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DEVELOPMENT OF A BUILDING INTEGRATED PHOTOVOLTAIC/THERMAL SOLAR ENERGY COGENERATION SYSTEM

ABSTRACT

Using renewable energy sources for onsite cogeneration from structural building elements is a relatively new concept and is gaining considerable interest. In this study the design, development, manufacturing and testing of a novel building integrated photovoltaic/thermal (BIPVT) solar energy cogeneration system is discussed.

Adhesives (ADH), resistance seam welding (RSW) and autoclaving (ATC) were identified as the most appropriate for fabricating BIPVT roofing panels. Of these manufacturing methods ADH was found to be most suitable for low volume production systems due to its low capital cost.

A prototype panel, fabricated using ADH methods, exhibited good thermal performance. It was also shown that BIPVT performance could be theoretically predicted using a one-dimensional heat transfer model and showed excellent agreement with experimental data. The model was used to suggest further design improvements. Finally, a transient simulation of the BIPVT was performed in TRNSYS and is used to illustrate the benefits of the system.

INTRODUCTION

With concern growing over the environment and resource use, there has been greater emphasis placed on sustainability, particularly in the built environment. One aspect of sustainable urban environments is the need to increase population density. 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 particularly 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.

In the late 1970's, a number of studies began to investigate incorporating photovoltaic and solar thermal into a single device, referred to as Photovoltaic/Thermal (PVT) solar collectors. There are two benefits to PVT: firstly, the efficiency of PV cells can be improved by actively cooling them using a solar thermal system. Secondly, by incorporating both systems into a single unit, the area dedicated to solar energy devices can be reduced.

In an early study Andrews (1981) showed that PVT collectors were, at the time, suited to low temperature heating operations such as pool heating but were not suitable for medium temperature operations due to the low cost of energy. However, 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.

Recently, He et. al. (2006) examined 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. Van Helden et. al. (2004) noted 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.

To date many of the studies conducted on water heating PVT collectors 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”.

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 and fulfills the need for a sustainable urban environment. 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 been largely 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”. Moreover, the EU-supported PV-Catapult program (PV Catapult, 2005) noted that the integration of PVT style collectors into a “plug-and-play” configuration, and the integration of PVT with roofing and facades, presented a number of challenges in the longer term.

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 – A NEW CONCEPT

As has already been noted, there is a strong need for PVT’s to be better integrated within the built environment. As a response to this need, a novel BIPVT collector has been developed that integrates photovoltaic cells with sheet metal roofing, as shown in Figure 1. Unlike many of the systems that have been proposed however, this system uses the roof of a building to act as the BIPVT solar collector, in this case a trough sheet-metal roof.

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.

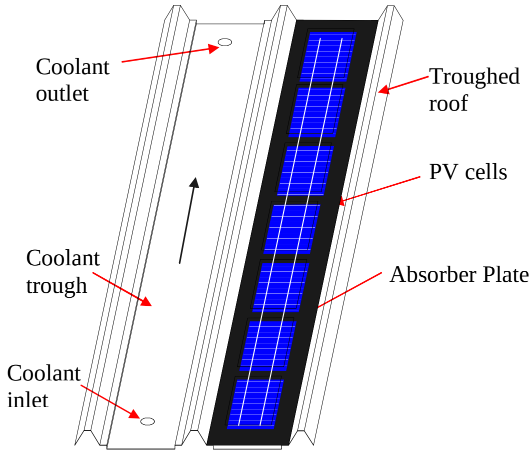

Figure 1: Schematic of BIPVT Collector

DESIGNING BIPVT FOR PRODUCTION

In a production environment eight production steps were identified as necessary in the manufacture of the BIPVT to ensure quick and efficient manufacture. These are:

1. Corrugating a flat metal sheet to form the trough roofing profile and central channel.
2. Punching holes in the central channels for thermal fluid inlets and outlets.
3. Bonding the collector plate to the troughed roof to form a confined passage for thermal fluid flow.
4. Sealing the central channels to prevent thermal fluid leakage.
5. Mounting fittings to connect manifolds to the central channels inlets and outlets on the underside of the troughed roof.
6. Laminating PV cells onto the collector plate and installing electrical fittings.
7. Sealing the edges between collector plate and troughed roof to prevent any water or dirt ingress into the joint.
8. Connecting manifolds to the inlet and outlet fittings for thermal fluid flow and operation of BIPVT system.

To fabricate BIPVT panels, adhesives (ADH), resistance seam welding (RSW) and autoclaving (ATC) were identified as suitable methods for bonding the collector plate, onto which the PV cells would be laminated, to the troughed roofing sheet in which the cooling troughs were formed. The method for the corrugation of the plain sheet, producing holes on the troughed roof sheet, sealing the edges between the collector plate and troughed roof sheet and the connection of the manifolds to the inlet and outlet points were common to all production methodologies.

In the ADH system, bonding the collector plate with the troughed roof sheet, sealing the central channel ends and mounting the fittings at the inlet and outlet points would be carried out using adhesives. In the RSW system, the collector plates would be resistance seam welded to the troughed roof sheet. Subsequently, the central channels end sealing and the mounting of nut fittings used to attach the manifold would be carried out. Finally, for production by both the ADH and RSW systems, a vacuum laminator could be used for the laminating the PV cells onto the collector plate after it had been bonded to the troughed roof sheet. In the ATC system, bonding collector plates onto the troughed roof sheet, sealing the central channel ends, mounting the fittings at the inlet and outlet points and lamination of the PV cells on the collector plate could be carried out in an autoclave in a single set-up using adhesives.

Although there is ample evidence to show that solar collectors have a positive aspect in terms of sustainability, from a commercial perspective there needs to be an incentive for companies to undertake the development of such products. As such, the capital cost for establishing a

BIPVT production system (Table 1) using ADH, RSW and ATC was determined for a "green field" site. For this scenario the equipment costs were multiplied by a Lang factor of 3.06, as suggested by Bouman et al. (2004) and were based on the assumption that the installed manufacturing equipment would operate 1,920 hours per annum, as shown in Table 2. Essentially, this means that more equipment must be installed if the production volume is to be increased but operation time remains fixed. Finally, it was assumed that each process step can process 1 BIPVT panel at a time except for ATC which could process 3 panels at time.

Table 1. BIPVT capital costs for ADH, RSW and ATC production systems.

Operation no.	Production step	Equipment cost		
		ADH	RSW	ATC
1	Corrugation of plain sheet	$250,000 (McClew,2007)	$250,000 (McClew,2007)	$250,000 (McClew,2007)
2	Punching holes on corrugated sheet	$10,000*	$10,000*	$10,000*
3	Joining collector plate with corrugated sheet	$33,500 (Loctite, 2007)	$80,000 (Tagg, 2007)	$600,000** (Spire, 2007 and Matches, 2003)
4	Sealing ends on central channel		$5,000*	
5	Mount fittings on corrugated sheet	$5,000*	$5,000*	
6	Laminating PV strings on collector plate	$400,000 (Spire,2007)	$400,000 (Spire,2007)	
7	Sealing the bonded edges between collector plate and corrugated sheet	$5,000*	$5,000*	$5,000*
8	Attaching manifolds to the corrugated sheet	$5,000*	$5,000*	$5,000*
Total equipment cost (TEC)		**$708,500**	**$760,000**	**$870,000**
Capital investment (CI = TEC x Lang factor 3.06)		**$2,168,010**	**$2,325,600**	**$2,662,200**

*equipment used would be custom made and associated costs were assumed
** $200,000 for 12 m^3 vacuum autoclave (Matches, 2003) and $400,000 for laminating fixtures (Spire, 2007)

The slowest production steps, including the total time at which the panel is at rest or moving between process steps, for the proposed manufacturing methods are: joining the collector plate to the corrugated sheet, autoclaving and PV lamination (Table 2). RSW has the slowest panel cycle time due to it having more process steps and resting time than ADH (42.5 minutes) and ATC. ATC has the fastest process cycle time of 32.5 minutes as multiple operations are performed at once, thus reducing overall processing time.

Additionally, process times for each BIPVT production step were compared to determine the time consuming or rate limiting steps, presented as a production rate in panels per minute. The step with the lowest throughput, or rate limiting step, was used to determine the total process throughput. Although the autoclave step in the ATC process took 20 minutes per cycle it could process 3 panels at a time, hence the 0.15 panels per minute. ATC had the greatest process throughput and for an operating time of 1,920 hrs per annum (8 hour per day, 5 days per week for 48 weeks) could produce 17,280 panels (Table 2). It is possible to increase production capacity by installing additional equipment to increase throughput at the rate limiting steps. For example two seam welders could be installed for operation number 3 for RSW raising throughput from 0.06 to 0.12 panels per minute.

Table 2. Process times for each BIPVT production step and production capacity.

Operation no.	Production step	Time per panel (minutes)		
		ADH	**RSW**	**ATC**
1	Corrugation of plain sheet by	2 (McClew,2007)	2 (McClew,2007)	2 (McClew,2007)
2	Producing holes on corrugated sheet	2.5*	2.5*	2.5*
3	Joining collector plate to corrugated sheet	10 (Loctite, 2007)	18***	20** (Krauter,2006)
4	Sealing central channels at each end		5*	
5	Mounting fittings to the corrugated sheet	5*	5*	
6	Lamination of PV strings on collector plate	15 (Krauter,2006)	15 (Krauter,2006)	
7	Sealing the edges between bonded corrugated sheet and collector plate	4*	4*	4*
8	Attaching manifolds to corrugated sheet	4*	4*	4*
Total labour per panel (min)		**42.5**	**55.5**	**32.5**
Rest time in cycle between steps (min)		**5**	**7**	**5**
Total panel processing time (min)		**47.5**	**62.5**	**37.5**
Process throughput (panels/min) based on slowest step		**0.07**	**0.06**	**0.15**
Panels per year for 1,920 hrs operating time		**7,680**	**6,400**	**17,280**

*The process times were estimated from building the prototype and taking into account that skilled labourers would be carrying out the operations.
**The cycle time for ATC is more than lamination as more steps are processed in single set-up.
***Resistance seam welding (welding speed of 1.8 m/min, 24 m total weld length for one panel)

Although the production of PV modules can be highly automated, it was assumed that a degree of manual labour would be needed to produce a BIPVT panel. In New Zealand the average pay rate for a fitter and turner is $20 per hour (Labour, 2006). Overheads charged at 100% of the hourly pay rate to cover administrative costs are shown in Table 3. Machine operating costs were assumed to be 10% p.a. of the equipment purchase cost. Energy consumption (Table 3) for the equipment was estimated to represent approximately 1% of the total equipment purchase cost per annum. This was multiplied by a factor to account for expected energy intensity of each production methodology: these were set at 1 for ADH, 2 for RSW and 4 for ATC. ATC was expected to use the most energy as it would require a 12 m^3 chamber to be heated to 175^{o}C to cure each panel under vacuum.

ATC has the lowest labour costs per panel (Table 3), as it has the lowest number of process steps. In addition, it has the lowest operating cost per panel because it has the greatest production capacity. Operating cost per panel for ATC was only $29 per panel greater than the material costs, whereas ADH was $38 and RSW was $51. Labour costs, machine and energy costs combined represent only 2.6, 3.6 and 4.9% of the operating costs for ATC, ADH and RSW respectively. This shows that the major contributor to operating costs is the material costs for the panels. Therefore any savings should be made by trying to reduce material costs, and more specifically, ways of reducing PV costs should be investigated.

Table 3. Cost per panel including labour, machine and energy.

Parameter	Production system		
	ADH	RSW	ATC
Total equipment cost (TEC)	$708,500	$760,000	$870,000
Panels per year for 1,920 hrs operating time (N)	7,680	6,400	17,280
Labour per panel (min)	42.5	55.5	32.5
Labour cost per panel (including overhead) (LC)	$28	$37	$22
Labour cost per year (A=LC x N)	$217,600	$236,800	$374,400
Machine operating cost per year (B = 10% of TEC)	$70,850	$76,000	$87,000
Equipment energy consumption per year (C=1% of TEC x factor*)	$7,085	$15,200	$34,800
Material cost per panel (Unglazed) (MP)	$1,050	$1,050	$1,050
Material cost per year (D=MP x N))	$8,064,000	$6,720,000	$18,144,000
Total operating costs per year (TO = A+B+C+D)	**$8,359,535**	**$7,048,000**	**$18,640,200**
Cost per panel (CP = TO/N)	**$1,088**	**$1,101**	**$1,079**

* Factor is 1 for ADH, 2 for RSW and 4 for ATC.

To demonstrate the business case for establishing a BIPVT production system, the net profit per year and payback time were calculated for a factory producing unglazed steel BIPVT collectors using the capital cost, revenue and operating costs per year and depreciation as shown in Table 4. Each panel was assumed to have a market value of $1,400, and the production equipment life time was assumed to be 5 years, depreciating 20% each year. Each process was assumed to be operating at 100% production capacity (1,920 hours per year) and that all panels produced each year would be sold.

Table 4. Payback period, net profit analysis for production systems.

Production step	Production system		
	ADH	RSW	ATC
Capital investment (CI)	$2,168,010	$2,325,600	$2,662,200
Deprecation (DC = 20% of CI)	$433,602	$465,120	$532,440
Panels per year for 1,920 hrs operating time (N)	7,680	6,400	17,280
Total operating costs per year (TO)	$8,359,535	$7,048,000	$18,640,200
Cost per panel (CP = TO/N)	$1,088	$1,101	$1,079
Market value per panel (MV)	$1,400	$1,400	$1,400
Revenue before tax (RT = MV x N)	$10,752,000	$8,960,000	$24,192,000
Gross profit before tax (GP = RT – TO)	$2,392,465	$1,912,000	$5,551,800
Gross profit after tax (33%) (GPT = GP x 0.67)	$1,602,952	$1,281,040	$3,719,706
Net profit per year (NP = GPT + DC)	$2,036,554	$1,746,160	$4,252,146
Gross margin (GM = GPT/RT)	14.91%	14.30%	15%
Return on investment (ROI = NP/CI)	94%	75%	160%
Payback time (years) (PT = CI/NP)	**1.06**	**1.33**	**0.63**

RSW generated the lowest net profit per year (Table 4) and has a payback time of 1.3 years. ATC, despite having the greatest capital investment, has the lowest payback time, the greatest return on investment and the greatest net profit. This is attributable to the fact that it has the greatest production capacity. However ADH also presents an attractive alternative as it has the lowest capital cost, the second highest production capacity and second shortest payback period. In light of this, it would appear that the use of ADH presents a reasonable compromise for manufacturing BIPVT collectors.

BIPVT ANALYSIS AND TESTING

Having established a suitable manufacturing method, a prototype BIPVT panel was fabricated and tested to determine its thermal efficiency using a steady state outdoor thermal test setup similar to that recommended in AS/NZS 2535.1 (1999). A one dimensional steady state thermal model was developed to examine the design of the BIPVT collector using the modified Hottel-Whillier equations presented by Vokas et. al. (2006). The results in Figure 2 show that the model is able to predict the thermal efficiency of the BIPVT collector extremely well.

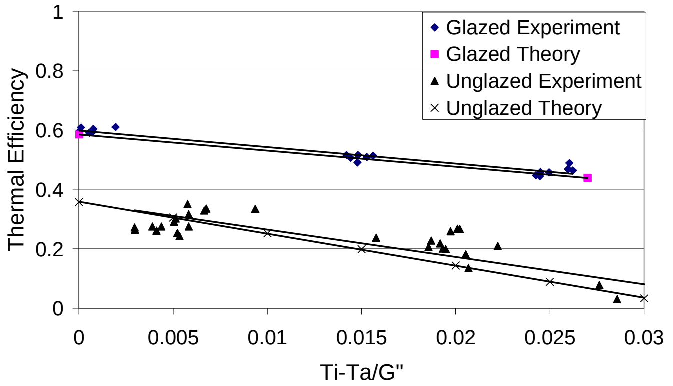

Figure 2: Schematic of BIPVT Collector

Results from this model, showed BIPVT electrical and thermal efficiency could be significantly improved by increasing the geometric fin efficiency, or the ratio of the cooling trough hydraulic diameter (d) to the space between adjacent cooling troughs (W) (Figure 3). By increasing the fin efficiency cheaper materials with lower thermal conductivity, such as steel, can be used (Figure 4). Given that one of the biggest impediments to the uptake of solar water heaters is initial cost (EECA, 2004) this is a desirable outcome.

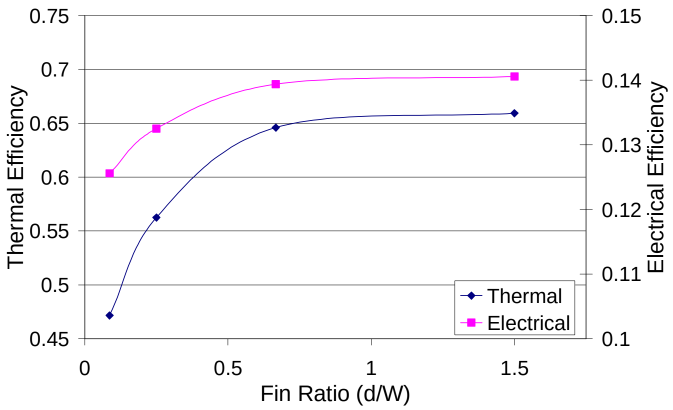

Figure 3: Efficiency v Fin Ratio

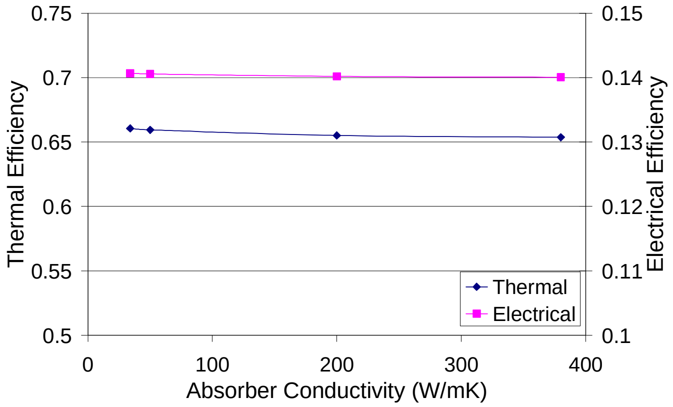

Figure 4: Efficiency v Absorber Conductivity

LONG TERM PERFORMANCE BENEFITS OF A BIPVT

As mentioned earlier, 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. To demonstrate the advantage of the optimized BIPVT discussed above, 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.

The 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). A 4m^2 BIPVT system, with a packing factor of 50%, coupled to a 300 L (Type 4) stratified tank, was simulated using the water use profile specified in AS 4234:1994 for a typical meteorological year in Auckland. This is similar to what might be used in a large apartment complex to provide water heating and power to an individual apartment.

The simulations demonstrated several advantages in using a BIPVT collector, the most obvious being to reduce the PV cells operating temperature, thereby improving their electrical performance. However, the most significant benefit of the BIPVT is that it reduces electricity, or fuel consumption, for water heating. This is clearly illustrated in Figure 5 where it can be seen that the BIPVT reduces the auxiliary heating load significantly. Furthermore, in Figure 6 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.

Based on these results it can be concluded that there is a significant long-term benefit in using a combined BIPVT style collector. Furthermore, 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.

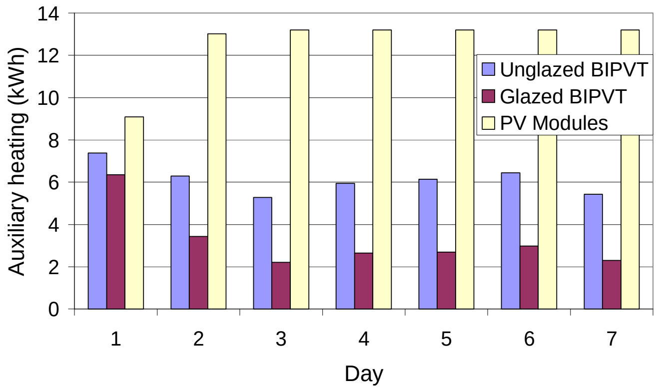

Figure 5: Auxiliary water heating demand for different collectors

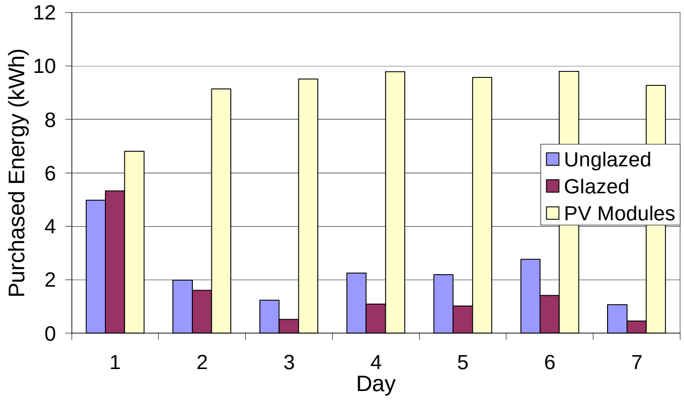

Figure 6: Net energy purchased to meet water heating load

CONCLUSION

Over the course of this study a number of the parameters associated with the development of a novel building integrated photovoltaic/thermal (BIPVT) solar collector have been examined. The influence of these parameters on the economics of manufacturing BIPVT collectors as well as the performance of the BIPVT collectors themselves 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 façade elements it is possible to reduce the complexity associated with traditional solar installations while also achieving an architecturally sensitive appearance. As such 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, and the sustainability of, our built environment, the increasing use of building integrated photovoltaics and a trend towards high density and sustainable living practices, it is surely only a matter of time until BIPVT collectors become widely used.

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