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Chapter 12

DESIGNING PHOTOVOLAIC/THERMAL SOLAR COLLECTORS FOR BUILDING INTEGRATION

T.N. Anderson**, M. Duke and J. K. Carson

Department of Engineering, University of Waikato
Private Bag 3015, Hamilton 3240, New Zealand

Abstract

With concern growing over the environment and resource use, there has been greater emphasis placed on sustainability, particularly in the built environment. One of the key points of sustainable urban environments is the need for an increase in the densification of the population. A by-product of increased densification however, is a reduction in the area per person that can be used for on-site renewable energy generation from the solar resource. Where previously it would have been possible to have a photovoltaic array and solar water heater side-by-side for a free-standing household, this may not be achievable in a high-density living situation.

As a counterpoint to this issue, the design of a novel combined photovoltaic/thermal for building integration (BIPVT) solar collector is analysed and discussed. The panel has a higher efficiency per unit area, than an array of photovoltaic panels in combination with solar thermal panels. In addition, by integrating electricity generation, water heating and facade elements it is possible to reduce the complexity associated with traditional solar installations while also achieving an architecturally sensitive appearance. As such the BIPVT is ideally suited to environments where facade space with suitable solar access is limited, or where large numbers of people share a single building.

In this study, the influence of key design parameters on the performance of a BIPVT collector are presented and discussed. Finally, a transient systems analysis is used to illustrate the performance benefits of BIPVT style collectors over traditional technologies.

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

* E-mail address: timothy.anderson@UNSWalumni.com (Author for correspondence).

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 (Prasad and Snow, 2005).

By and large the two technologies have, for the majority of their lives, remained as separate entities. In the late 1970's however, a number of studies began to investigate incorporating photovoltaic and solar thermal into a single device, commonly referred to as Photovoltaic/Thermal (PVT) solar collectors. There are two benefits to PVT: firstly, the efficiency of PV cells can be increased by actively cooling them using the solar thermal system. Secondly, by incorporating both systems into a single unit, the area dedicated to solar energy devices can be reduced. It is well known that for mono and polycrystalline silicon PV-cells, their efficiency decreases with increasing temperature by approximately 0.5%/°C. In PVT systems, the solar thermal is used to reduce the temperature of the PV-cells and thus improve their efficiency.

PVT Air Heating Collectors

Arguably, the simplest, and cheapest, configuration for a PVT collector is as an air heating device. Simply put, a cavity is formed behind a PV panel (module) where air is circulated; this cools the panel and heats the air. This concept is illustrated in Figure 1.

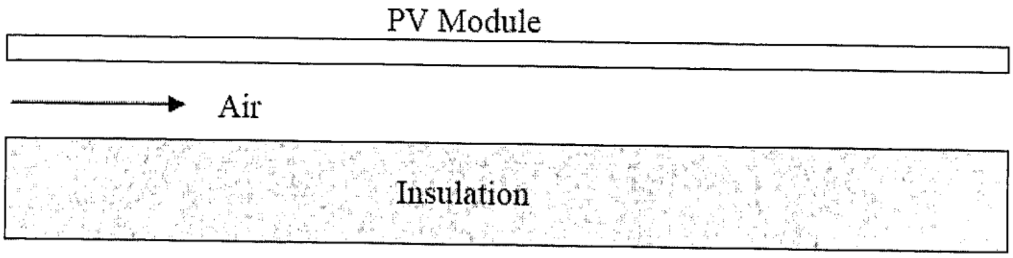

Figure 1. PVT Air Heater.

Hegazy (2000) examined four types of PVT air heating solar collectors using a numerical model. Unlike the collector shown in Figure 1, the systems in the study utilised a glass cover mounted above the PV module thus forming a second air gap. This is commonly used on collectors for solar water heating to reduce convection heat losses from the top surface of the collector plate.

Hegazy found that a system where air was circulated along the back surface of the module between it and the insulation layer, as well as along the top surface between the module and the glass cover, gave the best compromise between electrical and thermal performance.

Tripanagnotopoulos et. al. (2002) also demonstrated the use of a PVT air heating system similar to those of Hegazy. However, they also studied a system that utilised a static reflector plate that directed solar radiation from an area of similar size as their PVT, onto their collector, thus giving a concentration ratio of approximately 1.3. They found that an unglazed PVT collector, similar to that shown in Figure 1, had a maximum thermal efficiency of 38%. By glazing the system or adding the static reflector this efficiency could be increased to approximately 60%, and by both glazing and adding the reflector 75% was possible. Tripanagnotopoulos et. al. also noted however, that although glazing improved the thermal efficiency it tended to increase optical losses, resulting in a decreased electrical efficiency.

Although the previous studies discussed examined cooling of flat-plate PV modules, Tonui and Tripanagnotopoulos (2007, a and b) showed that a number of simple low cost alterations could be made to PVT air heaters to improve their performance. They showed that by adding fins to the rear of the PV module they could improve the electrical and thermal efficiency of their PVT systems. Also they found that, using a system like Hegazy's, by adding a thin metal sheet in the air passage behind the PV module the electrical and thermal efficiency were improved.

PVT Water Heating Collectors

Another common application for PVT collectors is as a water heating device. In its simplest form a PVT could look very similar to a "standard" solar thermal collector with the PV module taking the place of the collector plate, as shown in Figure 2. 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.

Further, 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. However, Andrews suggested that PVT would not be suitable for medium temperature operation at the time due to the cost of energy.

With the cost of energy and technology having changed considerably since these early studies there has been a high degree of interest again focussed on PVT for water heating. Bergene and Lovvik (1995) conducted a theoretical examination of a flat plate solar collector with integrated solar cells. They developed a series of algorithms which they utilized in calculating both the thermal and electrical efficiency of a PVT system. They suggested that such systems might be useful as pre-heaters for domestic hot water services. Garg and Agarwal (1995) also demonstrated the ability of a 2 m^2 domestic solar water heater to generate a useful amount of electricity when integrated with a series of PV cells.

Van Heiden et. al. (2004) noted that PV collectors absorb 80% of the incident solar radiation but convert only a small portion of this to electrical energy, the remainder being dissipated as thermal energy. Furthermore, they note that the temperatures reached by PV cells can be much higher than the ambient temperature and that the efficiency of PVTs is greater than the combined sum of separate PV and thermal collectors. In light of this, they suggested that PVT systems offer a cost effective solution for applications where roof area is limited.

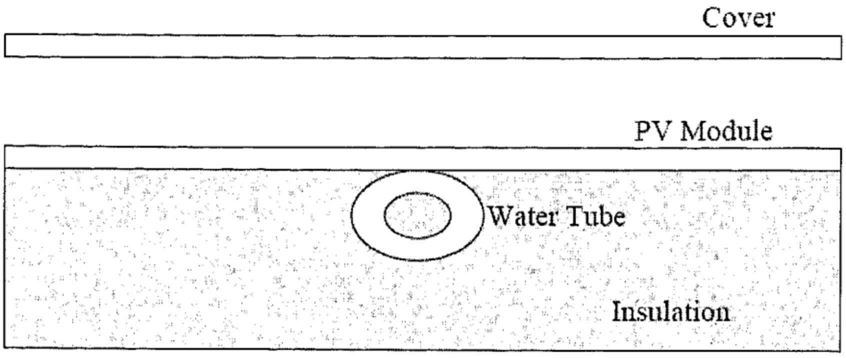

Figure 2. PVT Water Heater.

Tripanagnostopoulos et. al. (2002) conducted tests on hybrid PVT systems using polycrystalline-Silicon and amorphous-Silicon PV cells. They found that the cooling provided by the thermal integration assisted in improving the efficiency of the PV cells by approximately 10%. Additionally, they found that water cooling provided better cooling than air circulation. Finally, they suggested that the performance of these systems could be further improved through the use of diffuse reflectors or through glazing. However, as they found with their air heating collectors, glazing the collectors would improve thermal performance to the detriment of the electrical efficiency.

He et. al. (2006) recently studied a hybrid PVT system which used natural convection to circulate the cooling water. They found that their system showed a combined efficiency in the order of 50%, with the thermal efficiency contributing approximately 40%. Although they found that the thermal efficiency was less than a conventional thermosyphon solar water heater they note that the energy saving efficiency was greater.

Chow et. al. (2006) also examined the hybrid PVT system of He et. al. (2006) and developed a dynamic thermal model. They suggested that this system could be improved by placing the PV cells on the lower portion of their collector. They noted that there was a larger temperature gradient between the water entering the thermosyphon tubes and the PV cells in this region and so the electrical and thermal efficiency could be improved by placing the cells there.

Recently, Kalogirou and Tripanagnostopoulos (2007) showed that PVT was economically viable in industrial applications in a Mediterranean environment. They showed positive life cycle savings for medium temperature industrial applications. Furthermore, they suggest that PVT systems based on amorphous silicon technology, although having lower electrical efficiencies, would have shorter payback times.

Concentrating PVT Collectors

A final less common variation on the PVT collector is the concentrating PVT. As the name suggests, this involves the concentration of solar radiation onto a PVT collector.

The system of Tripanagnostopoulos et. al. (2002) that has been discussed previously is perhaps the simplest incarnation of a concentrating PVT concentrator. As mentioned this used a reflector plate to direct extra solar radiation onto a PVT collector. However, concentration of solar radiation can also be achieved with compound parabolic concentrators (CPC), linear or circular Fresnel lenses or reflectors or with parabolic dishes. A typical arrangement of a CPC PVT collector is shown in Figure 3.

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. (2005). 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. Moreover, they identified the fact that one of the main thermal resistances in their PVT was that between the PV cell and the absorber plate to which it was bonded.

Another variation on line focusing PVT collectors is the CHAPS (concentrating heat and power system); currently in use at one of the residential colleges at the Australian National University (ANU). This system, discussed by Coventry (2005), uses a parabolic trough reflector with a PVT module mounted at its focus. The system has a concentration ratio of 37 and has a maximum reported combined efficiency of 69%.

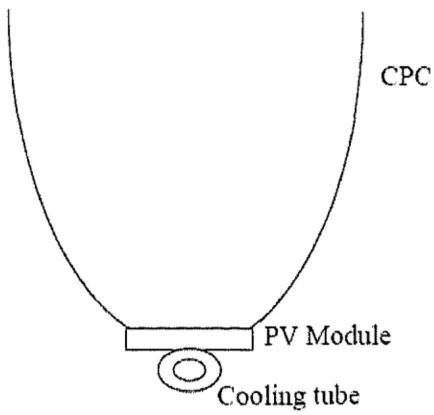

Figure 3. CPC PVT Collector.

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.

Kribus et. al. (2006) discussed the design of a PVT system using a small-scale parabolic dish concentrator. Unlike the systems discussed earlier, their system design was able to provide very high temperature heating. They suggest that such systems could be used in residential applications for driving absorption cooling systems.

Market Potential for PVT Collectors

As can be seen from the previous discussion, a significant amount of research has been conducted into PVT collectors in recent years. This research has also been complemented by very large growth in both photovoltaic and solar thermal markets. A survey by the International Energy Agency Solar Heating and Cooling programme (IEA SHC) (2006) found that, in 2004, there was approximately 141 million m^2 of solar thermal collectors in its 41 member countries. It also found that the solar thermal collector market in Australia and New Zealand was growing at a rate of 19% per annum. Furthermore it showed that the use of solar thermal energy made significant reductions in the use of energy from other sources. In addition, the market for photovoltaic solar collectors has experienced a very high rate of growth during the last decade, as can be seen in Figure 4. The majority of this growth is due to significant increases in the use of grid connected PV systems.

By spanning both the PV and solar thermal markets, it is possible that PVT systems could draw from both these existing markets. Zondag et. al. (2005) noted that based on current European targets for the installation of PV and solar thermal collectors, the use of PVT systems could meet the entire PV quota while also providing 30% of the solar thermal target.

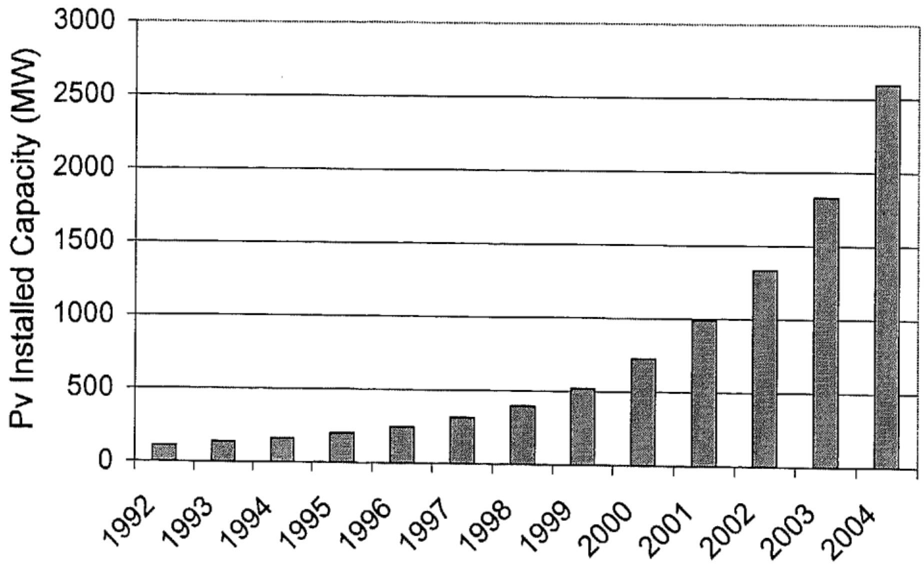

Figure 4. Cumulative installed PV capacity in IEA PVPS member nations.

More specifically, PV Catapault (2005) suggests that the market for PVT collectors can be divided into several smaller markets. Of these, the largest is the domestic sector, where there is a need for low to medium temperature heating and power generation. Furthermore, in the short to medium term they suggest PVT will find "niche market" applications such as pool heating and hospitals. Finally, PV Catapult also notes that there is still a significant amount of work to be undertaken before PVT systems will become more widely used.

Building Integration of PVT Collectors

From the studies discussed, it can be seen that a significant portion of studies into PVT systems 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 facade.

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 similar to the PVT air heaters discussed previously. In this regard, studies such as those of Mosfegh and Sandberg (1998) and Brinkworth (2006) have concentrated on using natural convection to cool the rear surface of vertically mounted BIPV panels. These studies have paralleled, and in some respects led to, the development of dual façade and ventilated wall buildings.

The use of water cooled solar collectors as building elements has until recently been largely ignored. Ji et. al. (2006) and Chow et.al. (2007) both examined a PVT system for integration as building walls in Hong Kong. They showed that these systems could make useful heat gains while also acting to reduce thermal load on the building. However, these systems were essentially individual standalone PVT panels integrated *onto* a building rather than *into* the building.

Similarly, Kang et. al. (2006) discussed the performance of a roof integrated solar collector that again consisted of an array of "standalone" solar thermal collectors used as a roof, thus being integrated *onto* a building rather than *into* the building.

In a study by Probst and Roecker (2007) this method of integrating solar collectors was considered to be "acceptable" to architects. However they note that in the future building integrated solar collectors "should be conceived as part of a construction system". Although they would seem self-evident, the comments of Probst and Roecker appear to have been overlooked or ignored by the research community.

BIPVT — An Innovative Approach

As has already been shown, there is a strong need for PVT's, and solar collectors in general, to be better integrated within the built environment. As a response to this need Anderson and Duke (2007) proposed a novel BIPVT collector that integrates photovoltaic cells with sheet metal roofing, as shown in Figure 5.

Unlike many of the systems that have been proposed, this system uses the roof of a building to act as the BIPVT solar collector, in this case a trough sheet-metal roof. Typically these roofs are made from aluminum or coated steel that are rolled or pressed into a shape that gives the roof stiffness, strength and provides weather proofing. This collector utilises the high thermal conductivity materials used in standard roofing systems to form the BIPVT collector.

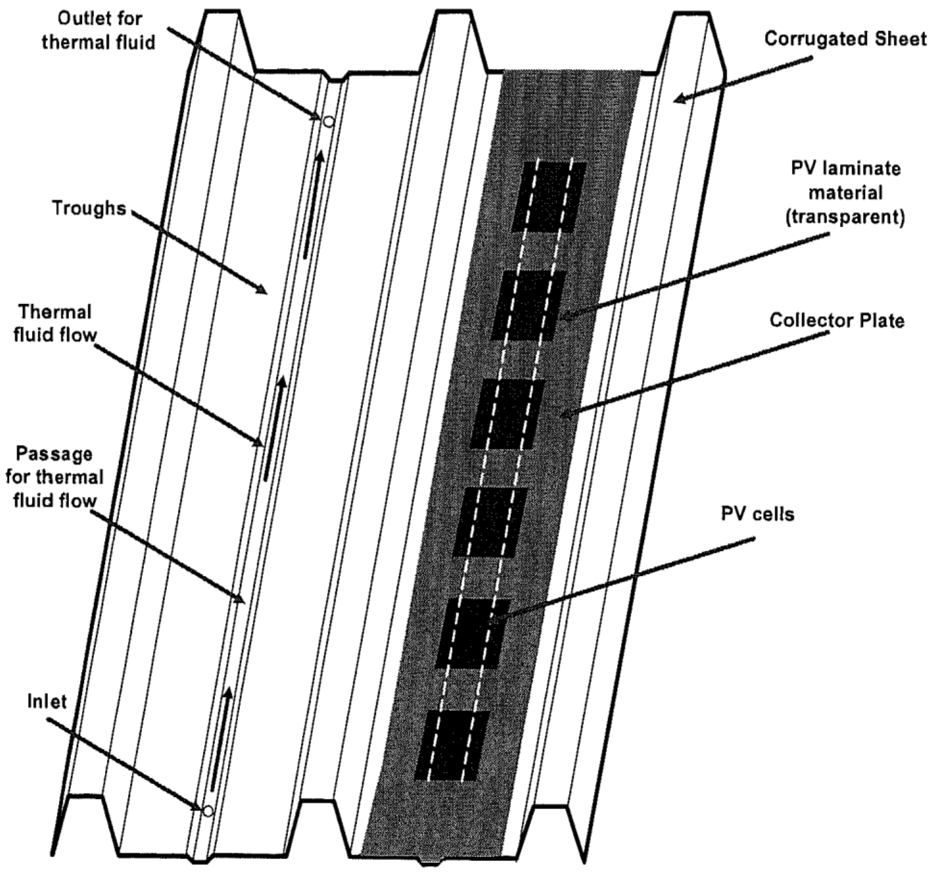

Figure 5. Schematic of BIPVT Collector.

During the manufacturing process, passageways are added for the thermal cooling medium to travel through in addition to the normal trough shape. Subsequently, a PV module is laminated into the trough thus forming a covered passageway through which a cooling medium can be circulated, thereby providing cooling to the cells. In addition a glass or polymer glazing may be added to the collector to create an air gap between the outer surface of the PV module surface and the ambient air thus reducing heat loss by convection.

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 absorption of longer wavelengths results 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.

Analysis

In order to analyse the thermal and electrical performance of the BIPVT a one dimensional steady state thermal model was developed with the collector treated as a flat plate thermal collector. As such the modified Hottel-Whillier equations presented by Anderson and Duke (2007) and Vokas et. al. (2006) were used.

Under these conditions the useful heat gain is represented by Equation 1.

$$Q = AF_R[(\tau\alpha)_{PV} \bullet G\ U_{loss} (T_1 — T_a)] \qquad (1)$$

In this equation the useful heat gain *(Q)* is represented by a function of the collector area (A), the heat removal efficiency factor *(F_R),* the transmittance-absorptance product of the photovoltaic cells *(rapt.),* the solar radiation (G), the collector heat loss coefficient *(U105)* and the temperature difference between the cooling medium inlet temperature(T_i) and the ambient temperature(Ta).

However, unlike the analysis of a standard solar thermal or standalone PVT collector, if the collector is integrated into the roof of a building then the calculation of the heat loss through the bottom or rear surface is less straight forward. Typically, when analysing solar thermal collectors and standalone PVT systems the rear surface heat loss coefficient is given by the inverse of the insulation R-value (ie. k_b/L_b). However, for a truly building integrated PVT it was recognised that the BIPVT should interact with the building rather than merely be added onto the building.

With this in mind it was recognized that under typical conditions, for an Australian or New Zealand building, the BIPVT would operate in conjunction with a "cold roof' insulation system. In such an installation the building is insulated at ceiling rather than roof level, therefore the correlation for free convection in a triangular enclosure developed by Ridouane and Campo (2005) (Equation 2) was used to determine the heat loss from the rear surface of the BIPVT.

$$Nu = 0.286 A^{-0.286} Gr^{1/4} \qquad (2)$$

where *A* is the aspect ratio of the attic or enclosure and is the ratio of the vertical height *(H)* and the horizontal width and the Grashof number *(Gr)* given by Equation 3 assuming properties based on the average of the BIPVT mean temperature and the ambient temperature:

$$Gr = \frac{g\beta(T_{pm} - T_a)H^3}{\upsilon^2} \qquad (3)$$

Hence it is possible to calculate the heat transfer coefficient due to natural convection along the rear of the BIPVT collector. Subsequently by combining the rear surface heat loss with the other losses accounted for by the Hottel-Whillier equations it was possible to determine the overall heat loss coefficient for Equation 1.

Additionally, in practical terms, it is not always possible to have complete coverage of a panel with photovoltaic cells. As such Equation 1 can be modified to account for this through the inclusion of a packing factor, or fraction of the collector surface covered by PV cells, (S), and the transmittance-absorptance product of the collector material *(τα_T)* on to which the PV cells are laminated, as shown in Equation 4.

$$Q = S\left[AF_R\left[(\tau\alpha)_{PV}.G - U_{loss}(T_I - T_a)\right]\right] + (1-S)\left[AF_R\left[(\tau\alpha)_T.G - U_{loss}(T_I - T_a)\right]\right] \qquad (4)$$

From the modified Hottel-Whillier equations it is also possible to calculate not only the useful heat gain by the solar collector but also the mean temperature of the BIPVT (Tpm). Now, because the efficiency on PV cells is related to their temperature the electrical efficiency can be calculated based on the difference between the mean temperature of the BIPVT and the Nominal Operating Cell Temperature (NOCT), typically taken as 298K. For this study it was assumed that the cell had an efficiency of 15% (typical of a crystalline silicon PV cell) at NOCT, and that the temperature dependent efficiency could be represented by Equation 5; where it was also assumed a 0.5%/°C decrease in electrical efficiency would occur (Green, 1998).

$$\eta_{electrical} = 0.15(1 - 0.005(T_{pm} - NOCT)) \tag{5}$$

Finally, by rearranging Equations 1 or 4, we can develop an equation for determining the thermal efficiency of the BIPVT, based on the average transmittance-absorptance product of the BIPVT accounting for the packing factor. This equation is then expressed in the form shown in Equation 6.

$$\eta_{thermal} = F_R((S \times \tau\alpha_{PV}) + (1 - S) \times \tau\alpha_T) - F_R U_{loss} \frac{T_I - T_a}{G} \tag{6}$$

Having established the methodology for calculating the performance of a BIPVT solar collector, some typical design values were chosen, as shown in Table 1, to examine the range of possible performance.

Table 1. BIPVT physical characteristics

Parameter	Symbol	**Value**	Unit
Number of covers	N	1	
Ambient Temperature	T_a	293	K
Emittance of plate	ε_p	0.95	
Emittance of cove	ε_c	0.88	
Number of tubes	n	66	
System flow rate	m	2	1/s
Collector Area	$A_{collector}$	100	m^2
Collector Inclination	β	37	degrees
Collector Length	L	6	m
Collector Width	h	16.67	m
PV Trans/Abs (de Vries, 1998)	$\tau\alpha_{PV}$	0.74	
Thermal Trans/Abs (Medved, 2003)	$\tau\alpha_T$	0.82	
Absorber thickness	t	0.5	mm
PV thickness	L_{PV}	0.4	mm
PV conductivity	k_{pv}	84	W/mK
Tube Hydraulic Diameter	d_h	9.7	mm

Table 1. Continued

Parameter	Symbol	Value	Unit
Tube Spacing	W	0.1	m
Ratio of Tube width to spacing	d/W	1.5	
Heat transfer coefficient from cell to absorber (de Vries, 1998)	h_{PVA}	45	W/m^2K
Insulation Conductivity	k	0.045	W/mK
Edge Insulation Thickness	L_{edge}	0.025	m
Absorber Conductivity	k_{abs}	50	W/mK
Packing Factor	S	0.4	

Design Results

From the design parameters shown in Table 1, it is obvious that there are a number of variables that could be modified to improve the efficiency of the BIPVT. As such a sensitivity analysis was conducted to determine how some of these variables would affect the thermal and electrical efficiency of the BIPVT collector. This allows us to determine the parameters that have the greatest influence on the BIPVT performance, and to provide an insight into what gains could be made by modifying any design parameter.

Perhaps the obvious starting point for analyzing any heat exchanger is to examine what influence flowrate has on its efficiency. Typically, heat transfer is controlled by the Reynolds number which is a function of flow rate; as such flow rate was varied to examine its effect on the collector. In Figure 6 it can be seen that over a typical range of operating flowrates there is a slight increase in the thermal efficiency. More importantly however, the increase in the Reynolds number with increased flowrate means that heat transfer from the PV cells is improved, thus meaning that electrical efficiency increases marginally.

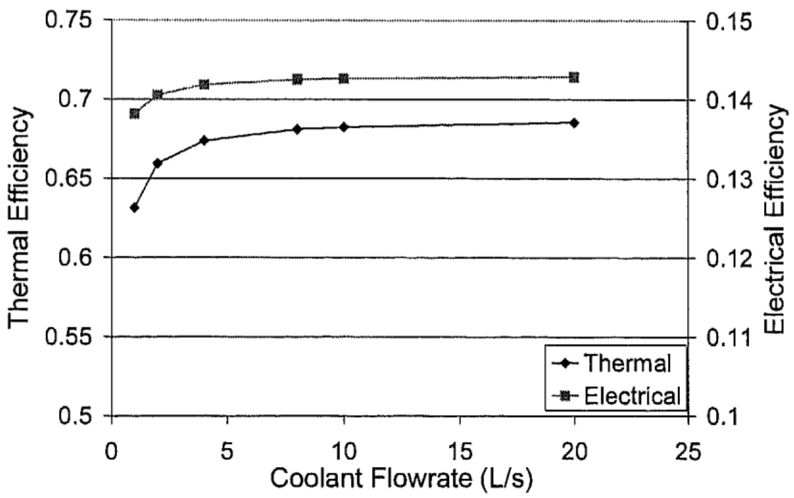

Figure 6. Efficiency v Collector Flowrate.

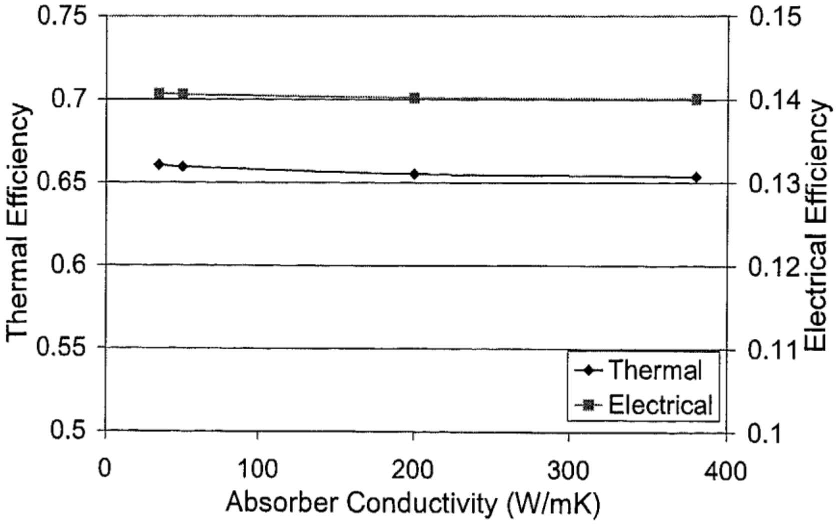

Figure 7. Efficiency v Absorber Conductivity.

Another key parameter to consider in the design of the BIPVT is the material from which it is fabricated. In Table 1 it was assumed that the collector was made from steel as a means of obtaining a low cost product, although, materials such as copper or aluminum could also be used. However, as shown in Figure 7, the material from which the collector is made does not significantly change either the electrical or thermal efficiency. This could be considered to be a somewhat surprising result, as a solar collector for water heating would typically be constructed of copper to maximise the fin efficiency. However for the BIPVT design parameters given this appears to have negligible impact.

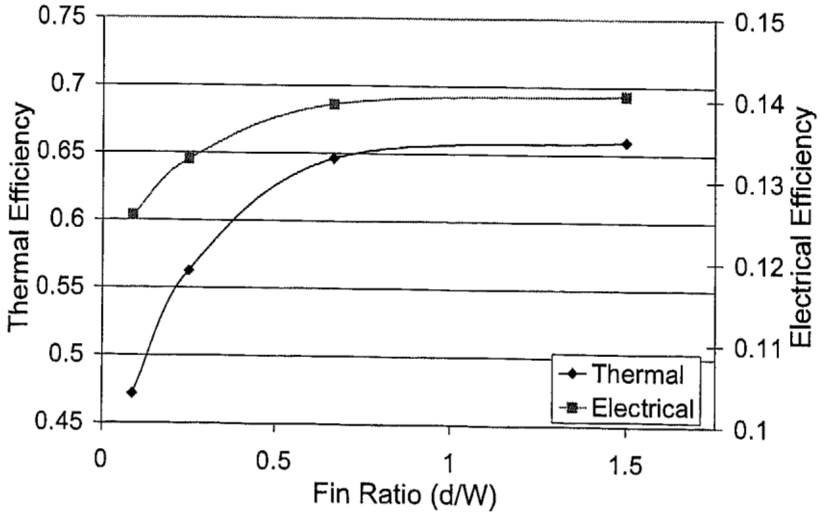

Figure 8. Efficiency v Fin Ratio.

The reason for the lack of sensitivity to change in the thermal absorber plate conductivity presented in Table 1 is the high geometric fin efficiency used in the design of the BIPVT. The fin efficiency used in the Hottel-Whillier method is a function of the rectangular tube width (d) used in the BIPVT and the spacing between adjacent tubes (W). For the results shown in Figure 8, based on the data in Table 1, it was assumed that the width of the tube extended almost the entire width of the trough between consecutive ridges. As such the fin efficiency begins to approach unity, meaning that a high proportion of the heat is transferred to the cooling fluid. To further illustrate this point it can be seen in Figure 4 that decreasing the ratio of tube width to spacing (d/W) while maintaining a constant hydraulic diameter results in a decrease in both the electrical and thermal efficiency of the BIPVT.

Another key parameter that sometimes impacts on the efficiency of solar thermal collectors is the bond resistance between the riser tubes and the fin absorber plate. In analyzing the BIPVT collector a value of 45 W/m^2K (h_{PVA}) was used as a "quasi" heat transfer coefficient between the PV cells and the absorber plate, rather than the bond resistance normally used in the Hottel-Whillier equations (the experimental derivation of this value was reported and discussed by de Vries (1998) and Zondag et.al. (2002)). De Vries noted that this value was low in comparison to his theoretical value of 450W/m^2K. This suggests that there is a need to ensure that there is good thermal contact between the PV cells and the supporting roof material. This could be achieved through the use of thermally conductive adhesives to join the cells to the roof.

In Figure 9 it can be seen that by increasing the value of this "quasi" heat transfer coefficient to de Vries theoretical value, the maximum thermal efficiency is improved by approximately 5%. Furthermore it can be seen that by improving the thermal conductivity between the PV cells and the roof there is a marked increase in the electrical efficiency. In light of this observation there is a significant need to ensure that good thermal coupling between these bodies is achieved.

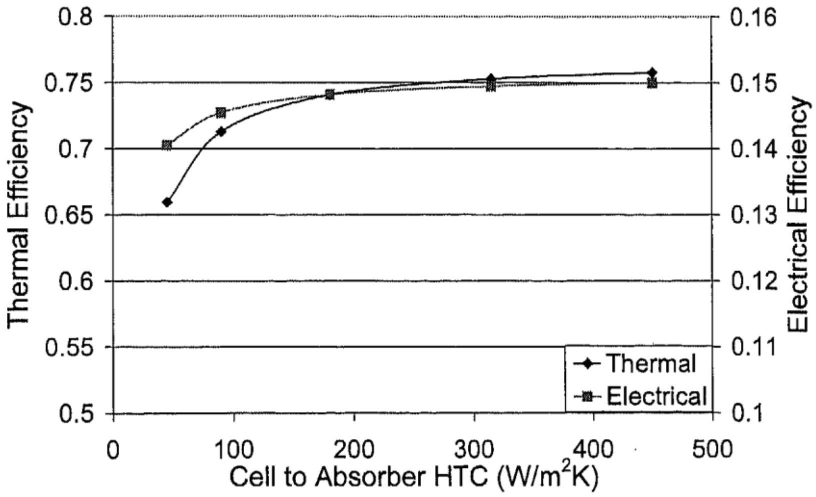

Figure 9. Efficiency v Cell to Absorber Heat Transfer Coeefficient.

In recent times, Santbergen and van Zolingen (2006) have suggested a number of modifications that could be made to PV cells to improve their suitability for use in PVT collectors. These suggestions have included ideas such as replacing the back contact with a material with a greater absorptance of long-wave radiation, in order to increase the transmittance/absorptance product of PV cells. For the current design, a value of 0.74 was specified for the transmittance/absorptance product for the PV cells based on the work of de Vries (1998). De Vries derived this value from a theoretical optical analysis of a photovoltaic laminate and found that it compared well with an experimentally determined value of 0.7 for a PVT collector producing electricity.

However in another study, Coventry (2004) found that the transmittance/absorptance product was 0.82 for his concentrating PVT system. There are a number of reasons for the discrepancies in the reported values including the differing lamination methods and materials, and the method of practical implementation analysed by the authors. That said however, the potential influence of modifying PV cells to increase their transmittance/absorptance product is clearly illustrated in Figure 10.

From Figure 10 it is clearly shown that increasing the transmittance/absorptance product improves the thermal efficiency. Typically PV cells are designed to maximize their absorption of wavelengths where the photoelectric effect occurs to silicon cells, in the range from 400nm up to approximately 1200nm. However, the solar spectrum continues to approximately 2500nm and these long wavelengths tend to be reflected whereas they are absorbed by solar thermal collectors. The modifications suggested by Santbergen and van Zolingen (2006) increase the absorption of these longer wavelengths, while the use of a silicone encapsulant by Coventry (2004) meant that a greater portion of the longer wavelengths were absorbed by the silicone encapsulant. One of the drawbacks of increasing the absorption of longer wavelengths is that it tends to result in the PV cell temperature being increased thus resulting in a decrease in the electrical efficiency.

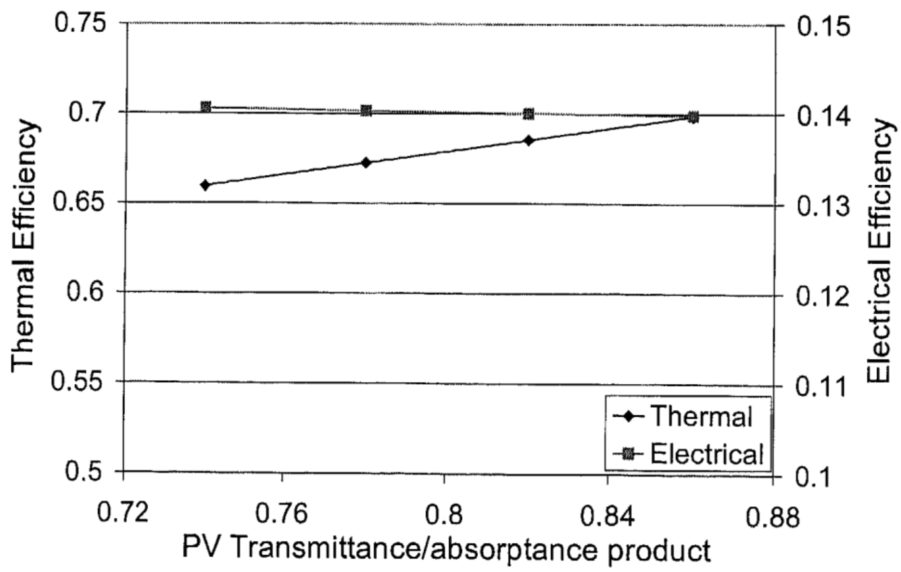

Figure 10. Efficiency v PV Transmittance-absorptance product.

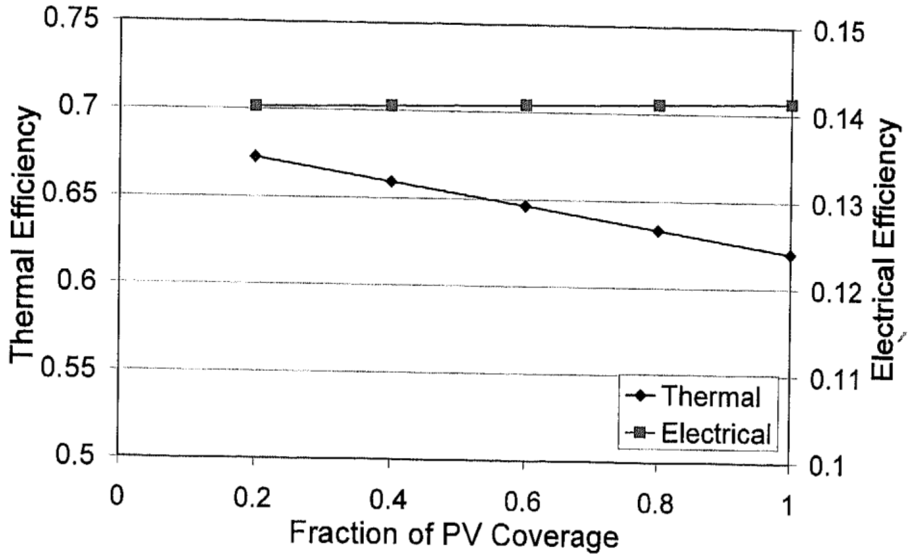

Figure 11. Efficiency v Packing Factor.

As an alternative to modifying PV cells to improve the thermal efficiency, it is also possible to vary the fractional area that is covered by the cells. Now in the design parameters a value of 0.82 was assumed as the transmittance/absorptance product for the BIPVT roofing material, typical of a commercial painted roofing material (Medved, 2003). As this is greater than transmittance/absorptance product of the unmodified PV cells (0.74) it is apparent that by decreasing the area covered by PV cells that the thermal efficiency increases. In Figure 11 it can be seen that increasing the area covered by PV cells results in a decrease in thermal efficiency, however it also results in a slight improvement in the electrical efficiency.

Another method of modifying the transmittance/absorptance product of the BIPVT is to remove the glazing. The presence of glazing means that some of the available radiation is transmitted to the PV cells while some is reflected by the glazing. As such, by removing the glazing we can improve the optical efficiency of the BIPVT. For this style of collector de Vries (1998) suggested a transmittance/absorptance product of 0.78.

However, by removing the glazing the thermal efficiency of the collector becomes strongly related to the external wind speed. Where a glazed collector has a "pocket" of air trapped between the absorber plate and the glazing that suppresses the heat loss due to forced and natural convection, this layer of air is not present in an unglazed collector and so the wind speed tends to dominate the performance of the collector. In Figure 12, it can be seen that the maximum thermal efficiency is lower than for the previously illustrated cases and it reduces significantly at increasing wind speeds. Furthermore, the higher wind speeds mean that greater heat losses are occurring and so the BIPVT operates at a lower temperature. This leads to an increase in the electrical efficiency at higher wind speeds.

Finally, from the results so far the BIPVT has been assumed to be mounted at a fixed angle. However, as a roofing or façade element it will often be mounted at an angle chosen by a builder or architect. In a typical Australian or New Zealand "cold roof' system the ceiling is insulated rather than the rear of the roof. Thus heat loss from the back surface of the BIPVT occurs via natural convection in the attic space. In Figure 13 it can be seen that as the pitch of the roof decreases so too does the thermal efficiency. This is particularly pronounced at low roof inclinations with high temperature gradients. This suggests that the natural convection in low pitched roof spaces is significant in determining the BIPVT thermal efficiency. Conversely in Figure 14, it can be seen that by decreasing the roof pitch, there is actually an increase in the electrical efficiency. This is the result of the higher heat loss occurring at lower roof angles meaning that the BIPVT is operating at lower temperatures.

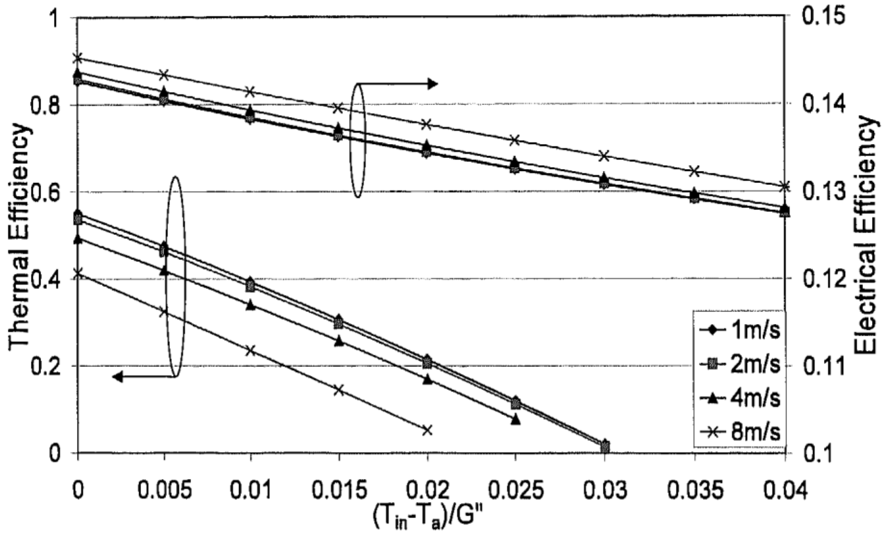

Figure 12. Efficiency of unglazed BIPVT for varying wind speed.

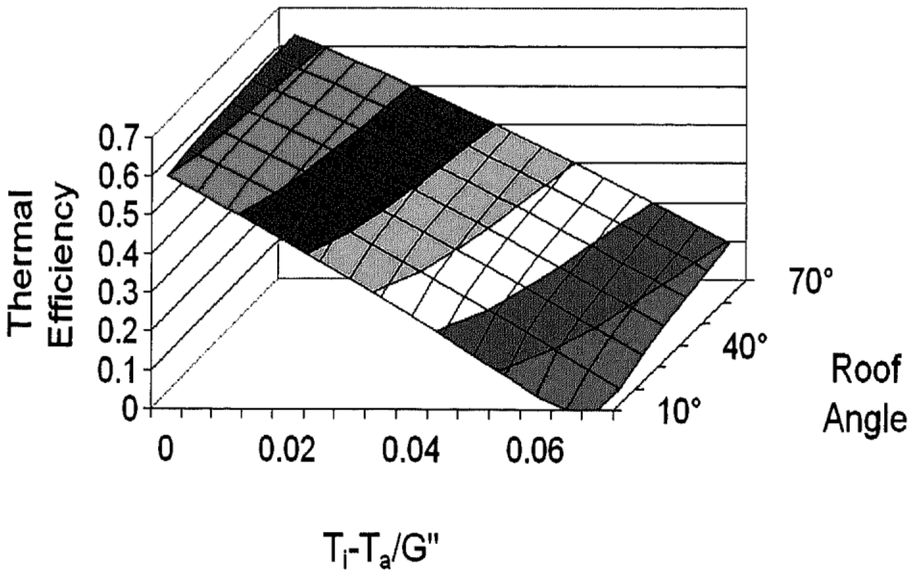

Figure 13. Thermal Efficiency v Roof Inclination.

From these findings it is possible that the rear air space in the attic could provide a level of insulation equivalent to a highly insulating material, essentially this is what the glazing on the front surface does. There is obvious scope for reducing the cost of construction of a BIPVT by effective integration with the roof space.

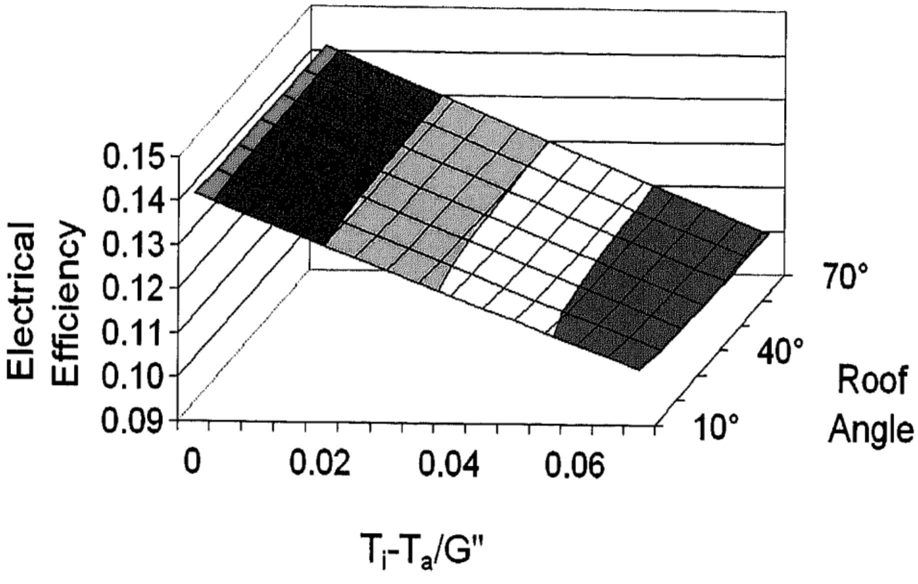

Figure 14. **Electrical Efficiency v Roof Inclination.**

At the most basic level it is possible to rely on natural convection in attic spaces or wall cavities to provide a satisfactory degree of insulation and remove the need for additional and possibly unnecessary insulation. Furthermore, the results show that key design parameters such as the fin efficiency, the thermal resistance between the PV cells and the supporting roof material, the optical characteristics of the PV cells and the lamination method had a significant influence on both the electrical and thermal efficiency of the BIPVT. More fundamentally however, it was shown that the BIPVT could be made of lower cost materials, such as steel, thus reducing the initial cost and payback time of the system.

Long Term Performance Benefits of a BIPVT

As mentioned earlier, perhaps one of the greatest advantages of a BIPVT system is that by providing cooling to the PV cells it is possible to improve their electrical efficiency. In order to demonstrate the advantage of the BIPVT, a long term simulation was performed using TRNSYS (SEL, 2007).

TRNSYS is a commonly used software tool for conducting transient simulations of solar thermal energy systems using quasi-steady models. The mathematical representations of the components of the solar energy system are presented as algebraic or ODE models, that it interconnects depending on energy and mass flows. Its flexible nature allows the user to configure any number of systems and to determine their performance at a large number of sites worldwide.

To demonstrate the performance of the BIPVT collector it was modeled using the TRNSYS Type 50 Photovoltaic/thermal collector model. This model uses a similar method of analysis to that that of the Type 1 flat plate collector and is based on the method outlined by Florschuetz (1979). For the simulations the collector is coupled to a Type 4 stratified tank as shown in Figure 15.

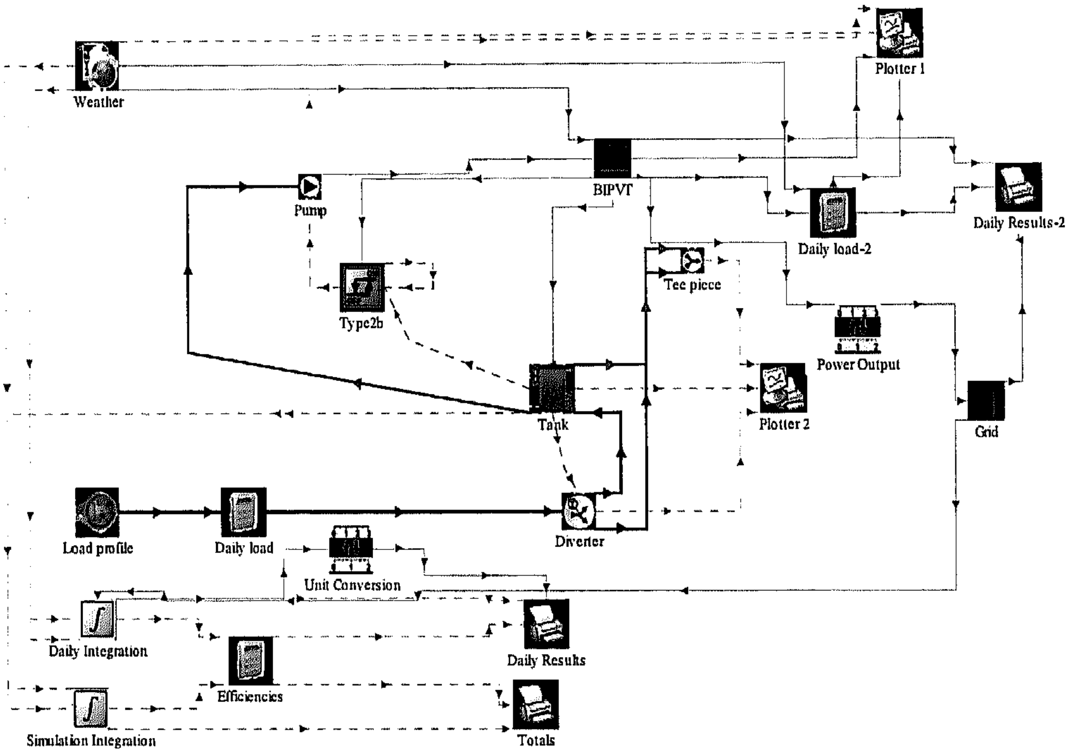

Figure 15. TRNSYS model of BIPVT.

In the simulation it was decided to examine a smaller single residence scale BIPVT system. As such, a collector of 4m^2 with a packing factor of 50% was assumed to be used in conjunction with a 300 L storage tank in Auckland, NZ. Furthermore, the water use profile of the system was given by Figure 16 and is typical of the use in an Australian or New Zealand residence (AS 4234:1994).

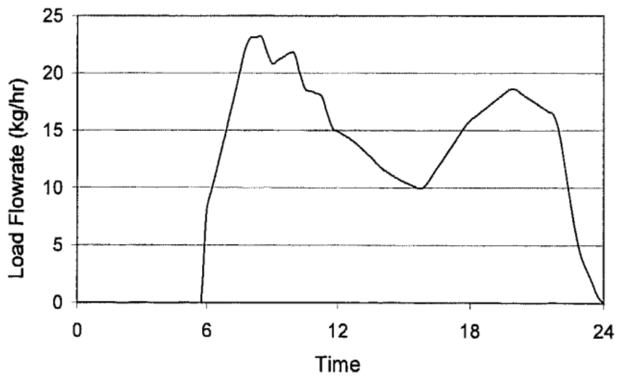

Figure 16. Hot water load profile.

From the simulations it was found that there were a number of advantages in using a BIPVT collector, the most obvious being to reduce the operating temperature of the PV cells, thereby improving their electrical performance. Take for example a plain PV module and an unglazed BIPVT collector, in Figure 17 it can be seen that during a week of operation during summer, that the cooling provided by the BIPVT results in a significantly lower cell temperature.

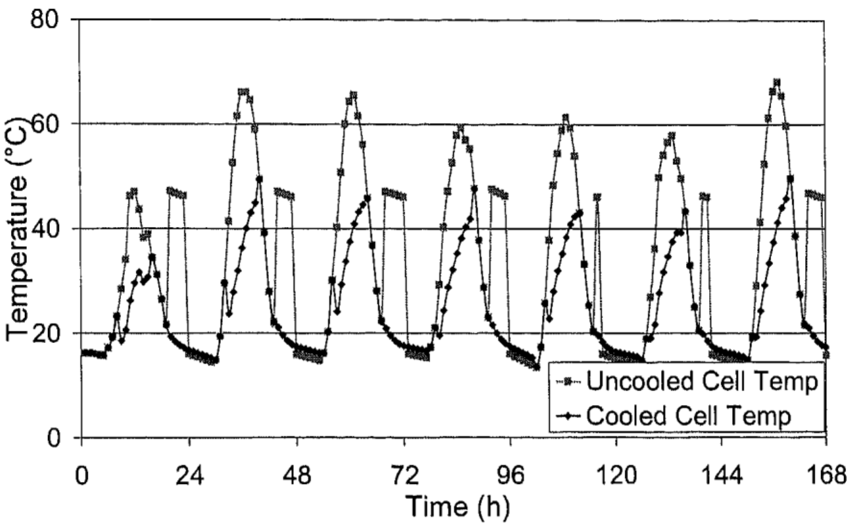

Figure 17. PV cell temperature during a summer week.

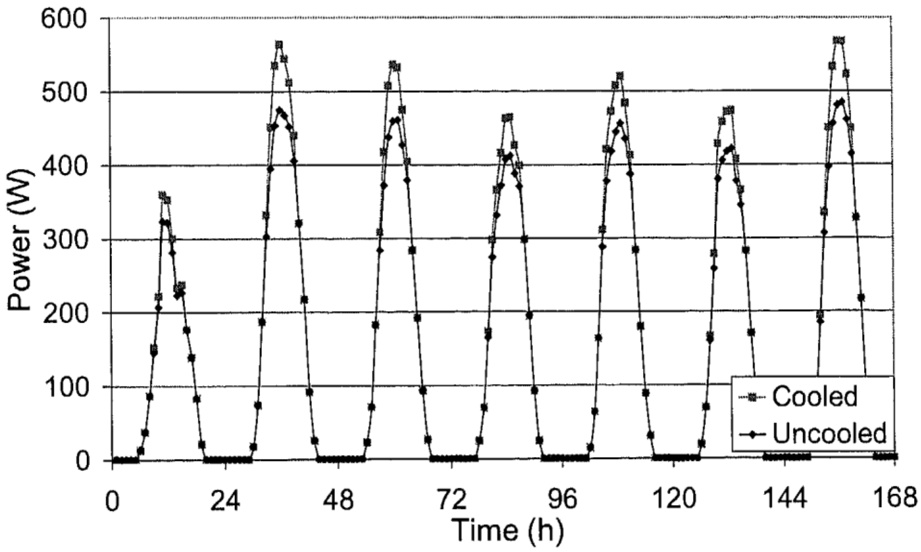

Figure 18. Power output from BIPVT and an uncooled PV module.

Furthermore, it can be seen that the decrease in temperature results in a significant improvement in the electrical output from the PV cells, as illustrated by Figure 18. This is due to the fact that the PV cells efficiency decreases with increased temperature as mentioned previously.

Similarly, for a glazed BIPVT with and without cooling there is a marked difference in both the cell temperature and electrical output. In Figures 19 and 20 it is shown that by not providing cooling to a glazed collector that the cells operate at a very high temperature which significantly decreases their electrical output.

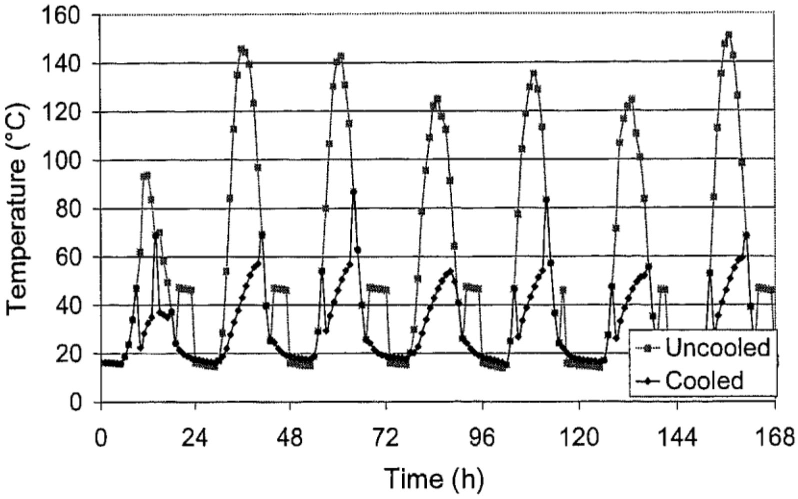

Figure 19. Cell temperature for glazed collector.

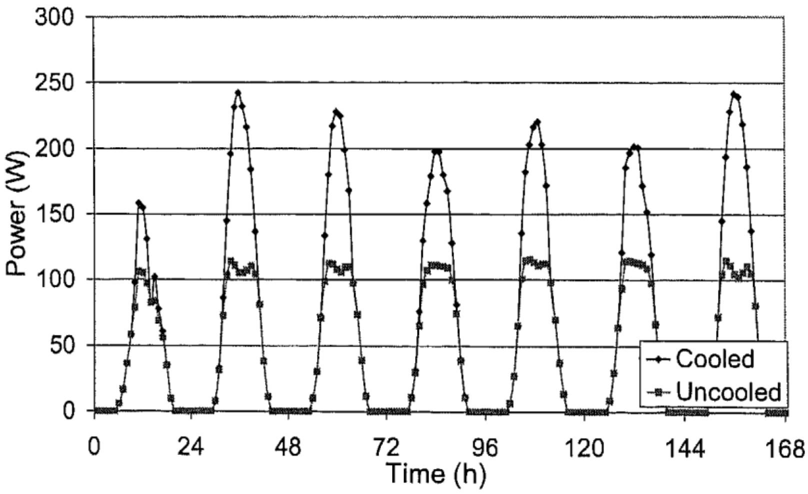

Figure 20. Electrical output from glazed collectors.

Moreover, in Figure 21 it can be seen that due to the increase in temperature of the cells in a glazed BIPVT system, that the electrical output from the PV cells is actually reduced when compared to standard PV module. However, perhaps the most significant benefit of the BIPVT is the fact that it reduces the use of electricity or other fuels for water heating. This is clearly illustrated in Figure 22 where it can be seen that the BIPVT reduces the auxiliary heating load significantly. Furthermore, in Figure 23 the benefits of using a layer of glazing to reduce heat loss from the collector are clearly illustrated. The addition of this glazing further reduces the net energy that needs to be supplied for water heating. As such, these results clearly demonstrate the potential advantages of BIPVT style collectors for areas where space is limited, but both electricity and water heating are required.

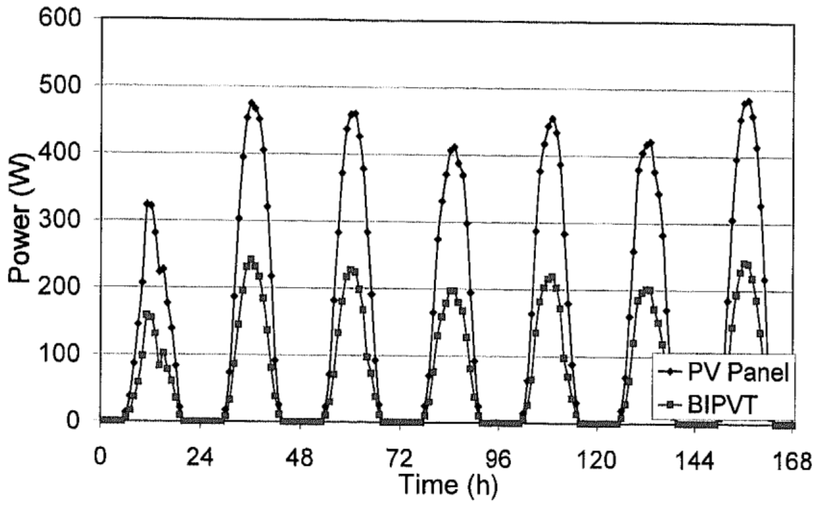

Figure 21. Electrical power from Glazed BIPVT and PV module.

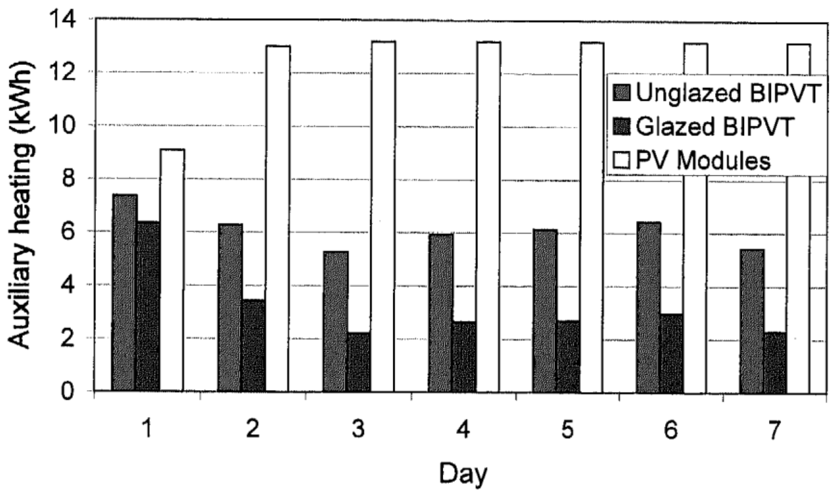

Figure 22. Auxiliary water heating demand for different collectors.

Based on these results it can be concluded that there is a significant long-term benefit in sing a combined BIPVT style collector rather than merely standard PV modules. Furtherore, although the use of glazing reduces the electrical performance of the collector, it offers significant savings in the energy used for heating. As such, for large high density residential installations where hot water and electricity are required, the glazed BIPVT has significant potential for energy savings.

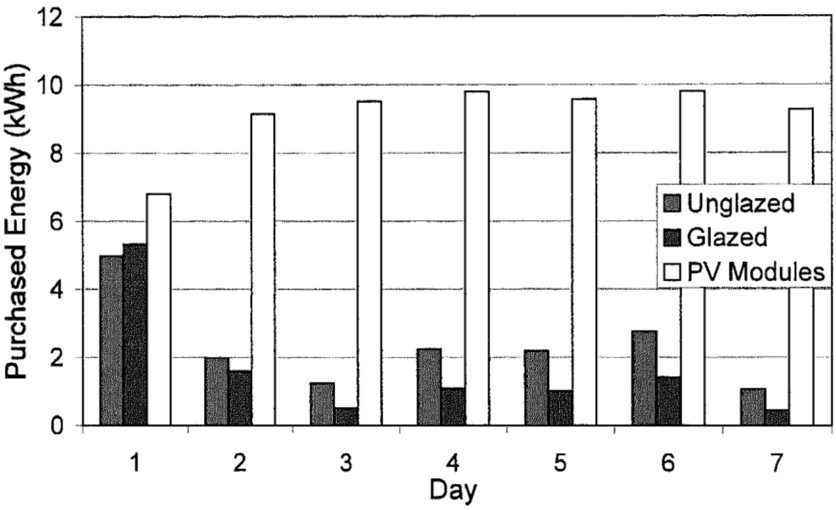

Figure 23. Net energy purchased to meet water heating load.

Conclusion

Over the course of this study a number of the design parameters associated with the development of a novel building integrated photovoltaic/thermal (BIPVT) solar collector have been examined. The influence of these on the performance of the BIPVT has shown that there are a number of ways in which to improve the performance of these collectors. Furthermore, by re-examining the design method, the possibility of using low cost materials such as steel, without significant performance reductions has been highlighted.

In addition, by integrating electricity generation, water heating and facade elements it is possible to reduce the complexity associated with traditional solar installations while also achieving an architecturally sensitive appearance. As such the BIPVT is ideally suited to environments where facade space with suitable solar access is limited, or where large numbers of people share a single building. The benefit of doing this has been shown through the use of transient simulation modelling.

Given the interest that surrounds the use of energy in our built environment, the increasing use of building integrated photovoltaics and a trend towards high density living, it is surely only a matter of time until BIPVT collectors become widely used.

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