluminium would result in an increase in the reflectivity to a value of 0.9 (Fend et al, 2003) which should in turn lead to higher irradiance at the absorber surface. In Figure 4 it can be seen that aluminium would further increase the peak irradiance, compared to a flat plate by over 30%, and the total daily energy yield on the BIPVTC absorber would be increased by 16%. However, though there could be a marked increase in the output of a BIPVTC using aluminium, this may be at the expense of the collector durability and was not considered a viable option.

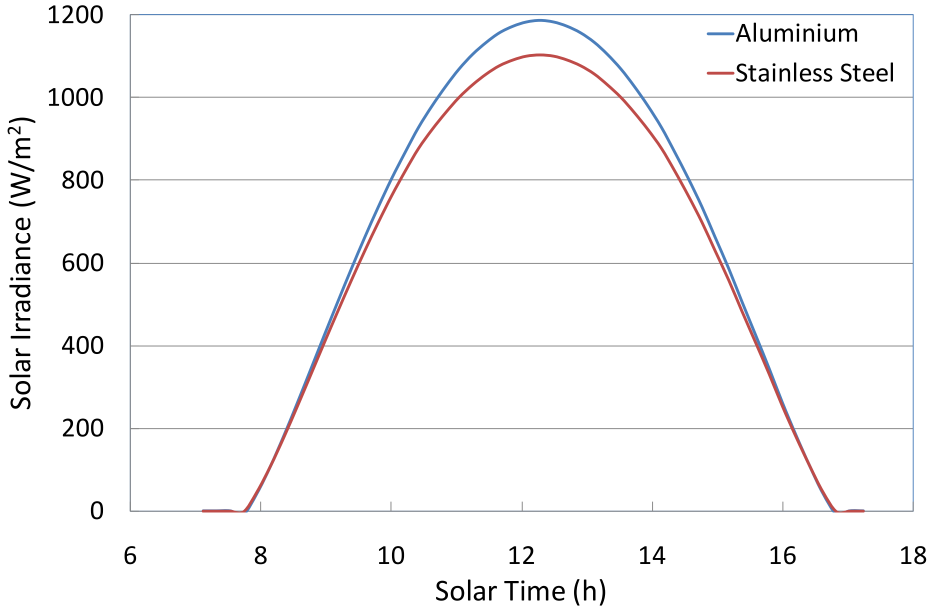

Fig. 4: Theoretical model of V-Trough with high reflectivity

Having ascertained the incident radiation it was possible to estimate of the power output from a flat photovoltaic module and an un-cooled BIPVTC module nominally rated at 49Wp, as shown in Figure 5. As with the irradiance values the BIPVTC module should produce 23% more power at midday compared to a flat panel module. However, in the morning and afternoon there is again a crossover point where the BIPVTC module produces less power than the flat panel due to shading of the BIPVTC module by the reflective sides of the V-trough.

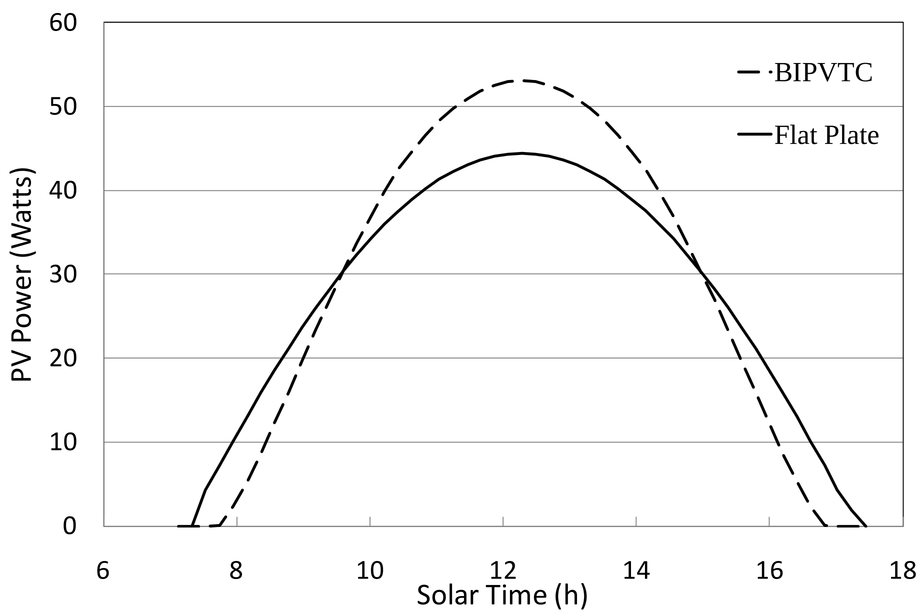

Fig. 5: Predicted power output

CONCENTRATOR DESIGN AND EXPERIMENTAL SETUP

In order for the outcomes of the theoretical assessment to be satisfactorily proven, it was necessary to validate the model against experimental data. To achieve this validation, it was decided to fabricate a prototype BIPVTC and examine its performance using a steady state outdoor thermal test. As previously discussed the collector was fabricated from a mirror finish stainless steel with the aim of providing a long lasting, reflective surface that is also suitable for fluid flow. Therefore a stainless steel sheet was folded to form a V-trough profile with a fluid channel in the centre. Photovoltaic modules were bonded into the trough creating a closed channel for fluid flow as previously shown in Figure 1. The photovoltaic modules comprised 14 polycrystalline silicon cells (156mm x 156mm) laminated onto a 1mm stainless steel sheet using EVA with a Tedlar top sheet with a rated output of 49Wp.

The fluid within the channel has two purposes; to produce useful thermal energy and reduce the temperature of the photovoltaic cells, as it is well known that cooling mono-crystalline and polycrystalline silicon PV cells results in increased electrical power output. Four BIPVTC modules were mounted on a frame and cooling fluid was pumped through the panels (Figure 6). Furthermore a flat PV module of the same rated power with no cooling and no concentration was mounted adjacent to the BIPVTC's to act as a reference collector. Finally, to simulate a building installation, standard roof insulation was attached to the rear of each panel to prevent heat loss.

Fig. 6: Experimental BIPVTC apparatus

To evaluate the BIPVTC performance T-type thermocouples were used to measure the inlet (T_{in}) and outlet (T_{out}) temperatures of the panels as well as their surface temperatures. The flow rate ($\dot{V}$) through the collector was measured using a paddle wheel flow sensor and the incident solar radiation (G) was measured using a pyranometer mounted parallel to the panels. To determine the electrical output of the modules, the data acquisition system switched between measuring the open circuit voltage (V_{oc}) across the panel and the short circuit current (I_{sc}) of each panel at 15-second intervals. From this it was possible to determine the output power of the collectors from Equation 1.

$$P = V_{OC} I_{SC} FF \qquad (1)$$

where I_{sc} is the short circuit current, V_{oc} is the open circuit voltage and FF is the fill factor, given by the PV cell manufacturer to be 0.72.

MODEL VALIDATION AND EXPERIMENTAL RESULTS

Electrical Output

In the theoretical assessment of the BIPVTC it was shown that for a clear sky mid-winters day the addition of the concentrator would lead to an increase of approximately 20% more power at midday compared to a flat plate module. In Figure 7 it can be seen that for an un-cooled BIPVTC there is good correspondence with the theoretical prediction. Furthermore, the prediction that the concentrating elements would lead to shading is also clearly illustrated by the morning and afternoon crossover point where the BIPVTC module produces less power than the reference flat plate module. However the experimental results show that the un-cooled BIPVTC module produces 6% more PV energy over the day, slightly less than the 10% predicted by the theory.

Now, it is well known that silicon photovoltaic cells suffer reduced efficiencies as their temperature increases and that this principally manifests itself as a reduction in the cell voltage (Green, 1998). As such the provision of a cooling system, as described in the description of the BIPVTC should lead to reduced cell temperatures and increased cell voltages.

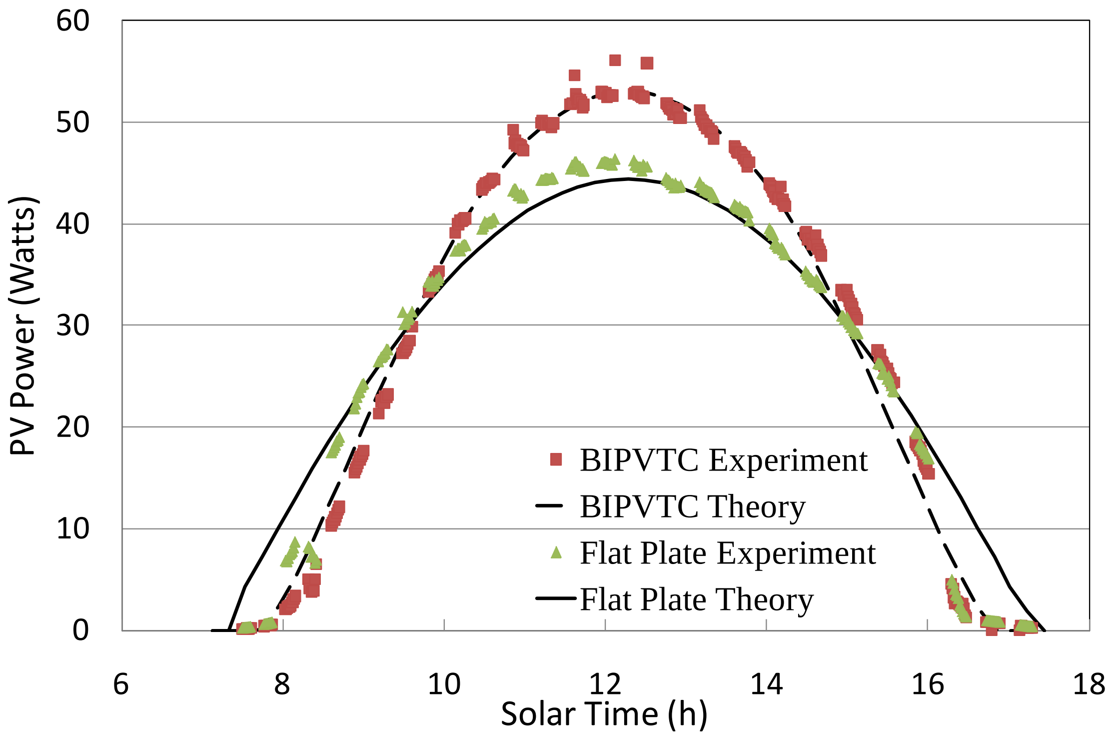

Fig. 7: Experimental and theoretical power output of BIPVTC and reference module

Therefore, on examining Figure 8, it can be seen that the operation of the cooling system leads to a reduction in the surface temperature of cells in the concentrator of approximately 20°C. It can be seen that the un-cooled module reaches a maximum temperature of 50°C whereas the cooled module is approximately 30°C.

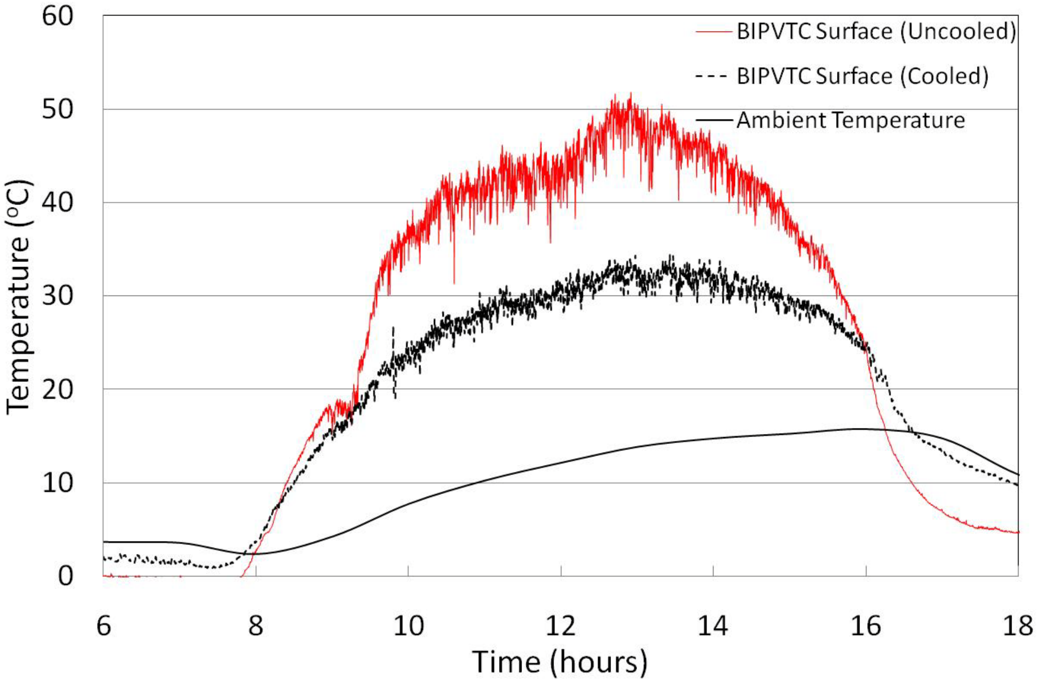

Fig. 8: Experimental PV cell temperature for un-cooled and cooled BIPVTC

Increasing the cell temperatures has been shown to lead to a reduced voltage of approximately 1.9mV/°C (Coventry, 2005). For a 20°C difference there should approximately be a 40mV per cell drop in the voltage. Therefore the total voltage drop across the cooled PV module compared to the un-cooled could be expected to be in the order of 500mV. In Figure 9 when the temperature difference is a maximum of 20°C the voltage difference is approximately 270mV, just over half what is expected. This suggests that the cooling channel behind the PV cells was not delivering the optimum heat transfer from the cells, possibly due to poor fin efficiencies (Anderson et al, 2009). This suggests that to achieve further gains in electrical output the PV cells must be cooled more uniformly through improved fin efficiency.

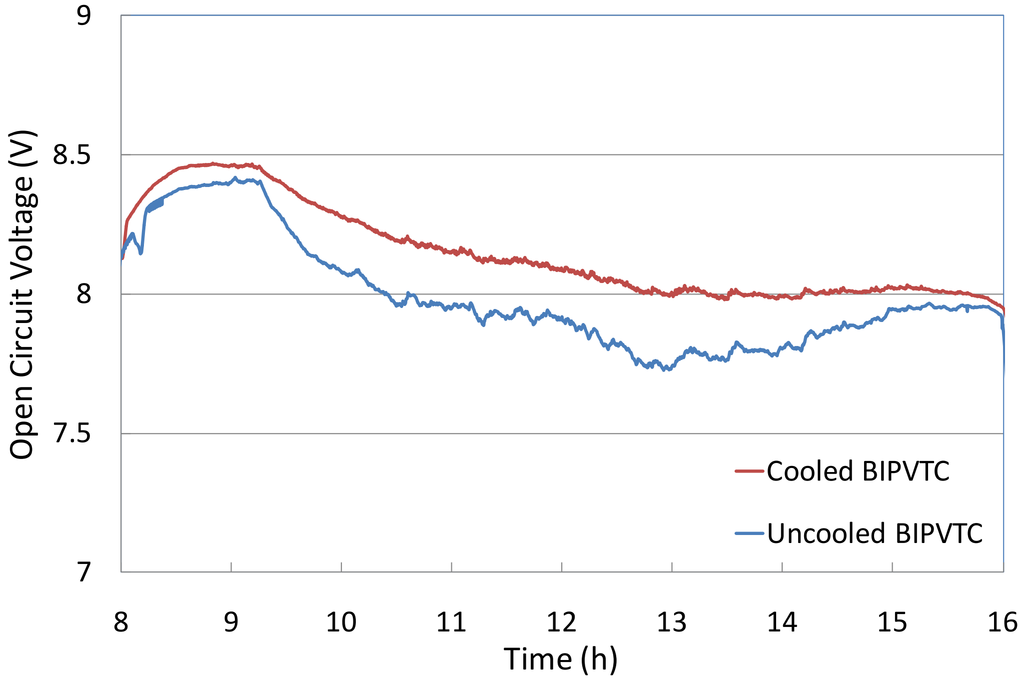

Fig. 9: Experimental PV cell temperature for un-cooled and cooled BIPVTC

Thermal Output

In addition to generating electrical output, the BIPVTC generates useful thermal energy while cooling the PV cells. In order to analyse the thermal energy being transferred to the BIPVTC cooling system, the energy was found from Equation 2.

$$P_{th} = \rho \dot{V} C_p (T_{out} - T_{in}) \qquad (2)$$

where P_{th} is the instantaneous thermal power, ρ is the density of the water flowing within the cooled BIPVTC, C_p is the specific heat capacity of the coolant, T_{in} and T_{out} are the inlet and outlet temperatures, and $\dot{V}$ the volumetric flowrate. In Figure 10 it can be seen that the concentrator's peak thermal power output on a clear sunny day was approximately 140W, or nearly three times that of the PV output.

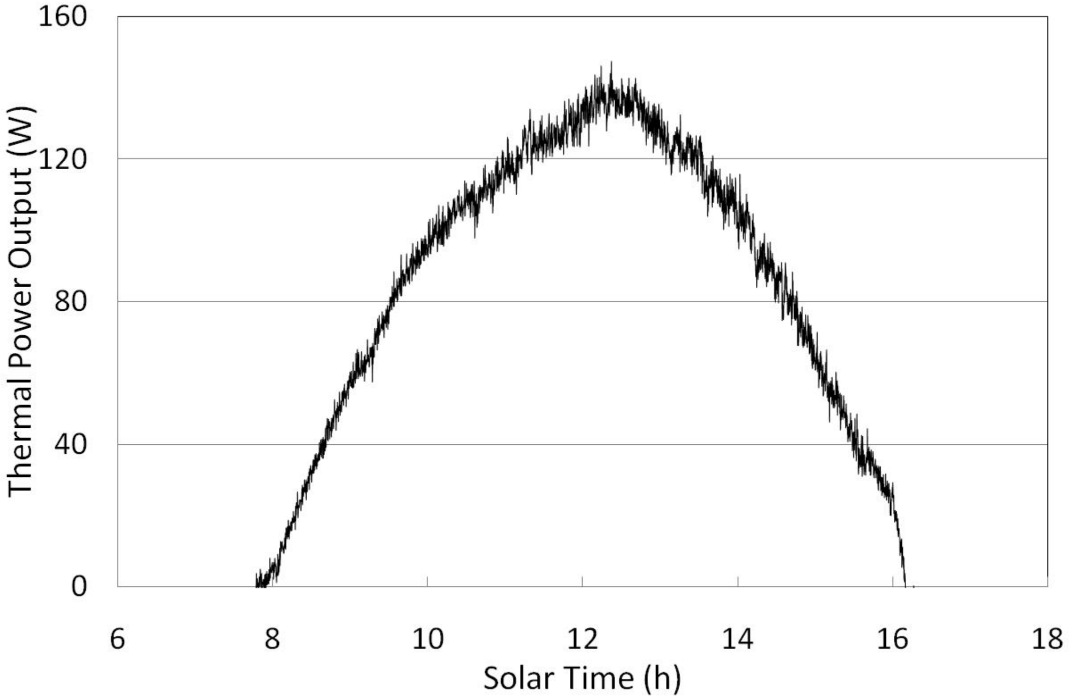

Fig. 10: Thermal power output of cooled BIPVTC Module

Using Equation 3 it is possible to determine the instantaneous thermal efficiency of the BIPVTC during its operation, where G is the incident solar radiation and A is the absorber area of the V-Trough.

$$\eta_{th} = \frac{\rho \dot{V} C_p (T_{out} - T_{in})}{GA} \qquad (3)$$

In Figure 11 it can be seen that the peak thermal efficiency of the collector is in the order of 40%. It could be argued that the BIPVTC performs poorly when compared to purpose designed solar water heaters with peak efficiencies in excess of 70%. This lower thermal efficiency however is due to the increased heat losses by radiation and convection in the absence of a glazing layer (Anderson et al, 2009).

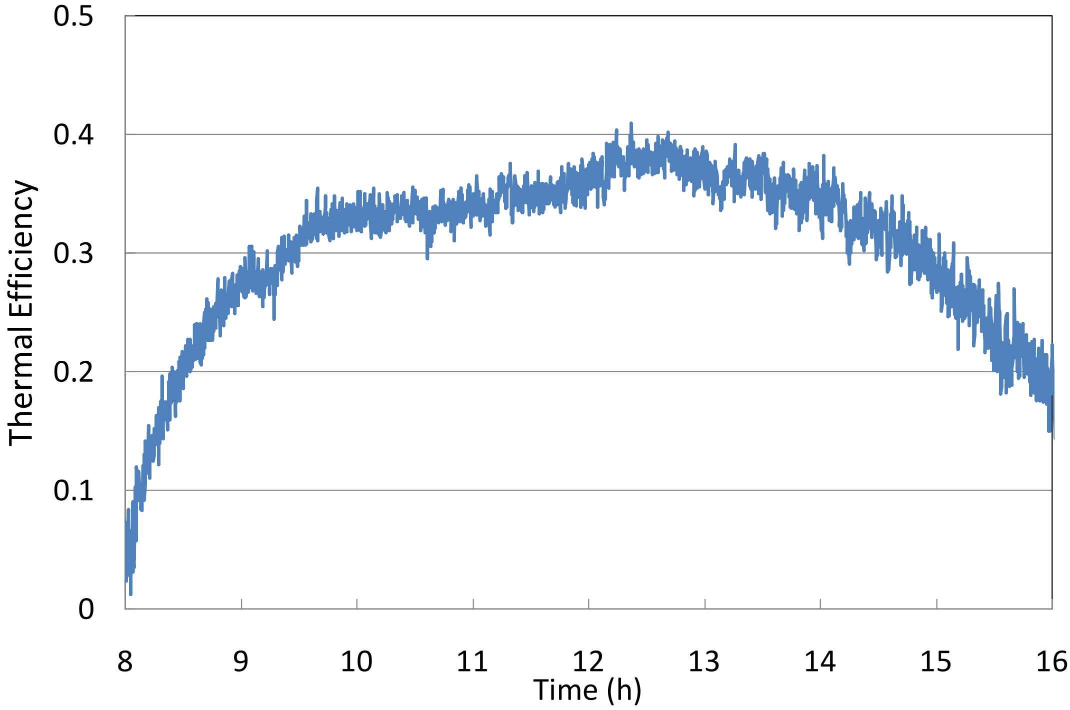

Fig. 11: Thermal efficiency of cooled BIPVTC module

Electrical and Thermal Output

One of principal advantages of the BIPVTC is that it provides not only an improved electrical output, but also the thermal output. In achieving this, the absorber is in effect improving the energy output compared to standard photovoltaic panels; similarly a solar thermal collector does not provide electrical energy. As such it is important to emphasise the total power output for the cooled BIPVTC module as shown in Figure 12, and how this would compare to the system if it were just a BIPV concentrator.

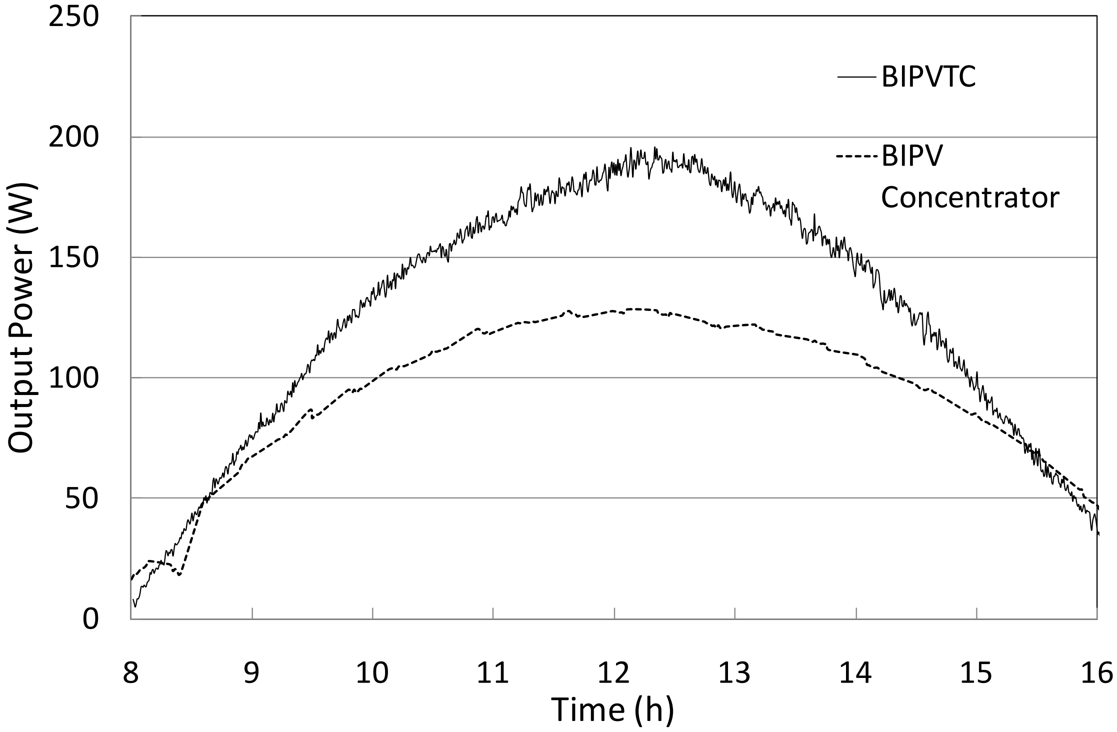

Fig. 12: Total output power with and without cooling

In summary, the BIPVTC module generates about 50% higher peak power and approximately 30% more total energy than if the same area was covered with PV only. The BIPVTC module uses a significantly lower area of photovoltaic cells for a great improvement in harnessed energy.

These advantages are emphasised by the total efficiency of the system taking into account PV and thermal power, shown in Figure 13. Here it can be seen the combined efficiency of the BIPVTC module is over 50%, whereas photovoltaic modules typically have efficiencies in the order of 10%. Hence a BIPVTC offers a significant benefit in terms of utilising the incoming solar energy.

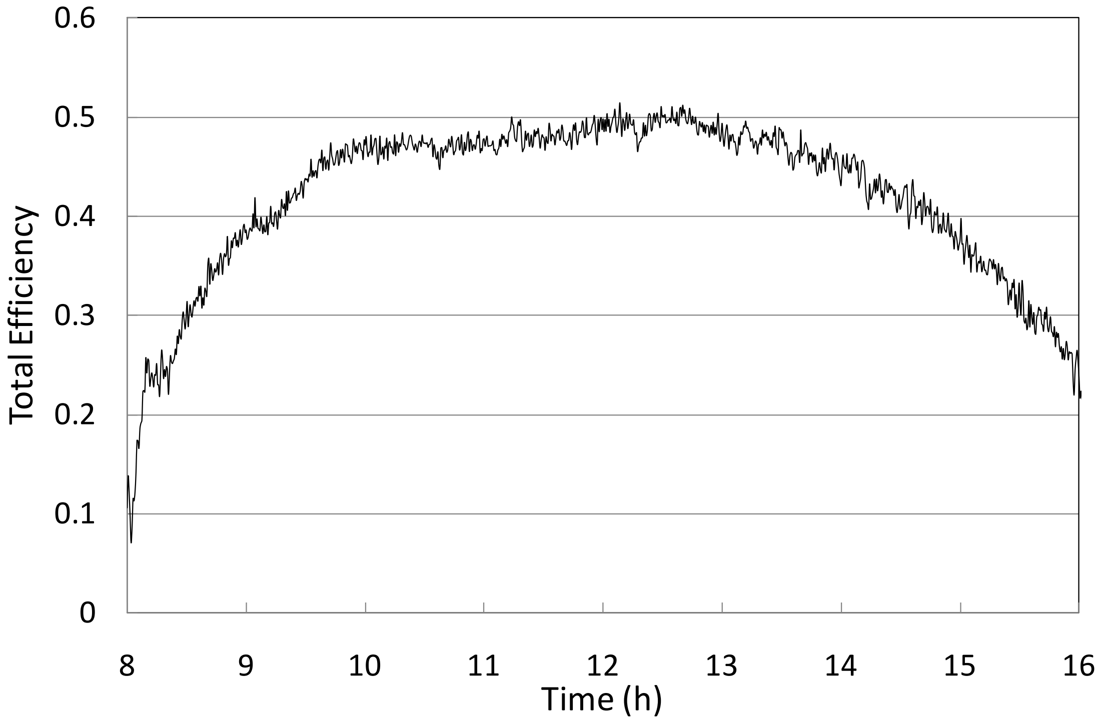

Fig. 13: Overall efficiency of BIPVTC module

ANNUAL PERFORMANCE

It was previously noted that at times during a day, self shading of the BIPVTC could occur and this leads to reduced output. Though shading of photovoltaic cells is generally undesirable at any time, it could be argued that this corresponds to times of low radiation and electrical demand, whereas the output is markedly increased around solar noon when electrical demand is typically highest. More tellingly, if we examine the now validated model output from the BIPVTC and explore the variation in concentration ratio (for each months median day) over the year based on the monthly average Linke turbidity index' (Figure 14), we see that the addition of the V-Trough results should lead to a 25% increase in output across the year, similar to that predicted by Bannerot and Howell (1979).

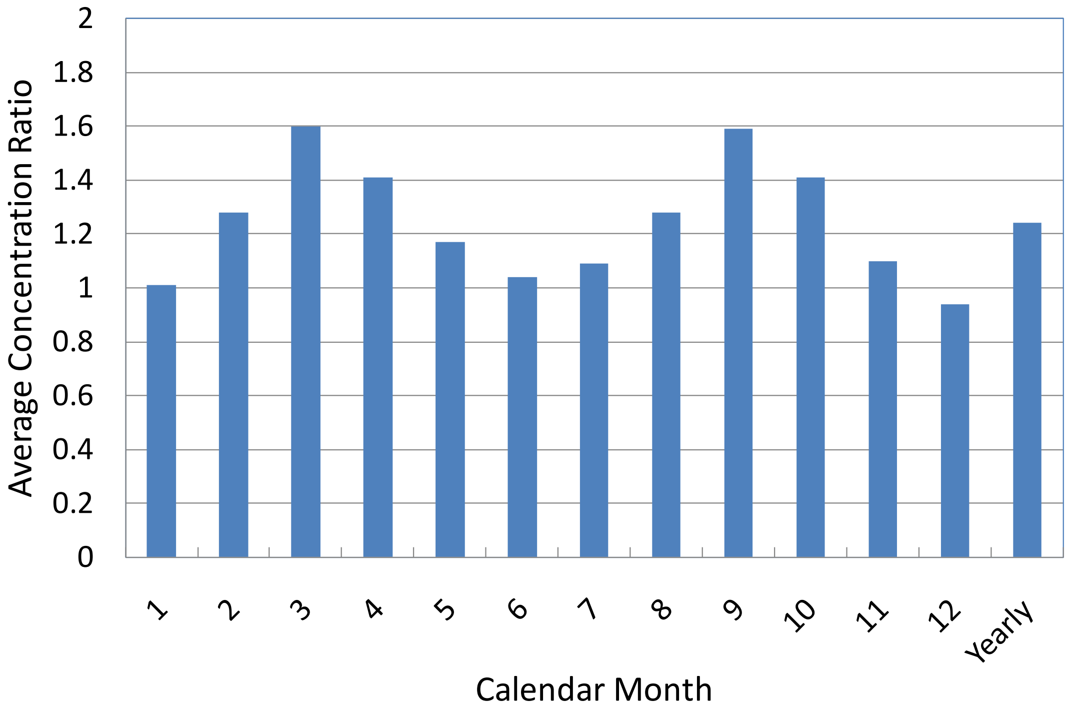

Fig. 14: Monthly mean BIPVTC concentration ratio

This result suggests that despite the small performance increases observed in the experiments (mid winter) the output from the collector will be dramatically increased around the equinoxes with a resultant increase in the annual output. This output profile could conceivably be modified by incorporating a similar system into the facade/walls of the building to improve output near the solstices.

CONCLUSION

Based on the results presented, it can be seen that the concept of a building integrated photovoltaic thermal concentrator is feasible and has the potential to offer significant efficiency improvements over existing photovoltaic modules. Though it could be argued that photovoltaic systems are reducing in price, they are still relatively expensive, and as such the use of low cost reflective elements offers the opportunity to improve electrical energy yields with lower capital outlays.

Moreover, the cooling of the cells in addition to improving the electrical output offers a thermal energy source. The efficiency of energy capture for the total area is markedly improved. However, it should also be noted that in order to achieve further improvements from the BIPVTC there is a need to closer examine the fin efficiency of the system and look at means of reducing convective and radiative heat losses.

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