INVESTIGATION OF PRODUCTION SYSTEMS FOR A BUILDING INTEGRATED PHOTOVOLTAIC THERMAL PRODUCT

SUNILKUMAR BURA, MIKE DUKE, MARK LAY, TIM ANDERSON

Department of Engineering, University of Waikato, Hamilton, New Zealand

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ABSTRACT

Integration of solar energy devices with building products is one of the fastest growing markets in the building industry. Building integrated products are multifunctional and fit into a standard façade or roofing structure. This paper discusses a building integrated photovoltaic thermal collector (BIPVT) capable of generating electrical and thermal energy. Different production methodologies for manufacturing of the BIPVT system are discussed. Prototypes were manufactured as per the researched production methodologies. The optimum production systems for manufacturing the building integrated system were selected from the economic analysis and performance of the manufactured prototypes.

KEYWORDS:

Building integrated photovoltaic thermal; payback time; production economics.

INTRODUCTION

Each year the solar energy received by the New Zealand land mass is approximately 3,000 times greater than current energy consumption (E.E.C.A, 2001). Furthermore, the average roof of a New Zealand houses is exposed to approximately 20-30 times more incident solar energy than the current energy consumed within it (E.E.C.A, 2004). Solar thermal and photovoltaic (PV) collectors are commonly used to harness the sun’s energy (E.E.C.A, 2001) and are typically installed as separate units on building roofs or walls to supply heat and electricity to the building. A current trend is to integrate these systems into the building roofing or cladding (Carrow, 1999) for a more aesthetically pleasing and multifunctional product. These products are known as building integrated energy products. They not only serve as weatherproofing a building, but also generate electrical (Building integrated photovoltaic) or thermal energy (Building integrated thermal) (Eicker, 2003). There are currently many building integrated photovoltaic (BIPV) products on the market, such as the Sunslate (Posnansky et al., 1998) and United Solar’s PV Shingles in the form of roofing components (United Solar Ovonic, 2003). Building integrated solar thermal systems (BIT) are less common due to complexities of manufacture and installation. Even though there are potentially several advantages to integrate both PV and solar thermal technologies into a building product (BIPVT) none have been produced commercially.

At the University of Waikato a BIPVT system is being developed that integrates PV and thermal systems into long-run metal roofing. The product is aimed predominantly for the New Zealand and Australian markets that could potentially be introduced into global markets.

BIPVT OVERVIEW

BIPVT components combine PV and solar thermal systems and integrate them into building components such as roofing or wall cladding allowing them to generate electricity and heat from solar radiation. The building product considered most suitable for BIPVT is troughed and standing seam profile long-run roofing systems commonly used in New Zealand. This is because these roofing products have profiles with long flat surfaces suitable for mounting PV cells.

Major components of the BIPVT developed at University of Waikato include the corrugated or torough? sheet roof, collector (absorber) plates, PV laminates, and manifolds. The corrugated sheet acts as the housing of the BIPVT system and supports the collector plate and PV laminates. The sheet has central channels in the troughs with inlet and outlet points for the thermal fluid to flow through this system (Figure 1). The collector plate acts as the backing plate for PV laminates, absorbs the heat from the laminates and transfers the heat to the thermal fluid. The collector plate is bonded into the trough section of the corrugated sheet and sealed along the outside edges and the central channel. The collector plate covers the central channel which creates a confined passage for thermal fluid flow. Inserts seal the central channels ends between the corrugated sheet and collector plate to prevent thermal fluid leakage from the system. Manifolds are used to supply and collect the thermal fluid flowing through the product and are mounted underneath the corrugated sheet using nut and stud bolt fittings. Hollow stud bolt fittings are used to carry the thermal fluid from the manifolds to the corrugated sheet.

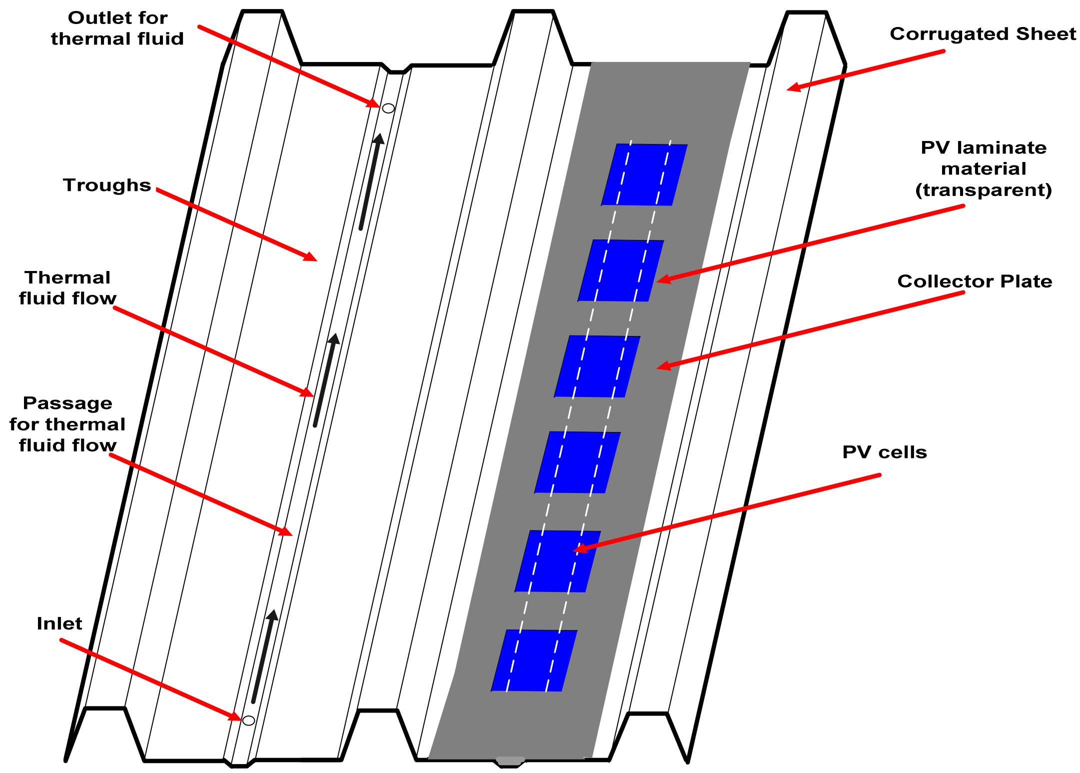

Figure 1: Schematic view of BIPVT product

BASIC PRODUCTION METHODOLGY

The manufacturing of the BIPVT would consist of a series of production and quality control steps, organised and specific processes selected so manufacture is quick and efficient. Eight production and three quality control steps were identified as necessary in the manufacture of the BIPVT. These are:

Production steps:

1. Corrugating flat metal sheet by press-brake to form the roofing profile including troughs and central channel.
2. Punching holes in the central channels for thermal fluid inlets and outlets.
3. Bonding the collector plate into the trough sections of the corrugated sheet to form a confined passage for thermal fluid flow.
4. Sealing the central channels at each end of the roofing section by special inserts to prevent thermal fluid leakage.
5. Mounting nut fittings for connecting manifold to the central channels inlets and outlets on the underside of the corrugated sheet.
6. Laminating glass sheet, ethyl vinyl acetate (EVA), PV and EVA onto the collector plate and installing electrical fittings.
7. Sealing the edges between collector plate and corrugated sheet by adhesives/sealants for preventing any flow into the join.
8. Connecting manifolds to the inlet and outlet points with stud bolt fittings for thermal fluid flow and operation of BIPVT system.

Quality steps:

1. Between steps 5-6 the central channel is checked for fluid leakage from bonds between collector plate and corrugated sheet, from seals at each end of the channel and the inlet and outlet fittings.
   At this point the product is suitable for Building integrated thermal (BIT).
2. Between steps 6-7 the product is checked for lamination quality and electrical properties.
3. After step 8 the manifolds are checked for leaks and the product for heating and cooling efficiency. Wouldn't this have been established during prototype testing and be set by the design assuming it was assembled correctly as established by the other quality control steps?

IDENTIFICATION OF MANUFACTURING METHODS

Adhesives (ADH), resistance seam welding (RSW) and autoclaving (ATC) were identified as suitable methods for manufacturing BIPVT collectors. These were categorised based on the method used for joining the collector plate to the corrugated sheet.

It was identified that the method for the corrugation of the plain sheet, producing holes on the corrugated sheet, sealing the edges between the collector plate and the corrugated sheet and connecting the manifolds to the inlet and outlet points could be made using three common production methodologies.

However, in the ADH system, the bonding of the collector plate with the corrugated sheet, sealing the central channel ends and mounting of the nut fittings at the inlet and outlet points would be carried out using adhesives. Similarly, in the RSW system, the collector plates would be resistance seam welded to the corrugated sheet. Subsequently, the central channels end sealing and the mounting of nut fittings at the inlet and outlet points would be carried out by brazing or soldering. Finally, for production by both the ADH and RSW systems, a vacuum laminator would be used for the laminating the PV cells onto the collector plate after it had been bonded into the trough.

In the ATC system, the bonding of collector plates onto the corrugated 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 would be carried out in an autoclave in a single set-up using adhesives.

PROTOTYPE PRODUCTION:

To confirm the use of the ADH method of manufacture, prototypes were constructed using Colorcote corrugated sheet (2 m long by 0.56 m wide and 0.55 mm thick, zinc or aluminium/zinc coated? Acrylic, Polyester or PFV2 coating type?) and two collector plates (2 m long by 0.18 m and 0.55 mm thick) supplied by Dimond Ltd. Mild steel connector pipes, 70 mm long, 10 mm ID and 12 mm OD with a 22 mm diameter and 1 mm thick flange were used for the thermal fluid flow at the inlet and outlet points. A silicon based adhesive (Dow Corning 732 ™) was used for the bonding of the corrugated sheet with the collector plate and sealing the central channel ends with the inserts (70 mm long by 20 mm wide and 5 mm thick). After the curing of the adhesive, the BIPVT was tested for any leaks through the central channel.

Subsequently, the PV strings, made from polycrystalline PV cells (125 mm by 125 mm, 0.5 V, 2 A), were encapsulated on the collector plate using a transparent resin (Figure 2). After the curing of the resin, the BIPVT prototype was connected to the mains water supply and water pumped through the central channels to check the thermal and electrical performance of the product.

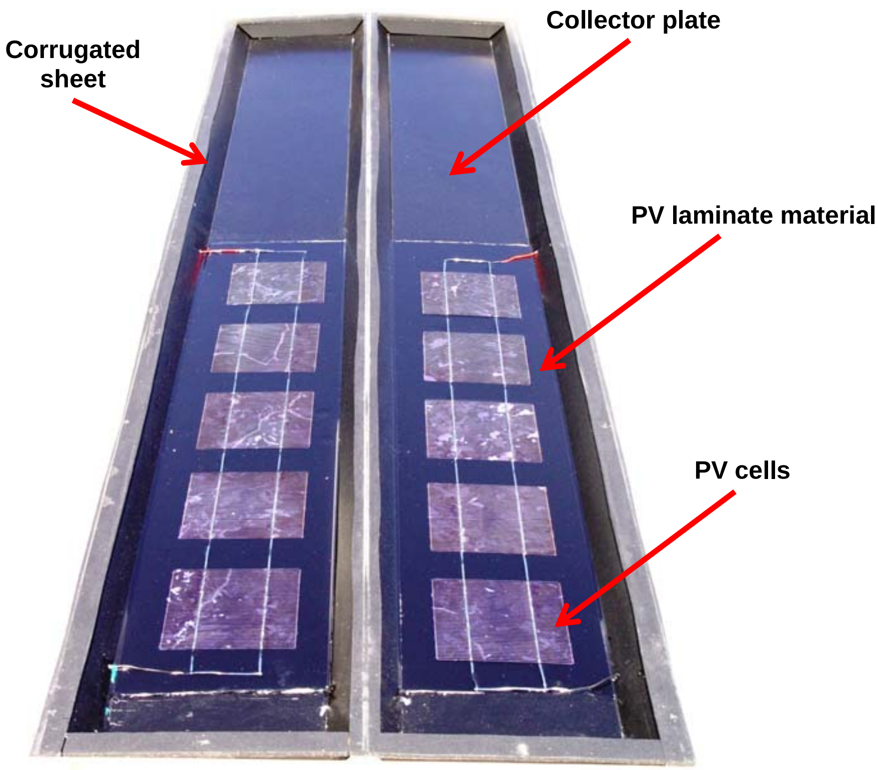

Figure 2: Unglazed BIPVT Colorcote prototype produced using adhesives

MANUFACTURING COSTS

Capital costs, process times and production capacity:

The capital cost for establishing a BIPVT production system (Table 1) using ADH, RSW and ATC was determined from the references shown or, where necessary, by estimating the equipment purchase costs. In addition, it was assumed that the BIPVT system would be applied to a "green field" site and as such the equipment costs were multiplied by a Lang factor of 3.06, as suggested by Bouman et al. (2004). Furthermore, the equipment costings were based on the assumption that the installed manufacturing equipment would have a fixed operation time of 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, in the process costings, it was assumed that each process step can process 1 BIPVT panel at a time except for ATC which can 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 by press-brake	$250,000 (Dimond,2007)	$250,000 (Dimond,2007)	$250,000 (Dimond,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 (RSW specialist, 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)

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 press-brake	2 (Dimond,2007)	2 (Dimond,2007)	2 (Dimond,2007)
2	Producing holes on corrugated sheet by punching	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)

In Table 2 it was observed that the slowest production steps for the proposed manufacturing methods are joining the collector plate to the corrugated sheet, autoclaving and PV lamination. Included in the process times is the total time at which the panel is at rest or moving between process steps. Furthermore, it was found that RSW had the slowest panel cycle time of 62.5 minutes, this is due to it having more process steps and resting time than ADH (42.5 minutes) and ATC. The use of ATC had the fastest process cycle time of 32.5 minutes, this is explained by noting that 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, this can be holistically 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. From Table 2 it was shown that 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.

To overcome the influence of time consuming production processes, 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 thus raising throughput from 0.06 to 0.12 panels per minute.

Materials costs:

For the purposes of this study it was assumed that the area of the corrugated sheet and the collector plate used for a BIPVT panel were 3.384 and 2.16 m^2 respectively and were made from Colorcote steel. In addition 4 pairs of nuts and custom built hollow stud bolts would be required to join the collector to the distribution manifolds. Furthermore, it was assumed that the manifolds were to be made of copper tubing, with a total length of 0.6 m and were to be fitted with standard fittings used in hot water systems.

Based on this, the typical PV module for a BIPVT panel of 3.384 m^2 (6m x 0.564m) would have a PV area of 1.50 m^2 which would be evenly spread across two collector plates. For each collector plate the PV lamination area would be 0.75 m^2. On each collector plate, up to 36 mono or poly-crystalline 150 x 150 mm cells could be laminated. Each cell generates a maximum of approximately 3Wp, therefore each BIPVT would generate approximately 200 Wp. PV cell prices, including materials for lamination, are $3/Wp estimated from the current module and retail price (Solarbuzz, 2007), therefore the materials for PV lamination including the cells is estimated to be $600 per panel. The component costs per panel are summarized in Table 3.

Table 3. Component costs for BIPVT unglazed made from Colorcote steel.

Component	Qty.	Cost per panel($)
Corrugated sheet	3.384 m^2	$228 (Rawlinsons, 2005)
Collector plate	2.16 m^2	$146 (Rawlinsons, 2005)
PV laminates (total)	1.49 m^2	$600 (Solarbuzz, 2007)
Nuts and hollow stud bolts	4	$40 (EDL and ARP, 2007)
Copper tubes for manifolds	0.6 m	$30 (Micometals, 2007)
Consumables		$6
Total cost per panel		**$1050**

Labour, machine, energy costs and operating cost per 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). Furthermore, overheads charged at 100% of the hourly pay rate to cover administrative costs are shown in Table 4. In addition, in Table 4, it was assumed that the machine operating costs per year were 10% of the equipment purchase cost. This would include the cost of consumables such as hydraulic fluid for the press-brake, repairs, and maintenance necessary for keeping the machine at the required operating level.

Although equipment energy consumption costs per year were not known, it was estimated that this would be approximately 1% of the total equipment purchase cost. Furthermore, 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 requires a 12 m^3 chamber to be heated to 175^{o}C to cure each panel under vacuum. Approximate energy costs are shown in Table 4.

Table 4. 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 min (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 Colorcote (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.

In Table 4 it can be seen that ATC has the lowest labour costs per panel, this is because it has the lowest number of process steps. In addition, it also 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 showed that the major contributor to operating costs were 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.

Economic analysis:

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 Colorcote BIPVT using the capital cost, revenue and operating costs per year and depreciation as shown in Table 5. Each panel was assumed to have a market value of $1,400, based on a mark-up of approximately 1.3 times the operating cost. The production equipment life time was assumed to be 5 years and depreciating 20% each year. Furthermore, it was assumed that each process would be operating at 100% production capacity (1,920 hours per year) and that all panels produced each year would be sold.

Table 5. 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 (D = 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**

From Table 5 it can be seen that RSW generated the lowest net profit per year, of $1.75 million, and had a payback time of 1.3 years (Table 5). ATC, despite having the greater capital investment, had the lowest payback time (7-8 months) the greatest return on investment and the greatest net profit, of $4.25 million per year. This is chiefly attributable to the fact that it has the greatest production capacity. ADH also presents an attractive second alternative as it has the lowest capital cost and second highest production capacity.

Payback time with production volume:

Process payback time was investigated for ADH, RSW and ATC systems for 1,920 operating hours per year for unglazed Colorcote BIPVT production volumes from 5,000 to 90,000 panels per year (Figure 3). The BIPVT product was sold at $1,400 per panel.

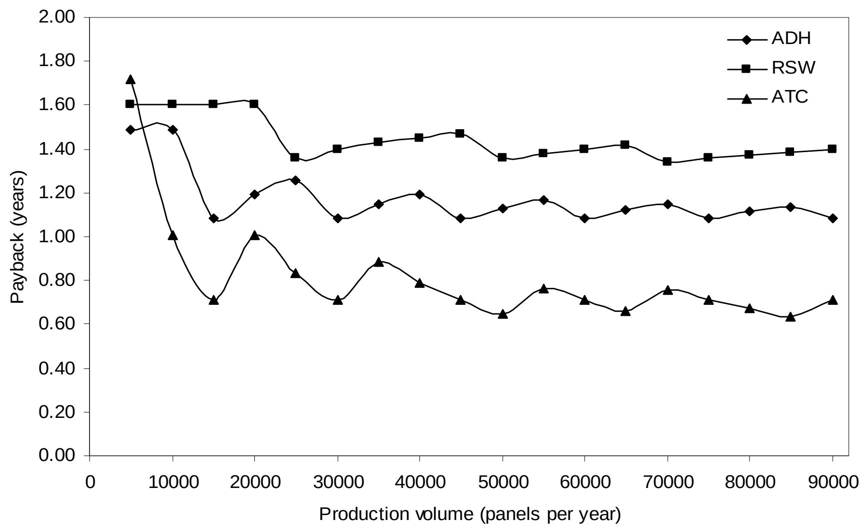

Figure 3. Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/year).

For each production system, additional production lines were included when the production volume was higher than the installed capacity. This is reflected in the crests for each plot in Figures 3. As production volume approached installed production capacity the payback time decreased until additional equipment was installed. Minimum payback times for 1,920 hrs process in Figure 3 are the same as in Table 5 when machine utilisation approaches 100%.

Similarly, increasing process operating time in a year reduces payback because of the increased production volume. The lowest payback time (~3 months) was for ATC working for 3 shifts a day (24 hrs per day, 5 days per week and 48 weeks a year) producing 50,000 panels a year. Therefore rather than increasing the number of production lines, the company could increase the number of shifts the process operated over each day to avoid the additional capital costs involved in installing additional production lines.

Material costs

As has been noted previously, the material costs play a vital role in the operating costs and the payback time of the manufacturing operation. The total cost per panel for an ADH production system operating 1,920 hours with a production volume of 7,680 panels per year is $1,088 (Table 4). To illustrate the dominance of the material costs in the operation the percentage contribution of the operating and materials costs with respect to the total operating cost per panel are shown in Figure 4.

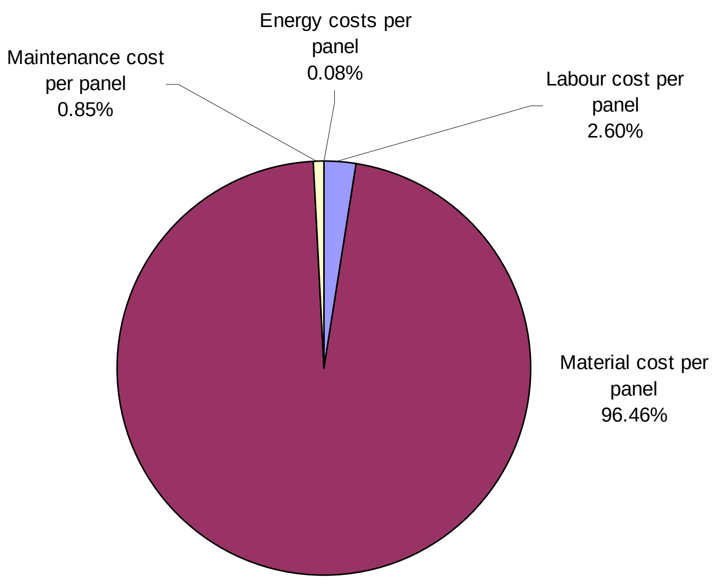

Figure 4. Materials, maintenance, labour and machine costs per panel

As is clearly illustrated, the material costs per panel account for 96.46% of the total operating cost per panel followed by labour, maintenance and energy. As such, the operating cost per panel and the payback time are dependent on the material costs. By reducing the material costs and maintaining the same market value per panel the payback time of the manufacturing operation is reduced and vice versa.

Material costs and payback time

To further analyse the sensitivity of the manufacturing process to the material cost, the change in material costs vs payback time for ADH, RSW and ATC systems operating 1,920 hours per year at 100% production capacity was analysed (Figure 5). The change in material costs for an unglazed Colorcote BIPVT was analysed for a variation of -30% to +30% to the present estimated cost of $1,050 (Table 3). The total number of panels produced for 1,920 operating hours for ADH, RSW and ATC systems are 7,680, 6,400 and 17,280 respectively.

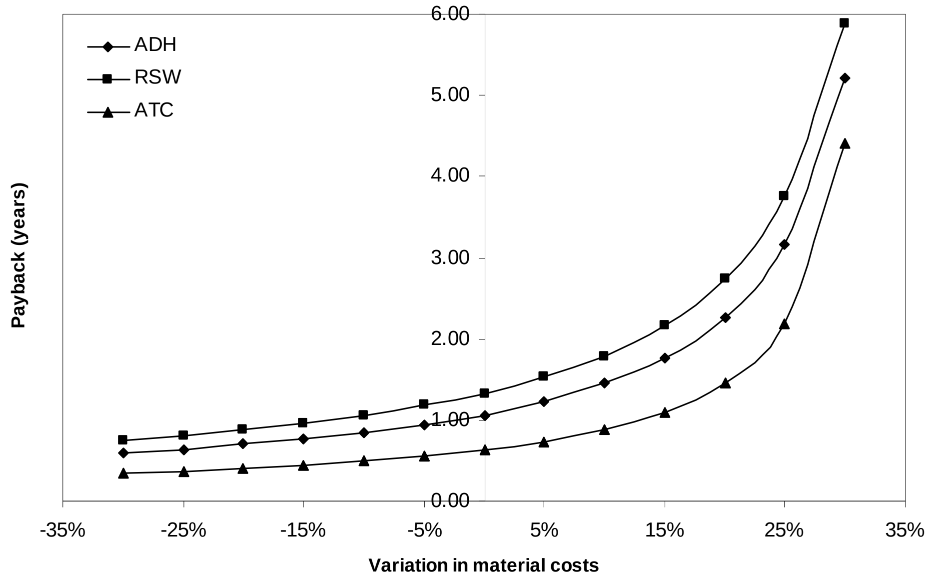

Figure 5. Payback time vs variation in material costs at fixed market value per panel for ADH, RSW and ATC systems operating 1,920 hours at 100% capacity.

From this it is again seen that the change in material costs affects the payback time for all the three production systems (Figure 5). The maximum change in payback time for change in material costs from -30% to +30% was observed in RSW (5.13 years) followed by ADH (4.63 years) and ATC (4.06) system.

CONCLUSIONS

In this study a number of methods for the manufacture of a BIPVT collector were analysed. Adhesives (ADH), resistance seam welding (RSW) and autoclaving (ATC) were considered the most suitable. Processes were designed for the three methods and investigated through economic analysis. ATC was found to be the best for production volumes greater than approximately 6,000 BIPVT panels per year this is because it has greater production capacity and lower capital investment payback time than ADH and RSW. However ATC has several technical challenges that need to be overcome whereas ADH and RSW are proven production methods. Furthermore, ADH is more suitable for low production volumes below 6,000 panels per year as it has a low capital cost in comparison with RSW and ATC and can be readily optimised when increased production is required. Cost savings can be achieved by reducing material costs as they represent 95% of the total operating costs for all methods. The change in material costs at a fixed market value per panel affects the payback time for all the three production systems with the maximum variation being observed in RSW system.

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