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Investigation of production systems for a building integrated photovoltaic thermal product

A thesis submitted in partial fulfilment
of the requirements for the degree of
Masters of Engineering
in Mechanical Engineering

by

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Abstract

A building integrated photovoltaic thermal (BIPVT) system based on long-run metal roofing is being developed at the University of Waikato in partnership with Dimond Ltd., a long-run roof product manufacturer. The concept consists of a CNC folded metal roofing sheet with a central channel and a collector plate bonded to the roofing sheet to create a sealed channel for thermal fluid flow. PV laminates are bonded to the collector plate and inlet and outlet manifolds attached for thermal fluid distribution. When exposed to solar radiation the system generates heat and electricity for domestic and industry use.

BIPVT manufacturing methods were investigated for creating the sealed channel for thermal fluid flow. 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 20,000 BIPVT panels per year as it has greater production capacity and lower capital investment payback time than ADH and RSW. ATC had a payback time of 0.26 years for 90,000 BIPVT panels per year at a 40% mark up. However ATC has several technical challenges that need to be overcome whereas ADH and RSW are proven production methods. ADH is more suitable for low production volumes below 20,000 panels per year as it has a low capital cost compared to RSW and ATC and can be readily optimised when increased production is required. Cost savings can be achieved by reducing material costs as they were 95% of the total operating costs for all methods. ADH and RSW could be readily optimised to increase production at lower capital expenditure by installing additional equipment at production bottlenecks rather than installing new production lines. ATC could not be as readily optimised as it has high production capacities.

Installing a low volume BIPVT production facility into Dimond Ltd. could potentially generate an additional \$3.5 million per year in profit, for a process that produces 7,680 panels a year. Payback time for the capital investment including a PV laminator would be just over half a year making BIPVT an attractive possibility.

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Table of Contents

Abstract.....	ii
Acknowledgements.....	iii
Table of Contents	iv
List of Figures	vii
List of Tables	x
 Chapter 1 Introduction.....	 1
1.1 Energy overview	1
1.2 Renewable energy	2
1.3 Solar energy	4
1.4 Building integrated energy products	5
1.5 Research objective	5
1.6 Thesis structure	5
 Chapter 2 Literature review	 7
2.1 Introduction	7
2.2 Renewable energy	7
2.3 Solar thermal	8
2.3.1 Flat plate collectors	8
2.3.2 Evacuated tube collectors.....	10
2.3.3 Market overview	11
2.3.4 New Zealand market and initiatives.....	12
2.4 Solar PV	13
2.4.1 Crystalline cells.....	14
2.4.2 Thin-film cells.....	17
2.4.3 Sliver solar cells	18
2.4.4 PV modules	19
2.4.5 PV system types and applications.....	20
2.4.6 Market overview	20
2.4.7 Government incentives and initiatives.....	21

2.4.8 New Zealand market and initiatives.....	21
2.5 PV/thermal	23
2.5.1 Market	25
2.6 Roofing products	27
2.7 Building integrated energy products	29
2.8 Conclusion.....	32
Chapter 3 Manufacturing methodologies.....	33
3.1 Introduction	33
3.2 BIPVT concept.....	33
3.3 BIPVT Manufacture.....	37
3.4 Production steps, functions, methods and details.....	41
3.4.1 Step 1, corrugation of plain sheet.....	41
3.4.2 Step 2, producing holes on central channels	41
3.4.3 Step 3, joining the collector plate to corrugated sheet	43
Mechanical fasteners	44
Adhesives	44
Autoclaving	46
Welding	46
3.4.4 Step 4 and 5, sealing central channels at each end and mounting fittings to the corrugated sheet	52
3.4.5 Step 6, lamination of PV strings on collector plate.....	53
3.4.6 Step 7, sealing the edges between bonded collector plate and corrugated sheet	55
3.4.7 Step 8, attaching manifolds to the corrugated sheet.....	56
3.5 Quality steps.....	58
3.6 Identification of manufacturing methodologies	59
3.7 Material selection	63
3.8 Production types.....	63
3.8.1 Jobbing production.....	63
3.8.2 Batch production	63
3.8.3 Mass production	64
3.8.4 BIPVT production.....	64
3.9 Built-to-order BIPVT panels.....	65

Chapter 4 Prototype production and evaluation	67
4.1 Introduction	67
4.2 Prototype construction and testing	67
4.3 Findings from prototype construction	74
4.3.1 Aluminium BIPVT	74
4.3.2 Colorcote BIPVT	74
4.3.3 Zincalume BIPVT	74
Chapter 5 Economic analysis and discussion	76
5.1 Introduction	76
5.2 Capital costs	76
5.3 Process times and production capacity	78
5.4 Materials costs	80
5.5 Labour, machine and energy costs	81
5.6 Economic analysis	83
5.7 Payback time with production volume	84
5.8 Payback time vs market value	87
5.9 Process optimisation to increase throughput	90
5.10 Dimond scenario	93
5.10.1 Economic analysis for case study	94
5.10.2 Conclusions from case study	98
5.11 Potential Market	98
Chapter 6 Conclusions and Recommendations	99
6.1 Conclusions	99
6.2 Recommendations	100
References	102
Appendix 1	109
Appendix 2	114
Appendix 3	117
Appendix 4	120
Appendix 5	123
Appendix 6	124

List of Figures

Figure 1.1	Energy sources used today .	2
Figure 1.2	Worldwide investment in Renewable Energy sector in 2003.	3
Figure 1.3	Energy sources used 2050 .	3
Figure 2.1	Schematic view of a glazed flat-plate collector	9
Figure 2.2	Flat plate collector from Haithabu Far East Ltd.....	9
Figure 2.3	Evacuated tube collector with heat pipe.....	10
Figure 2.4	Evacuated tube collector from SolMaxx-20.....	11
Figure 2.5	Cumulative solar thermal installations worldwide (1998-2004) ...	11
Figure 2.6	Principle of working of solar cells.....	14
Figure 2.7	Czochralski method of producing single crystalline silicon cells .	15
Figure 2.8	Process for manufacturing multi-crystalline solar cells.	16
Figure 2.9	Side view of water cooled PV/T collector.....	24
Figure 2.10	Side view of air water cooled PV/T collector.	24
Figure 2.11	Low concentration non-tracking PV/T collector.....	24
Figure 2.12	A) PV/T liquid collector (PVTWIN) from PVTWINS and B) PV/T air collector (SolarRoof) from Conserva Engineering.	26
Figure 2.13	A) PV/T concentrator (Solar8) from Arontis Solar Solutions and B) Ventilated PV with heat recovery (TIS) from Italian company ...	27
Figure 2.14	A) Building with PV standing seam roofing, Colorado, USA and B) PV membrane roofing from SIT.....	30
Figure 2.15	A) PV integrated window Germany and B) The PV façade ELSA building in Italy.	30
Figure 3.1	Integration of PV, thermal and building products.....	33
Figure 3.2	BIPVT system.	33
Figure 3.3	A) Standing seam profile and B) Corrugated seam profile.	34
Figure 3.4	Schematic view of BIPVT product.....	35
Figure 3.5	An assembled BIPVT panel with all components.....	36
Figure 3.6	General flow chart for manufacturing BIPVT product.	38
Figure 3.7	Corrugated sheet with inlet and outlet points.	42
Figure 3.8	Collector plate bonded on corrugated sheet.	43
Figure 3.9	Lap joint in adhesive bonding for two workpieces.	45

Figure 3.10	Schematic view of an autoclave.	46
Figure 3.11	Resistance seam welding process.	47
Figure 3.12	Ultrasonic seam welding process.	48
Figure 3.13	Friction stir welding process.	49
Figure 3.14	Electron beam welding process.	50
Figure 3.15	Sealing central channels end by inserts.	52
Figure 3.16	Mounting fittings to corrugated sheet underside at inlet and outlet points.	53
Figure 3.17	Lamination of PV strings on collector plate.	54
Figure 3.18	Attaching manifolds to the corrugated sheet.	56
Figure 3.19	A) Front view and B) Underside view of an assembled BIPVT panel.	57
Figure 3.20	Flow chart for manufacturing BIPVT product by adhesives.	60
Figure 3.21	Flow chart for manufacturing BIPVT product by resistance seam welding.	61
Figure 3.22	Flow chart for manufacturing BIPVT product by autoclaving.	62
Figure 3.23	Flow chart for custom built BIPVT orders.	66
Figure 4.1	Modified corrugated roofing profile (All dimensions are in mm).	67
Figure 4.2	Corrugated sheet dimensions used for prototypes (All dimensions are in mm).	68
Figure 4.3	Connector pipe (All dimensions are in mm).	69
Figure 4.4	Connector pipes soldered to inlet and outlet points underside the corrugated sheet.	69
Figure 4.5	Prototype comprising corrugated sheet with collector plate made from Colorcote steel.	71
Figure 4.6	Unglazed BIPVT Colorcote prototype produced using adhesives.	73
Figure 4.7	(A) Underside view and (B) Top view of surface distortion from resistance seam welding of Zinalume corrugated sheet and collector plate.	75
Figure 5.1	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). . .	85

Figure 5.2	Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 3,840 hours production time (16 hours/day, 5 days/week at 48 weeks/year).	85
Figure 5.3	Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 5,760 hours production time (24 hours/day, 5 days/week at 48 weeks/year).	86
Figure 5.4	Payback time and machine utilisation vs production volume for unglazed Colorcote BIPVT with ADH system operating 1,920 hrs production time (8 hours/days, 5 days/week at 48 weeks/year)....	86
Figure 5.5	Payback time vs production volume for unglazed and glazed Colorcote and Zincalume BIPVT with ADH system operating 1,920 hrs production time (8 hours/day, 5 days/week at 48 weeks/year).....	87
Figure 5.6	Average payback time vs market value per panel for unglazed Colorcote BIPVT using ADH system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/year) for 5,000 to 90,000 panels per year.....	88
Figure 5.7	Average payback time vs market value per panel for unglazed Colorcote BIPVT using A) RSW and B) ATC system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/yr) for 5,000 to 90,000 panels per year.	89

List of Tables

Table 2.1	Energy sector and availability.	7
Table 2.2	Type, percentage, and collector area.	12
Table 2.3	Capacity and percentage installations in parts of world.....	12
Table 2.4	Commercially available single and multi crystalline wafer sizes .	16
Table 2.5	Efficiency table for PV cells and modules.	17
Table 2.6	PV installations in 2006 in major parts of world.....	21
Table 2.7	Government incentives and initiatives for promotion of PV installations in major countries.....	22
Table 2.8	Commercially available PV/T products.	26
Table 2.9	BIPV installations in US and other countries.....	31
Table 3.1	Operations with functions and details in BIPVT manufacturing. .	39
Table 3.2	Manufacturing possibilities for BIPVT production steps.....	40
Table 3.3	Comparison of welding techniques.	50
Table 3.4	Welding techniques advantages and disadvantages.	51
Table 3.5	Volume, area, type of production and system for BIPVT product.	64
Table 5.1	BIPVT capital costs for ADH, RSW and ATC production systems.	77
Table 5.2	Process times for each BIPVT production step.....	79
Table 5.3	Process times in terms of panels per minute.	80
Table 5.4	Component costs for BIPVT (glazed and unglazed) made from Zincalume and Colorcote steel.	81
Table 5.5	Cost per panel including labour, machine and energy for Colorcote unglazed BIPVT.	82
Table 5.6	BIPVT payback period, net profit analysis for production systems using unglazed Colorcote material.	84
Table 5.7	Comparison of individual process step throughput for unoptimised (unoptd.*) and optimised (optd.*)ADH BIPVT prod. Values based on Table 5.3.	90
Table 5.8	Capital costs for unoptimised and optimised ADH BIPVT production.....	91

Table 5.9	Comparison of individual process step throughput for unoptimised and optimised ADH BIPVT production.	92
Table 5.10	Press brake utilisation for panels produced in a year.	93
Table 5.11	BIPVT capital cost comparison.....	95
Table 5.12	Process time comparison for each BIPVT production step.....	95
Table 5.13	Process time comparison in terms of panels per minute	96
Table 5.14	Comparison of cost per panel including labour, machine and energy for all three scenarios.....	96
Table 5.15	Comparison of payback, net profit analysis for all three systems .	97
Table 5.16	Net savings per year comparison.....	97

Chapter 1 Introduction

1.1 Energy overview

Since the industrial revolution, mankind has become increasingly dependent on technology for many areas of human activity including; food, transport, medicine, shelter, light, medicine, communication and entertainment. Technologically advanced products and services are associated with improved quality of life and accordingly a vast range has been developed to meet the demand. These products and services require energy for their production and use [1]. Consequently, a global energy infrastructure has arisen that provides a range of energy systems to meet both production and use. The energy comes in a variety of forms such as liquid fuels for transport, electricity for services such as water treatment, communication or domestic appliances, natural gas for heating or energy stored in for example batteries [2].

Globally, the primary source of energy is fossil fuels, principally, oil, gas and coal with 75% of generated energy provided from these non-renewable resources (Figure 1.1). Fossil fuels are extensively used because they have a high energy density are easily stored, are relatively low cost and in the past have been abundant [3]. However, as demand has grown, reserves of fossil fuels, in particular oil and gas are being rapidly depleted. There is much debate about when demand will become greater than production, but it is generally accepted that oil will be first, followed by gas and then coal. The World Resources Institute gives the reserves to production (R/P) ratio of oil, gas and coal as approximately 40, 65 and 155 years respectively. Consequently, alternative energy sources will be needed to be developed and put into mass production within a few decades to offset the diminishing energy from predominantly oil and gas [2].

In addition to resource depletion, the combustion of fossil fuels for heating, electricity generation or transportation, releases carbon dioxide into the atmosphere [1, 4]. Over the last 60-70 years carbon dioxide has been steadily increasing in the atmosphere. Carbon dioxide is well known as a greenhouse gas

and has been implicated as the main cause of global warming [5]. 75% of total greenhouse gas emissions come from burning fossil fuels [6]. Depletion of fossil fuels and global warming has driven countries to examine alternative sources of energy, such as nuclear power, or renewable sources such as hydro electricity, solar, biomass and wind [1].

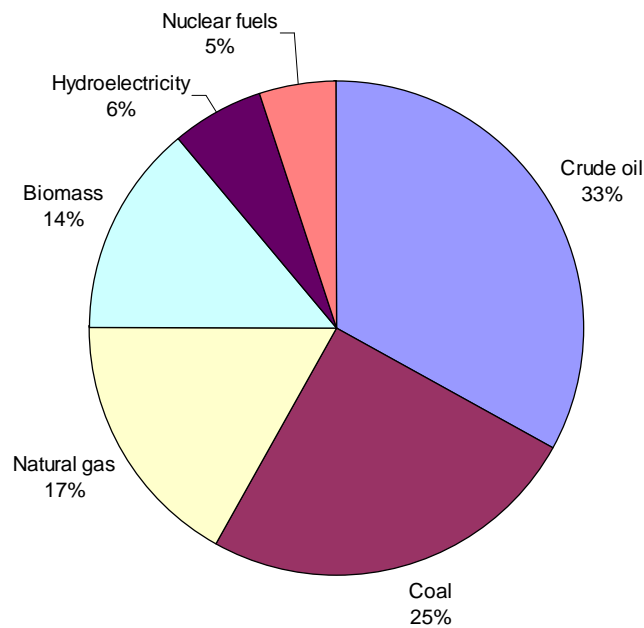


Figure 1.1 Energy sources used today [3].

1.2 Renewable energy

Renewable energy is obtained from sources that are inexhaustible or replaceable such as solar, wind, hydro, tidal, geothermal, and biomass [3, 7]. Solar, wind, and biomass are accepted as being reliable, widely available, with minimal impact on the environment and have the potential to sustainably meet future energy demands [3, 8, 9]. According to the IEA (1999), ‘The world is in the early stages of an inevitable transition to a sustainable energy system that will be largely dependent on renewable sources’[10].

Consequently, the interest in renewable energy has made it the fastest growing sector in the energy market. Approximately US\$22 billion was invested in renewable energy worldwide in 2003, with 45% invested in solar energy, 38% in wind and 17% in biomass, hydro and geothermal energy (Figure 1.2) [9]. The

European Commission projects that 95% of all energy will be from renewable sources by 2050, of which 40% is expected to come from solar energy [11] (Figure 1.3).

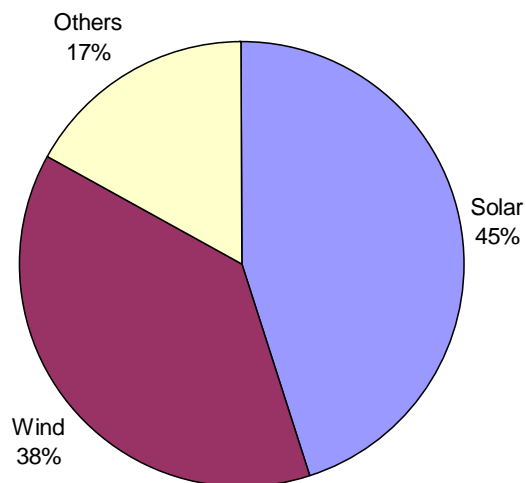


Figure 1.2 Worldwide investment in Renewable Energy sector in 2003 [9].

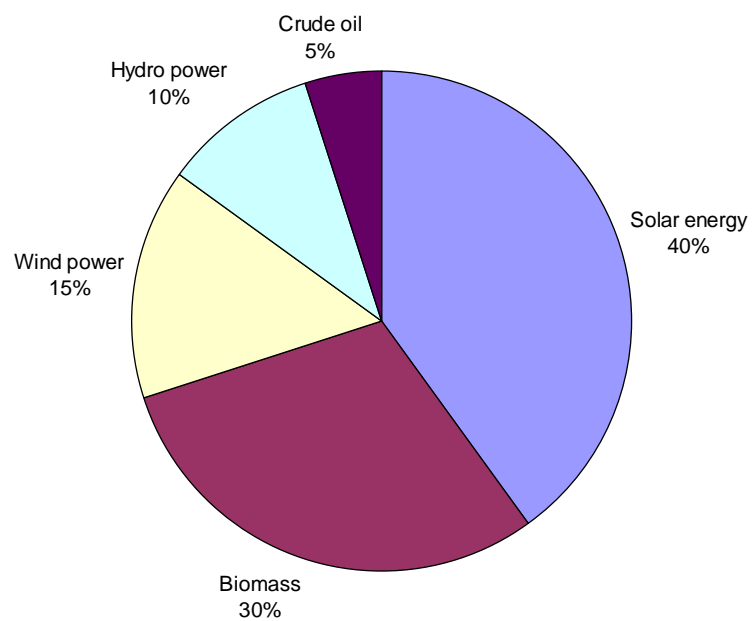


Figure 1.3 Energy sources used 2050 [11].

1.3 Solar energy

Solar energy is radiated from the sun and earth's atmosphere is exposed to 1.5×10^{18} kWh of solar energy annually [7]. Approximately 30% of the energy is reflected back to the space by the earth's atmosphere, 20% is absorbed by clouds, atmospheric particles and greenhouse gases and the remainder is absorbed by the earth's surface. The earth's surface receives approximately 1.73×10^{14} kW of solar power or on average 340W/m^2 [1, 7] and the solar energy received by the earth's surface over the year is 14,000 times higher than world's energy consumption (429.4×10^{18} J) [3, 11]. This highlights why solar energy has received more investment than other forms of renewable energy, principally because it has the potential to generate all of the world's energy many times over.

In New Zealand, the energy received from the sun ranges between 2.50 - 4.50 kWh/m²/day [12, 13] and the total solar energy received by the surface is 3,000 times more than current energy consumption [14]. Every year, the majority of New Zealand houses are exposed to approximately 20-30 times more incident solar energy than their current energy consumption (electrical and gas) [13]. Therefore there is the possibility of converting a proportion of that solar energy into useful heat and electricity and subsequently reduce the consumption of natural gas and electricity from the grid.

Solar thermal and photovoltaic (PV) technologies are commonly used to harness the sun's energy. Solar thermal uses the heat radiated from the sun in the form of infrared radiation to heat water or air for domestic use such as hot water supply or space heating [14]. PV technologies use the sun's light to generate electricity through the photoelectric effect. Solar thermal and PV systems are typically installed as separate units on building roofs or walls to supply heat and electricity to the building. However, such units are bulky and often unattractive, so the current trend is to integrate these technologies into the building roofing or cladding [15] for a more aesthetically pleasing and multifunctional product.

1.4 Building integrated energy products

Building integrated energy products are multifunctional as they not only serve as weatherproofing a building, but also generate electrical or thermal energy [16, 17]. There are currently many building integrated photovoltaic (BIPV) products on the market, such as the Sunslate that integrates PV with conventional roof tiles found on European houses [18]. Others, such as United Solar's PV Shingles are designed for the US market where many houses have roofs covered with asphalt shingles [19]. Most of these products are easy to install, integrate well with conventional roof systems and have become an accepted form of PV installation. 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 novel 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 but could potentially be introduced into global markets.

1.5 Research objective

The overall aim of this research was to investigate and develop an economically viable production system for manufacturing a building integrated photovoltaic thermal (BIPVT) product with long-run roofing systems. Long-run roofing systems are common in New Zealand and are made from steel or aluminium. They have large flat surfaces suitable for integrating solar technologies.

1.6 Thesis structure

An overview of solar energy is presented in Chapter Two, which focuses mainly on the types, markets, products, technology and their integration with buildings. The different production methodologies for the BIPVT product are discussed in Chapter Three. Prototypes constructed by the selected methodologies and their results are discussed in Chapter Four. Economic analysis of the selected

production methodologies is described in Chapter Five. Conclusions drawn and recommendations for future work are detailed in Chapter Six.

Chapter 2 Literature review

2.1 Introduction

This review covers the PV and solar thermal technologies, their manufacture and markets. Different roofing materials are also reviewed for their suitability for integrating PV and solar thermal technology into the product. From the review, a suitable roofing system and PV/T technology for integration will be chosen and form the basis for investigation in the thesis.

2.2 Renewable energy

Renewable energy contributes 20% to the world's energy production (Figure 1.1) and can be subdivided into three categories: solar energy, tidal energy, and geothermal energy. Solar energy is available in the form of hydro, wind, biomass and light and heat energy [1]. It is the largest available source of renewable energy (Table 2.1) and has the potential to supply the world's energy needs many times over.

Table 2.1 Energy sector and availability [3].

Energy Sector	Annual energy globally PJ/year
Solar	3,900,000,000
Tidal	94,000
Geothermal	996,000

Solar thermal systems use solar radiation to heat, for example, water or a house interior. Solar electric systems use PV cells to convert light from the sun into electricity. Solar PV/thermal systems produce both heat and electricity by combining thermal and PV technology [6].

Solar energy systems can be passive or active. Passive solar energy systems employ natural processes such as space heating utilising incident light through a window or heat from a house roof, without any mechanical or electrical equipment to facilitate the process. Active solar energy systems use mechanical

and electrical devices such as heat exchangers, thermal collectors and PV cells to generate electricity and heating [1]. Solar energy systems are as productive and economic as other renewable energy systems, with less environmental effects [20].

2.3 Solar thermal

The main function of a solar thermal collector is to convert the absorbed incident solar radiation into heat, and transfer this heat to a fluid such as water, air, or oil flowing through the collector system. The thermal energy in the fluid is then either stored in a thermal storage tank or used for hot water heating or space heating [21].

Solar thermal collectors are classified depending on the way in which the surface is exposed to the solar radiation. These types are further classified depending upon the thermal fluid used, system design and construction. Non-concentrating type collectors have a fixed flat area for absorbing and intercepting solar radiation. These include integrated collector storage (ICS) systems, flat plate collectors (FPC), evacuated flat plate collectors (EFPC), evacuated tube collectors (ETC), and compound parabolic collectors (CPC). Concentrating type collectors often use concave reflecting surfaces which focus the sun's radiation onto the collector. These include: parabolic trough collector, linear Fresnel collector, parabolic dish, and central receiver. Collectors used in the domestic and commercial applications are typically non-concentrating collectors such as FPC and ETC [3, 21, 22].

2.3.1 Flat plate collectors

Flat plate solar thermal collectors as shown in Figure 2.1 consist of a coated collector plate that absorbs the incident solar radiation. A thermal fluid flowing through tubes attached to the underside of collector plate absorb the heat from the collector. Manifolds provide entry and exit points for the tubes and thermal fluid. Insulation is fitted to the back of the collector to reduce thermal losses and a housing frame supports the components. Glazing on top of the housing reduces the convection heat loss due to wind and provides protection from the environment (Figure 2.1). The glazing may be plastic or glass having a low iron-oxide content which is thermally tempered and non-reflective [21].

Energy from the thermal fluid is either stored, for example, in domestic hot water tanks, or used directly for a given application. These type of collectors can use water or air as the thermal fluid [3, 22] and their efficiency is between 66-83% with a service temperature between 20-80°C [23]. A typical FPC is shown in Figure 2.2.

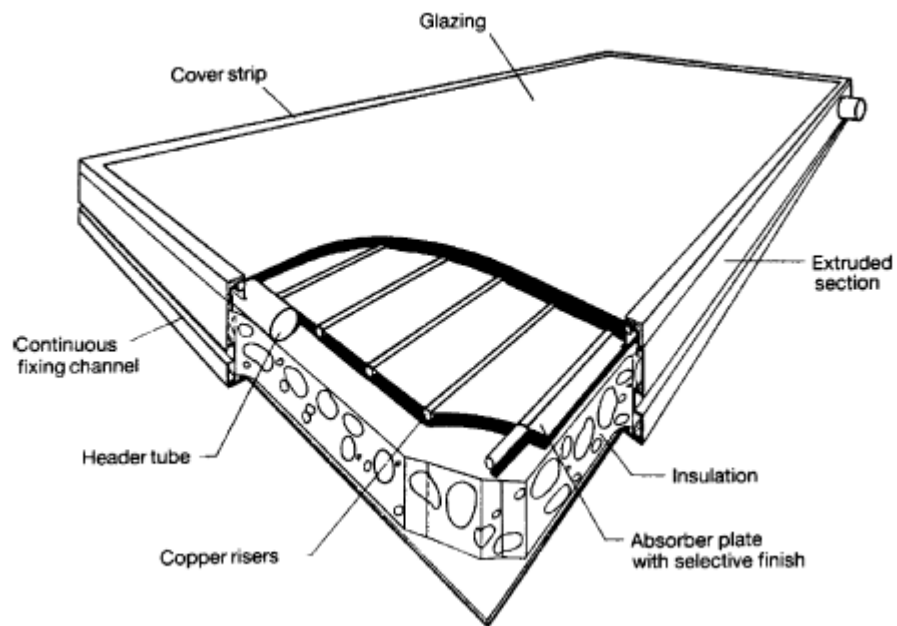


Figure 2.1 Schematic view of a glazed flat-plate collector [21].



Figure 2.2 Flat plate collector from Haithabu Far East Ltd. [24].

2.3.2 Evacuated tube collectors

Evacuated tube collectors often use a liquid-vapour phase change material for absorbing heat. In this configuration they comprise a metal absorber sheet with a heat pipe embedded inside a vacuum-sealed tube as shown in Figure 2.3. A heat pipe is a thermal absorber and consists of methanol that acts as heat transfer medium that undergoes an evaporating-condensing cycle during operation. The heat pipe is connected to a black copper fin which fills the tube [3, 21].

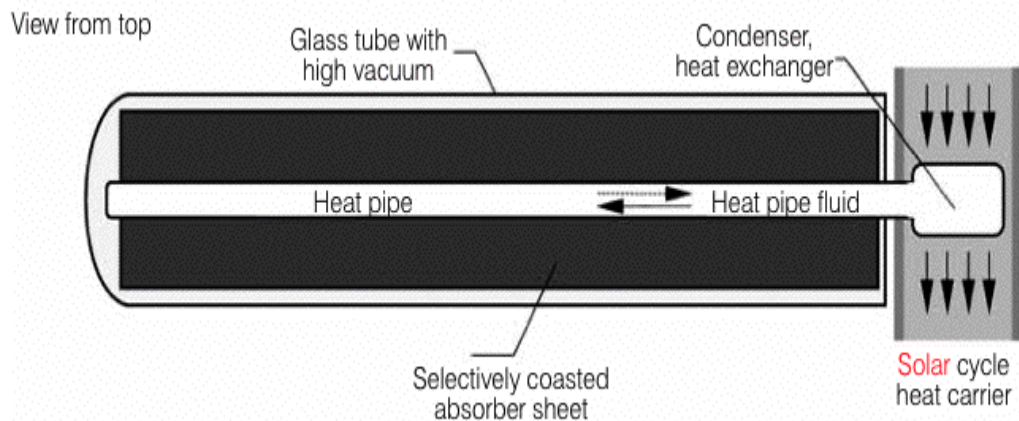


Figure 2.3 Evacuated tube collector with heat pipe [3].

During operation cycle, the incident solar radiation is absorbed by the metal absorber sheet which vaporizes the heat pipe fluid i.e. methanol in the heat pipe. The vapour rises to the heat exchanger and condenser where it condenses and the latent heat is released. The condensed thermal fluid flows back to the bottom of collector and the process is repeated. The solar cycle heat carrier used is normally water or glycol which absorbs the latent heat and the energy is used as per the application [3, 21]. The conversion efficiency for these collectors is between 62-81% with service temperatures between 50-120°C [23]. A typical ETC product is shown in Figure 2.4.



Figure 2.4 Evacuated tube collector from SolMaxx-20 [25].

2.3.3 Market overview

Solar thermal collectors are used in solar water heating systems, solar space heating and cooling, solar refrigeration, industrial process heat, solar desalination systems, solar thermal power systems, solar furnaces, and solar chemistry applications [3, 21].

Since 1998, on average installations have increased by 16% annually worldwide from 45,080 MW_{therm} to 98,416 MW_{therm} in 2004 (Figure 2.5). Total collector area in 2004 was approximately 141 million m² [26].

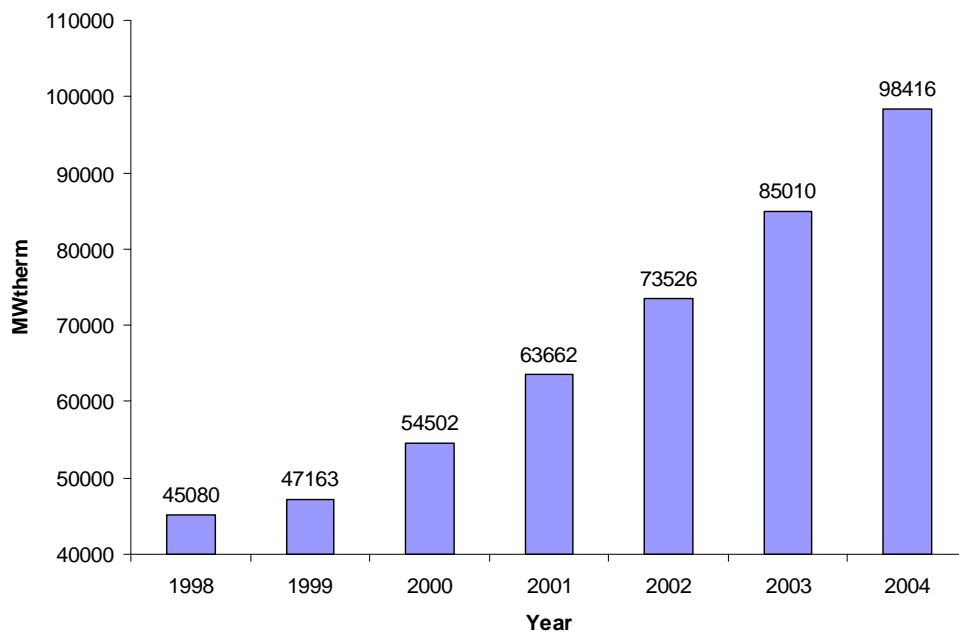


Figure 2.5 Cumulative solar thermal installations worldwide (1998-2004) [26].

99% of all solar thermal systems in 2004 were water based collectors contributing about 97,600 MW_{therm} with the remainder being air based systems which contributed about 816 MW_{therm} (Table 2.2) [26].

Table 2.2 Type, percentage, and collector area [26].

Based	Collector	Total Installations (MW _{therm})	% of total installations	Collector area (million m ²)
Water	ETC	40,299	41%	57.57
	Glazed Flat plate	34,184	35%	48.83
	Unglazed	23,117	23%	33.02
Air	Glazed	175	1%	1.16
	Unglazed	641		

The major solar thermal markets are countries of the European Union (EU), US, China, Japan, India, South Africa and Middle East. The largest single market is China which in 2004, accounted for 44% of total installations with the vast majority being ETC systems (Table 2.3) [26].

Table 2.3 Capacity and percentage installations in parts of world [26].

Country/Region	Total Installations (MW _{therm})	% of total installations
China	43,400	44.10%
United States	20,038	20.36%
Japan	5,408	5.50%
Europe	11,857	12.05%
ROW	17,712	18.00%

2.3.4 New Zealand market and initiatives

Solar hot water (SHW) has the largest market share of New Zealand's solar industry using mainly FPC and ETC systems. 60% of the total solar thermal collectors have an active heat transfer system such as pumped flow, whereas the rest are equipped with passive heat transfer systems such as a thermo siphon [13, 27, 28].

By 2005, 28,400 SHW systems had been installed nationwide, contributing approximately 59GWh or 0.20% of the total energy consumption of New Zealand. Presently, the New Zealand SHW industry has grown at approximately 40% per annum and aims to install 10,000 m² of thermal collectors per year by 2008. It further plans to install 40,000 SHW systems by 2015 [27, 28].

Government initiatives and incentives play a major role in promoting SHW installation. The New Zealand government has provided a rebate of \$300 per SHW installation to offset interest cost on loans [27]. In November 2006, the government allocated \$15.5 million over 3.5 years in a Green Party initiative to increase the number of installations. Further funding will be reviewed in 2009 [29]. The market growth, forecasts of the industry associations and Government incentives suggest a positive long term future for the solar thermal industry in New Zealand. Consequently there is an opportunity for innovative New Zealand market specific products to be developed.

2.4 Solar PV

Photovoltaics (PV) were first discovered by Edmund Becquerel in 1839 [30, 31]. PV convert incident solar radiation into electricity [11] and are made from semiconductor materials such as silicon, cadmium telluride (CdTe), gallium arsenide (GaAs) or indium phosphorus [32]. Silicon is most commonly used as it is abundant and easily extractable from silica sand. During PV cell manufacture, silicon is doped with phosphorus or boron to attain semi-conductor properties. Silicon has four valence electrons in its outermost orbit with a band gap of 1.12 eV, which is the energy required for an electron to jump free from an atom [31]. Electrons orbiting silicon atoms in PV cells absorb photons from light and this energy excites the electrons causing them to jump from one atom to another, generating a net voltage and current through an external circuit (Figure 2.6) [32]. The DC current produced can be used directly, stored in batteries, or fed to the grid via an inverter [31].

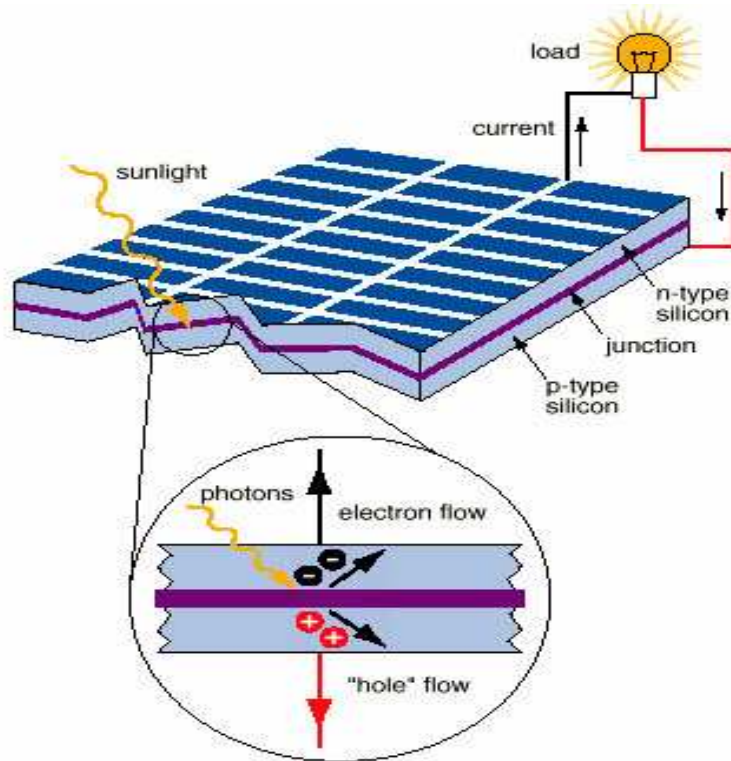


Figure 2.6 Principle of working of solar cells [33].

PV technology is modular, silent, emission free during operation and has a service life of over 20 years. Silicon cells are classified depending upon their production process, being either multi-crystalline, single-crystalline or thin-film [11].

2.4.1 Crystalline cells

Crystalline silicon (single and multi) PV cells are produced as flat wafers having a thickness of between 0.2-0.5 mm. These cells are most commonly used in the PV industry with a market share of 90% [31, 34]. Single crystalline PV cells are manufactured using the Czochralski (CZ) or float-zone (FZ) method, where a small seed of solid crystalline silicon is dipped in a crucible of molten pure silicon at a temperature of 1400°C. A large crystalline silicon ingot is grown by gradually pulling the seed crystal from the solution. The dopant, usually boron is added to the melt and p-type semiconductor ingots are obtained. The rods are 200 mm in diameter and 1.5-2 m in length. These rods are cut into wafers using a slurry-wire-saw (Figure 2.7) [11, 31].

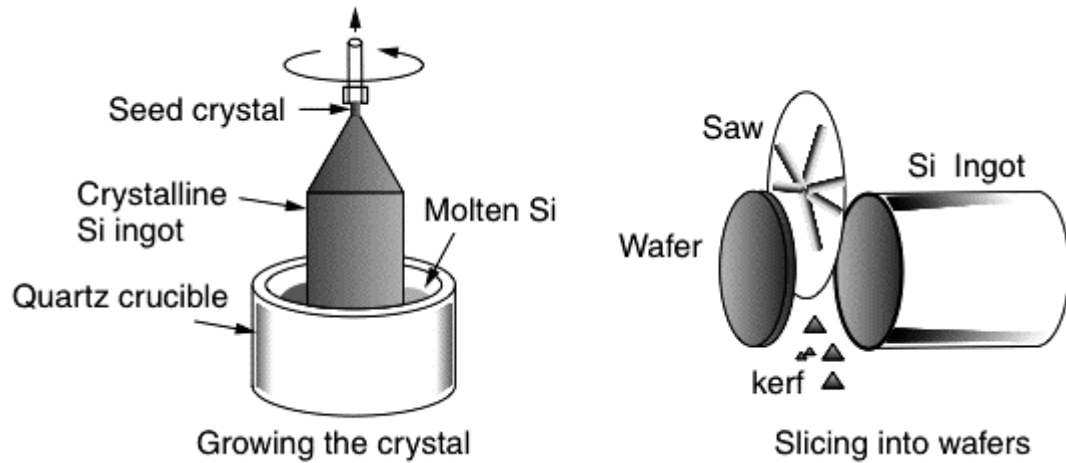


Figure 2.7 Czochralski method of producing single crystalline silicon cells [11, 31].

The wafers are cleaned by fine polishing with Al_2O_3 to remove any damage from the cutting process. Texturization is produced on wafers by damage-etching i.e. wet-chemical process. This process generates a pyramid like structure acting as an optical anti-reflective layer. After texturization, wafers (p-type) are doped using phosphorus to create a semiconductive p-n junction that allows electron movement. Phosphorus oxide formed during the doping process is removed by wet chemical process that etches away the phosphorus oxide at the side and back of the cell. After this process, electrical contact is attached at the front and back of the cells by a vacuum evaporation process in which aluminium metal is heated in a vacuum, evaporated and condensed onto the cooler solar cells. The cells are covered in an optical anti-reflective coating produced by sputtering TiO_2 on to the surface in a vacuum and sintering it at 400°C , after electrical contacts have been attached. Finished cells are visually inspected for; anti-reflective layer homogeneity, contact bonding, and light-current-voltage characteristics. The maximum cell and module efficiency is up to 25% and 23% respectively, under standard test conditions but typically the efficiencies of commercial silicon cells are approximately 14-17% (Table 2.5) [11, 31].

Multi-crystalline solar cells are manufactured by cooling and solidifying molten silicon in a crucible at a controlled temperature. The ingots obtained by this process are made up of many smaller crystals rather than a single crystal and are

40 x 40 x 40 cm in size. The ingots are cut into columns with a square base and then sliced into wafers (Figure 2.8). Crystal yield is higher and the process less costly than manufacturing single crystalline wafers [11, 31, 34]. Processes used in manufacturing cells from the wafers is similar to that of single crystalline cells but an extra process, grain boundaries passivation, is conducted after removal of phosphorus oxide. Maximum cell and module efficiency is up to 20% and 15% respectively under standard test conditions (Table 2.5) [11]. Typical efficiencies of commercially available multi-crystalline cells range from 10%-15%. Commercially available sizes of single and multi-crystalline wafers are shown in Table 2.4.

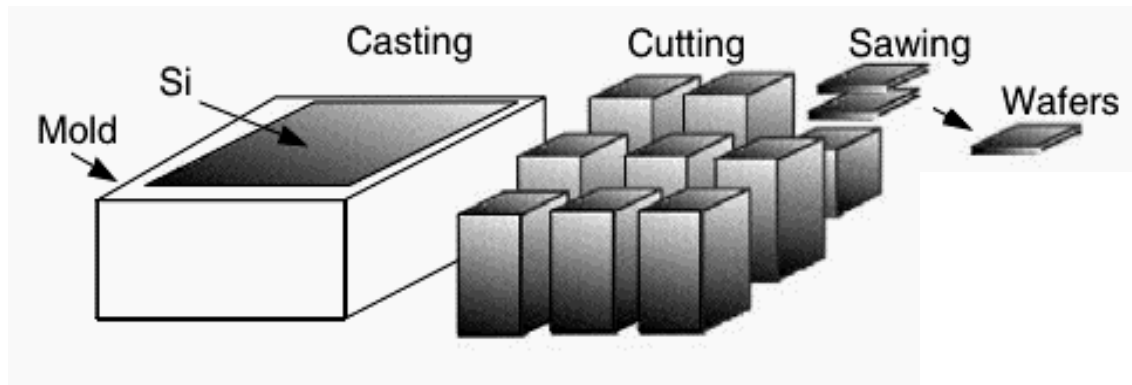


Figure 2.8 Process for manufacturing multi-crystalline solar cells [11, 31].

Table 2.4 Commercially available single and multi crystalline wafer sizes [35]

Nominal Size (mm)	Dimensions (mm)	Diagonal (mm± 1)
103	103 ± 0.5	146
125	125 ± 0.5	177
150	150 ± 0.5	212

There are in excess of 60 companies producing crystalline PV cells worldwide [36]. Manufacturing has become very efficient and often module production is separate from cell production with module manufacturers sourcing cells from the most economic supplier. This situation fits well with an embryonic New Zealand BIPVT industry as it too could source PV cells from off-shore suppliers. As production facilities for crystalline cells only become economically viable at over

100MWp per annum, this makes cell manufacture in New Zealand currently unviable. Therefore it is proposed that for this work the PV cells be sourced wholesale from the global market and integrated into the new product.

2.4.2 Thin-film cells

Thin-film cells are generally considered better suited to high volume production than single and multi-crystalline cells but have a lower efficiency of 5-11% (Table 2.5) [31]. Whereas silicon wafers have a thicknesses ranging from 0.2-0.5mm, thin film cells are between 1-10 μm , or $1/20^{\text{th}}$ to $1/50^{\text{th}}$ that of single and multi-crystalline wafer cells. They are produced by depositing layers of semi-conductor (PV) material onto a backing material such as glass, stainless steel or plastic. Thin-film cells are further classified depending upon the semi-conductor material being either, amorphous silicon (a-Si), GaAs, InP, CdTe, or copper indium diselenide (CIS). Due to their lower efficiency they require a larger area than crystalline cells to produce the same energy and hence they have a lower market share of approximately 10% [31, 34].

Table 2.5 Efficiency table for PV cells and modules [37-39].

Classification	Cell efficiency at STC* (%)	Module efficiency at STC* (%)	Commercial module efficiency (%)
Single crystalline silicon	24.7 ± 0.5	22.7 ± 0.6	10 – 17
Multi crystalline silicon	20.3 ± 0.5	15.3 ± 0.5	11 – 15
Amorphous silicon	16.6 ± 0.4	n/a	5 – 7
CIS	18.4 ± 0.5	13.4 ± 0.7	9 – 11
CdTe	16.5 ± 0.5	10.7 ± 0.5	6 – 9

**Cell and module efficiencies are measured under the global AM1-5 spectrum (1000W/m²) at 25°C.*

Amorphous silicon (a-Si) cells are manufactured by simultaneously depositing an antireflective coating, conducting oxide, semiconducting material, and back electrical contacts in a number of layers onto a substrate such as glass. As mentioned previously due their low thickness compared to wafer cells, less material is required for manufacturing [34, 40].

Copper indium diselenide (CIS) cells are manufactured by evaporation process, in which small quantities of copper, indium, and selenide are added and heated electrically until they vaporise and condense on a cooler substrate forming the CIS layer. Sputtering, spray pyrolysis, electrodeposition, and selenization methods are also used for manufacturing these types of cells. In the sputtering process, atoms of copper and indium are bombarded by high energy ions of selenium gas which condenses on the surface and forms a CIS layer. In the spray pyrolysis process, salts of copper, indium and selenide are sprayed onto a hot substrate where they react to form a CIS layer and the solvent evaporates. In the electrodeposition process, an electric current is passed through an electrode in a solution containing ions of copper, indium and selenide which deposit them on the electrode. In the selenization process, copper and indium are deposited on the substrate by either sputtering or electrodeposition process and selenium is added by hydrogen selenide (H_2Se) gas. Selenization and electrodeposition are the most popular techniques because of their ease of use and low cost [34, 40]. Maximum cell and module efficiency of these cells is up to 18% and 13% respectively when tested under standard test conditions (Table 2.5).

Cadmium telluride (CdTe) cells are produced by the similar methods used for producing copper indium diselenide (CIS) cells. Spraying and electrodeposition are the most common techniques used [40]. Maximum cell and module efficiency of these cells is up to 16% and 10% respectively when tested under standard test conditions (Table 2.5).

Thin-film PV cell production factories are purpose built for specific PV products and cost in the hundred of millions of dollars to install. The cells from these factories are not available for the wholesale market and as there is no such production facility currently in New Zealand thin-film PV cells are not viable for a New Zealand manufactured BIPVT product.

2.4.3 Sliver solar cells

Australian National University (ANU) with Origin Energy invented and developed sliver solar cell technology which reduces silicon consumption in

manufacturing. These cells are more expensive than conventional silicon solar cells as 59 processing steps are used in their manufacture. However, these cells have higher cell and module efficiency. The typical dimensions of a silicon solar cell are 50-100 mm long, 0.5-2 mm wide and 40-60 μm thick [41].

2.4.4 PV modules

Single and multi-crystalline wafer cells are very fragile and need to be encapsulated for their protection from physical and environmental damage. The encapsulation materials of a typical PV module comprise; low iron glass cover, Ethyl Vinyl Acetate (EVA) encapsulant, white Tedlar composite backing sheet and electrical junction box [11, 34].

PV cells are tested, sorted and grouped depending on their performance during testing. They are then connected in series using solder tabs to create strings. A typical module comprises 4 x 9 strings of cells giving a total of 36 PV cells. This module configuration has developed for charging 12V battery systems but is also suitable for grid connection via an inverter [11, 34].

The EVA used is in foil form and has a thickness of between 0.50-0.70 mm. The glass sheet used is iron-free, thermally tempered with a thickness of between 2-3 mm [11]. EVA is available in two forms depending on the curing period i.e. 22 minutes for normal EVA and 4 minutes for fast cure EVA. The back of the module usually consists of white Tedlar-Polyester-Tedlar or Tedlar-Aluminium-Tedlar [11, 34].

Modules are produced in a purpose built vacuum laminator. During the lamination process, the glass-EVA-PV strings-EVA-Tedlar composite, are heated and pressurised at temperature of 145°C – 200°C. The EVA melts and cures in an irreversible process followed by cooling. For mass production of laminates, curing is carried out in separate oven at normal pressure. This reduces the cycle time and allows the laminator to be available for the next process, saving energy as the laminator can be maintained at a constant temperature rather than cycling from hot to cold. [11].

Thin film modules are produced by assembling single sheets of thin film solar cells. These can be encapsulated into a fixed or flexible module by using transparent plastic or glass. Amorphous silicon modules use the Energy Conversion Device (ECD) roll-to-roll process and are produced on steel in a Tefzel/EVA/Tedlar package, or transparent oxide-coated glass with EVA and dielectric backside glass [34, 35].

2.4.5 PV system types and applications

PV systems are mainly classified into off-grid and on-grid. Off-grid systems store electrical energy produced by PV modules in batteries and typically are used in applications where electricity from the grid is unavailable, unreliable or uneconomic to supply. Typical off-grid applications include telecommunication repeater stations in remote areas, lighthouses, marine navigation lights and power for remote communities. On-grid systems, supply electricity generated by PV modules to the mains electricity network via an inverter. The inverter converts the DC current generated by the PV modules to AC and ensures the correct frequency modulation as well as safe operation of the system. The most common application of on-grid systems is installation on buildings [34, 42].

In total, between 1992 and 2004, 2596 MW of both on-grid and off-grid type PV systems were installed worldwide of which 2144 MW were on-grid and 452 MW off-grid [34, 42]. This highlights that the vast majority of installation are on-grid and installed on buildings and explains the growing number of products for integrating PV products into building materials.

2.4.6 Market overview

The global PV market has experienced high growth over 20% since 2000. For example between 2005 to 2006 the total PV installations grew from 1420 MW to 1744 MW an increase of 22%. This generated US\$4 billion in sales worldwide up from US\$1.8 billion in 2005 [43]. The major PV manufacturers include BP Solar, Kyocera, Shell Solar, Sanyo, and RWE Scott Solar, along with Sharp who were the leading producer with 27% of the PV market in 2002 [42]. Germany has the

highest number of installations worldwide with a total share of 55% in 2006 [43] (Table 2.6).

Table 2.6 PV installations in 2006 in major parts of world [43].

Country/Region	Total Installations (MW)	% of total installations
Germany	959	55
Japan	296	17
ROE	192	11
ROW	157	9
US	140	8

2.4.7 Government incentives and initiatives

In 2003 US\$5.28 billion was invested worldwide for promoting solar PV energy in the renewable energy sector [9]. Countries with government support programs include Japan, United States, Germany, Italy and China [42] (Table 2.7). Spain has recently introduced legislation for solar installations on buildings but limited information is available.

2.4.8 New Zealand market and initiatives

In New Zealand, PV systems are mainly used in hybrid or standalone off-grid power systems. These systems are used for isolated telecommunications, weather monitoring sites, marine safety devices, electric fences and navigation lights. The total installed PV grew from 0.75 MWp in 2001 to 1.4 MWp in 2004 of which 400 KWp was installed on BP petrol stations. Currently, no commercial PV cell or module manufacture takes place in New Zealand. All components and modules are imported except some batteries and inverters which are made locally on a small scale [28, 44]. The New Zealand government has not given any incentives to date to promote PV system sales [44].

Table 2.7 Government incentives and initiatives for promotion of PV installations in major countries [42, 44].

Country	Year	Program and Details:
Japan	1992	New Sunshine: For introduction of renewable energy throughout the country
	1994	70,000 Roofs: Subsidy of 50% on PV installations with a annual budget allocation of \$18.3 million. In 2003, the subsidy was reduced to 15% and budget was increased to \$186 million.
	2003	Renewable Power Portfolio Standard: Aims on providing renewable energy at a constant rate to the electric supply and the targets set by the government are about 3.2% of the total energy by 2010.
Germany	1998	100,000 Roofs: Provided 10-year loans with reduced interest to buyers of PV systems. After completing targets the program was ended in 2003.
	1999	Renewable Energy Sources Act: Customer applications receive 56 per kWh for solar-generated electricity sold back to the grid.
United States	1997	Million Solar Roofs: Target of installing solar energy systems on 1 million buildings in US by the year 2010
Italy	2001	10,000 Roofs: Different investment subsidies were offered to regions for the promotion of building integrated PV applications.
China	2004	\$1.21 billion was allocated by the government for the use of solar and wind energy for power generation in remote areas of West China.
United Kingdom		PV Demonstration: 50% of the cost on purchasing and installation on PV systems is claimed.

2.5 PV/thermal

As mentioned in section 2.4, single or multi-crystalline PV cells convert 12-17% of the absorbed solar radiation into electricity. The remaining radiation increases the PV cell temperature and reduces its conversion efficiency. Cooling the PV cells by circulating thermal fluid (air or water) past the cell retains its efficiency and transfers the energy to the fluid which could be utilized. In a PV/thermal (PV/T) module, PV modules are coupled with heat extraction devices. These coupled modules are also called combi panels, which convert sunlight into electricity, as well as collect excess thermal energy to produce heat [6, 45]. The thermal energy can be used to heat the building or water supply [46].

PV/T collectors generate more energy per unit surface area than PV panels and solar thermal collectors mounted in adjacent units. PV/T collectors require 40% less surface area than separate systems to generate the same amount of heat and electrical energy and are more efficient and cheaper [26, 47].

PV/T collectors are of two types; flat-plate and concentrating. Flat-plate PV/T collectors are similar in appearance to flat-plate thermal collectors in terms of glass cover, insulation and housing. The only major difference is the collector plate on top of which a PV panel is attached. In concentrating PV/T collectors, reflectors are used to concentrate the solar radiation onto the PV modules. They have a similar function to that of concentrating flat plate solar thermal collectors. These collectors are further classified by the type of thermal fluid (air or water) used [48].

Common configurations of flat plate (water cooled and air cooled) and concentrating PV/T collectors are shown in Figures 2.9 to 2.11 [48].

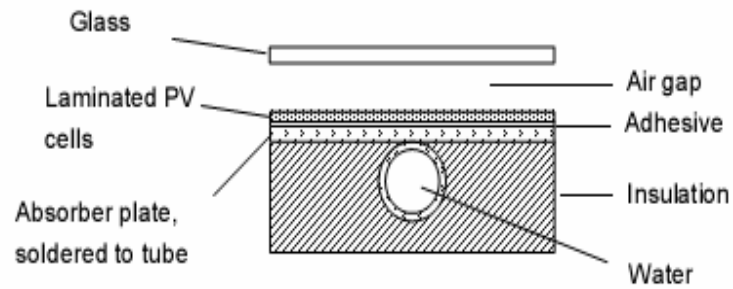


Figure 2.9 Side view of water cooled PV/T collector [48].

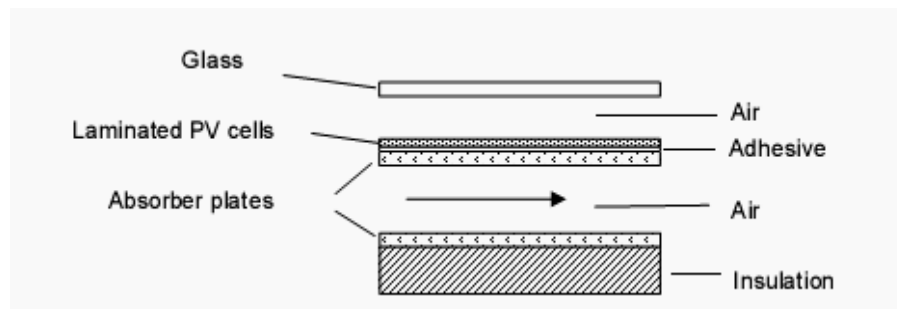


Figure 2.10 Side view of air water cooled PV/T collector [48].

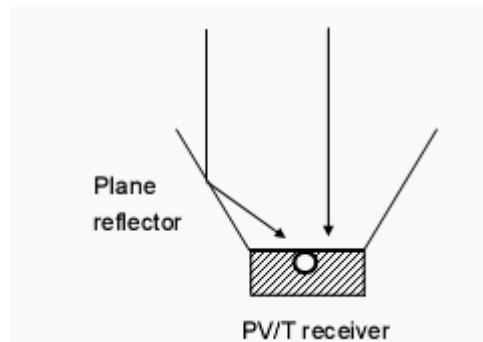


Figure 2.11 Low concentration non-tracking PV/T collector [48].

In most PV/thermal collectors, PV cells or laminates are joined onto the absorber plate. PV/T collectors are manufactured by using adhesives or by laminating PV cells [49, 50].

PV cells are bonded directly on the absorber (collector) plate of a commercial (standard) solar thermal collector using adhesives. However, this method is not used for commercial applications, because if the PV cells are not covered by

plastic or glass and properly sealed, they are not protected from moisture and the system has insufficient electrical insulation [49, 50].

Alternatively, PV cells are laminated using glass or plastic, hence protected from moisture, and bonded on the collector plate of commercial solar thermal collector using adhesives. However this method is not economic because of the additional step of joining the PV laminates with the absorber plate. Also the thermal resistance of the PV laminate between the PV cell and absorber reduces the absorber's ability in removing heat from the PV cell, decreasing the PV cell's electrical efficiency [49, 50].

Laminating is the most common and advanced methodology for manufacturing of PV/T collectors. In this process, all the components including top cover, PV cells, electrical insulation and absorber plate are laminated in a single step. Top cover material used can be either glass or tedlar [49, 50].

In both methods discussed, the encapsulating material and adhesive should have a high temperature resistance to prevent cell or adhesive delamination when the collector reaches temperatures greater than 130°C, the stagnation temperature of glazed PV/T collectors. This problem can be avoided by using silicon encapsulants that can withstand high temperatures, over 200C, but cure at low or room temperature [49, 50].

2.5.1 Market

Commercially, the only available PV/T collectors are air type with unglazed PV often known as a ventilated PV façade [51]. These collectors are used commonly for space heating. PV/T concentrators and PV/T liquid collectors (glazed and unglazed) are commercially available (Table 2.8) (Figure 2.12 and Figure 2.13); however they are not produced on a large scale. In most PV/T panels, the PV panels are typically laminated or glued to the surface of the solar thermal collector [49].

Table 2.8 Commercially available PV/T products [51].

Collector Type	Name of product	Company manufacturing the product
PVT liquid collector	PVTWIN collector	PVTWINS
	Multi Solar Panel	Millenium Electric
PV/T air collector	SolarVenti	Aidt Miljø
	Twinsolar	Grammer Solar
	Solarwall and SolarRoof	Conserval Engineering
PV/T concentrator	Solar8	Arontis Solar Solutions
	Harmony HD211	HelioDynamics
	Power Spar	Menova Engineering Inc
Ventilated PV with heat recovery unit	TIS	Secco Sistemi

**Figure 2.12** A) PV/T liquid collector (PVTWIN) from PVTWINS and B) PV/T air collector (SolarRoof) from Conserval Engineering [51].



Figure 2.13 A) PV/T concentrator (Solar8) from Arontis Solar Solutions and B) Ventilated PV with heat recovery (TIS) from Italian company [51].

PV/T air collectors have a 1% share of the worldwide PV/T market as they are only used in space heating. Glazed PV/T collectors can be used for domestic hot water heating and space heating. Unglazed PV/T liquid collectors could be used for pool heating and the potential for this application is relatively good in Australia and the US. With the increase of integration of building walls or facades with PV, the market for ventilated PV facades with heat recovery unit is also growing. The major area for this application is utility buildings, as heating demand and solar radiation are high during daylight working hours [47, 49].

2.6 Roofing products

Roofs are classified as low slope roofs and steep slope roofs. Slope is the degree of inclination of roof and is the ratio of the rise to the span. The materials used in roofing are shingles (wood, asphalt, glass fiber, fiber-cement, slate), tiles (clay and concrete), and metal products [52-54].

Wood shingles are cut from logs of red cedar, redwood, cypress or pine. In the United States, western red cedar is used in most of the shingles in wall and roof applications and has good thermal insulation. These shingles have a cellular composition which consists of millions of tiny air-filled cells per cubic inch [52-54].

Asphalt shingles are made from asphalt flux. Mineral granules are heavily coated on the top surface of these shingles which are exposed to the weather. They are the most common material used in the roofing industry and have good fire resistance, low cost, and good durability. They are available in a wide variety of colours and mainly manufactured as strip shingles, interlocking shingles, and large individual shingles [52-54].

Glass fibre shingles are made up of glass fibre material and asphalt flux. Glass fibre is waterproof and acts as reinforcement in the shingles. These shingles have good fire resistance and are very lightweight. Slate shingles are natural stone products and each stone piece has unique qualities. They are available in form of blocks/slabs which are removed from the ground and are further cut and trimmed into required sizes [52-54].

Clay tiles are manufactured from fine powder clay and water mixture. This mixture is extruded through dies, press formed and cut into required lengths. These processes during manufacturing improve their performance, quality, and product diversity. Clay tiles are most common roofing material in Europe and are available in different colours. Concrete tiles are manufactured from mixture consisting appropriate quantities of Portland cement, sand and water. The mixture is extruded under high pressure on individual molds. Concrete tiles are most used in Europe, Australia and United States and are also available in different colours [52-54].

In this work, the roofing material considered most appropriate for PV/T integration is long-run metal roofing as it has large flat surfaces and good heat conductivity. It is durable, lightweight, can be shaped as needed, available in different colours and is cheap, quick and easy to install. Metal roofing is easily incorporated into building designs and is compatible with all types of building materials. They are classified as structural or architectural standing-seam roof systems. Structural systems are used on both low-slope and steep-slope roofs. These systems have load-carrying capacities and do not need a substructure for support and are designed to be water resistant. Architectural systems are used on

steep slopes and require a substructure for support and are not used for load-carrying capacities [52-54].

The materials used in metal roofing include copper, aluminium, zinc, steel, and stainless steel. The most common roofing systems are made from aluminium or coated steel such as painted (Colorcote) or galvanised (Zincalume) [52-54].

Standing-seam metal roofing systems are made from low-carbon steel processed into hot rolled coils. These coils are cleaned with acid to remove surface oxides and are reduced to the required thickness (0.5-1mm) in a cold rolling mill. Cold rolled coils are further cleaned, annealed and hot dip galvanised. The coated coils are then be painted for corrosion protection and aesthetics, then cut, roll-formed and pressed into the required profiles for roofing or other products [52-54].

2.7 Building integrated energy products

New technological developments allow PV and solar thermal collectors to be integrated into building materials such as roofs, wall cladding and facades. These materials not only serve for weatherproofing a building, but also generate electrical or thermal energy. These integrated products show potential cost savings in labour and construction materials as compared to installing separate energy systems. Building cladding with integrated PV cells can have a greater aesthetic value [55, 56].

In building integrated photovoltaic (BIPV) technology, PV cells are laminated onto various building materials. BIPV products are readily available in the market and have been incorporated easily into standard façades and roof structures. Examples of BIPV products include crystalline PV modules designed and integrated into exterior building cladding such as curtain walls, spandrel panels, glazing, PV roofing tiles, shingles, standing seam products and transparent PV modules used for skylights, windows and transparent walls [56, 57]. These are wired into the building electrical systems with the majority being grid connected (on-grid) and have been successfully installed in residential (single-family housing), large commercial and industrial buildings [58, 59].

The first application of BIPV was in 1991 in Aachen, Germany where PV was integrated into an exterior wall cladding [59]. Since then, BIPV systems have been successfully installed on numerous commercial and industrial buildings both in roofing and cladding. (Table 2.9) (Figure 2.14 and 2.15) [57] Germany has the largest installed BIPV capacity of 41.8 MW, followed by Japan with 7.8 MW [60]. Some of the major IPV installations in the United States and other countries along with the PV module manufacture, type of BIPV system, PV area and power rating (size) are shown in Table 2.9.

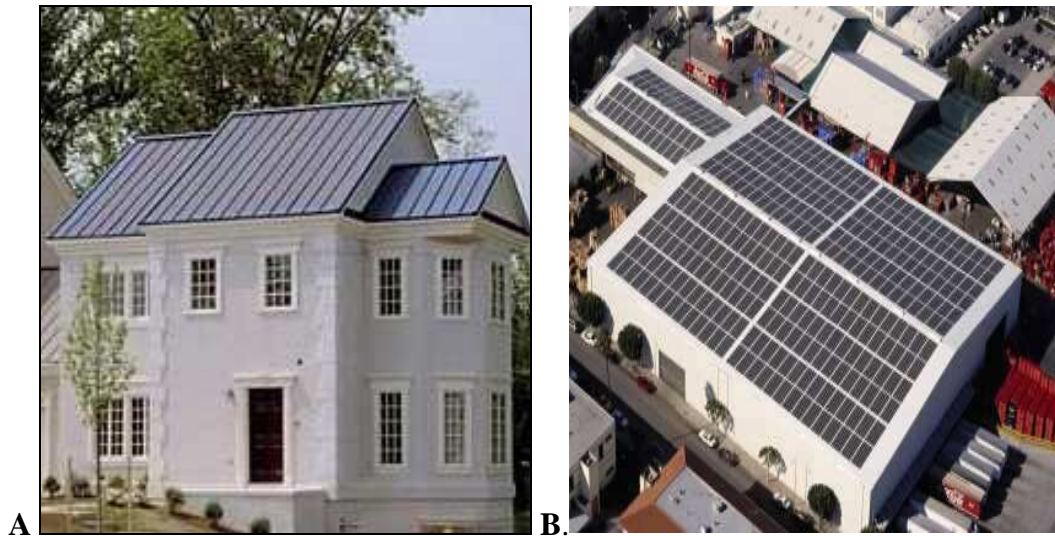


Figure 2.14 A) Building with PV standing seam roofing, Colorado, USA [61] and B) PV membrane roofing from SIT [62].

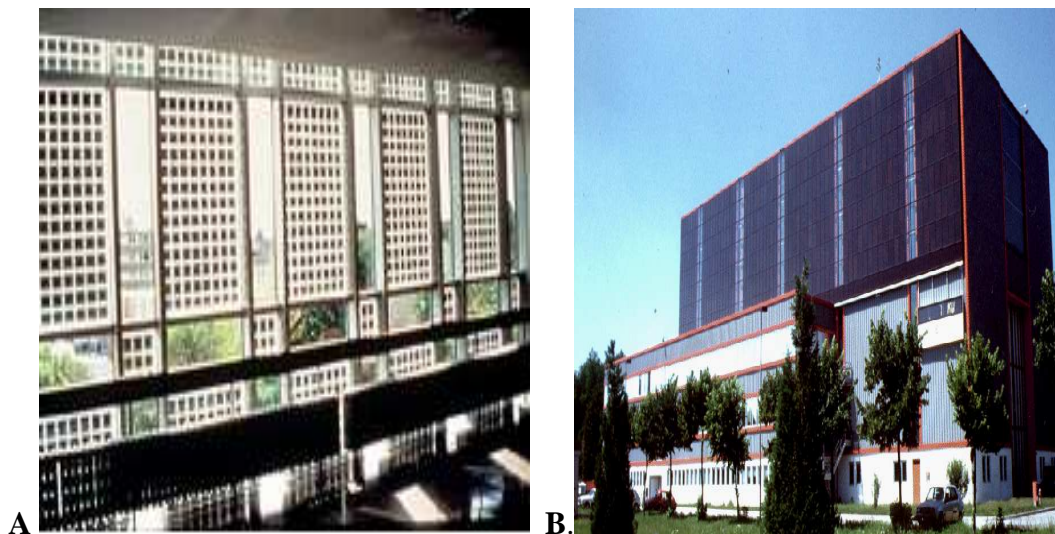


Figure 2.15 A) PV integrated window Germany [61] and B) The PV façade ELSA building in Italy [33].

Table 2.9 BIPV installations in US and other countries [57].

Year	BIPV System	Name and location	PV module manufacturer	PV s/f area (m2)	PV size
1993	Roofing	PV Manufacturing Facility, California	APS	184	9.5 kWp
1996	Roofing	Thoreau Centre, California	Solar building systems, Atlantis energy	20	1.25 kWp
1996	Roofing	Western Area Power Administration, California	Solarex	502	40 KW DC
1996	Façade	State University, New York	Solarex	140	15 kWp
1998	Roofing	Western Area Power Administration, California	Solarex and APS	921	38 KW DC
1998	Façade	Sun Microsystems Clock Tower, Massachusetts	Pilkington solar international	77	2.5 kWp
1999	Façade	4 Times Square, New York	Energy PVs, Inc.	288	14 kWp
1999	Roofing	Ford island, Hawaii	Uni-Solar	53	2.8 KW DC
1999	Roofing	Navajo Reservation, Arizona	Energy PVs, Inc.	58	4 kWp
1999	Roofing	General Services Adm., Massachusetts	ASE Americans, Inc.	353	37 kW DC
1999	Roofing	Academy of further education, Germany	Pilkington solar Int.	10000	1 MWp
1999	Roofing	Discovery science centre, California	BP Solarex	403	20 kWp
2000	Façade	Ijsselstein Row Houses, Holland	EPV	30/housing unit	1.6 kWp
2001	Roofing	Yosemite Transit Shelters, California	Energy PVs, Inc.	10	0.56 kWp
2002	Roofing	Denver Federal House, Colorado	Pilkington solar	172	15 kWp
2002	Roofing	Denver Federal House, Colorado	Pilkington solar	59	3.4 kWp

2.8 Conclusion

No PV cell production facilities currently exist in New Zealand. PV cells would need to be sourced off shore as production facilities for crystalline cells only become economically viable at over 100MWp per annum. Thin film cells are not available for sale as manufacturing facilities are purpose built for specific PV products and are expensive to install.

Solar thermal and solar PV installations for domestic and industrial purposes have been growing annually by 15% and 25% respectively. Subsidies and government sponsored programmes have helped promote PV and solar thermal use. Solar PV/T technology combines PV and solar thermal into one system that can be installed in buildings for providing energy and heating.

PV and solar thermal collectors have been integrated into roofing and wall cladding but they have not been integrated into long run roofing. Building integrated photovoltaics (BIPV) has been growing rapidly since 1991 and MW scale systems are currently being installed. Building integrated thermal (BIT) systems are used in domestic and commercial applications for hot water heating and space heating.

PV/T has not seen large scale integration into building components due to problems experienced in producing reliable and robust products. The majority are retrofitted or installed after the building has been completed. Long-run roofing systems typically used in New Zealand were identified as suitable for PV/thermal integration because they have standing seam and corrugated seam profiles with large flat surfaces suitable for attaching PV and modifying for solar thermal collector.

Chapter 3 Manufacturing methodologies

3.1 Introduction

The BIPVT (Building integrated photovoltaic thermal) concept, materials used, components and manufacturing possibilities are discussed in this chapter. Three manufacturing methods are identified as being suitable for BIPVT.

3.2 BIPVT concept

Traditionally, commercially available solar thermal, solar PV, and PV/T collectors are installed separately on buildings after the building components have been installed. BIPVT components have PV and solar thermal systems integrated into building components such as roofing or wall cladding (Figure 3.1) and generate electricity and heat from solar radiation (Figure 3.2).

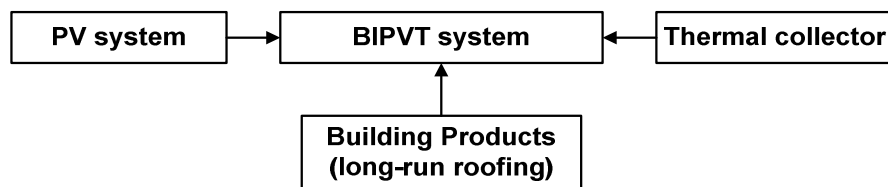


Figure 3.1 Integration of PV, thermal and building products.

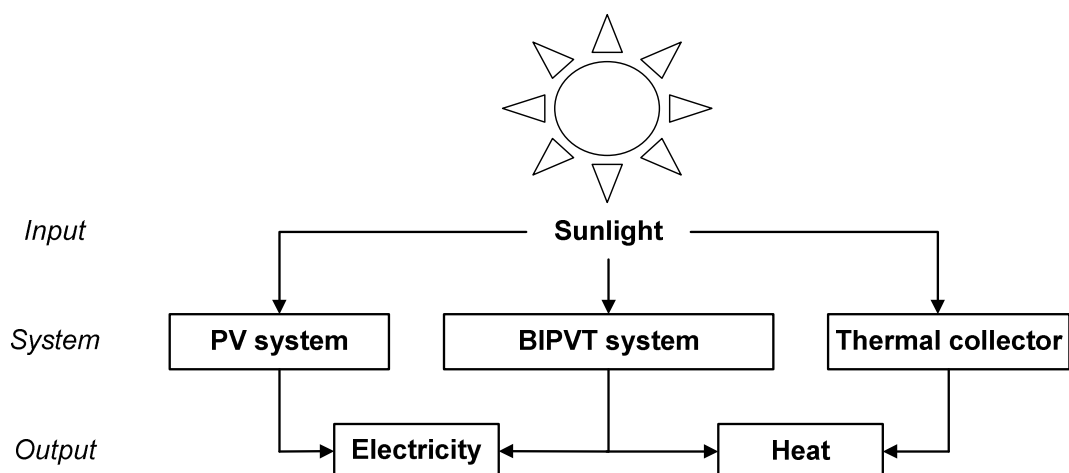


Figure 3.2 BIPVT system.

The building product considered most suitable for BIPVT is long-run steel and aluminium roofing systems commonly used in New Zealand. This is because long run roofing products mainly have corrugated and standing seam profiles (Figures 3.3) with long flat surfaces suitable for mounting PV. The metal is readily shaped to include channels for thermal fluid flow for solar thermal systems. Also the roofing is near perpendicular to the radiation from the sun as compared to typical vertical building walls so energy generation is greater from roofing systems than BIPVT systems in building walls.

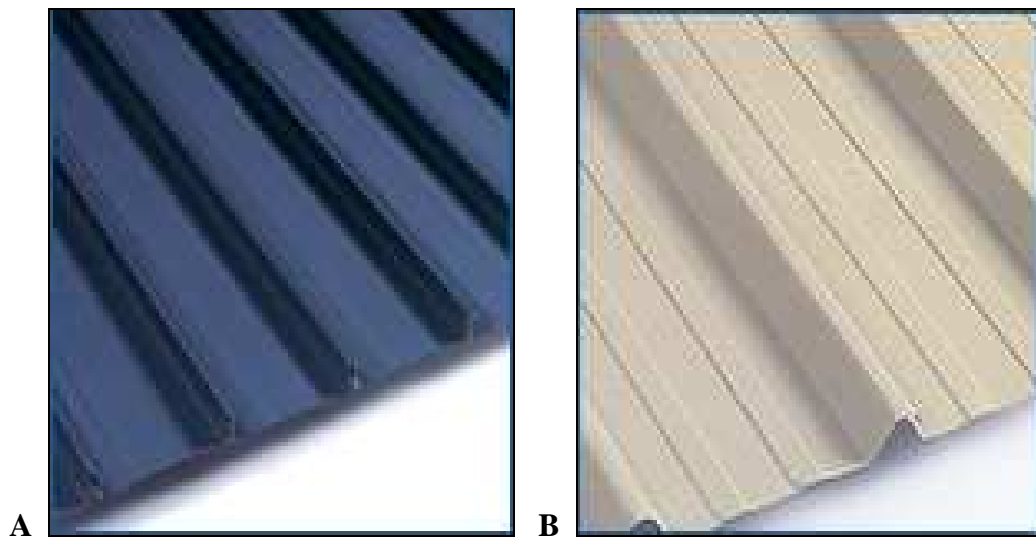


Figure 3.3 A) Standing seam profile [63] and B) Corrugated seam profile [64].

Major components of the BIPVT product include corrugated sheet, collector (absorber) plate, 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 the system (Figure 3.4). This minimises the use of tubes and pipes for fluid flow.

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 (Figure 3.4 and 3.5). The collector plates are made from the same material as the corrugated sheets to keep the appearance and material properties the same. This prevents one material being a sacrificial anode in corrosion processes and avoids the problem of having to electrically seal one metal from another. Inserts seal the central channels ends between the corrugated sheet and collector plate to prevent thermal fluid leakage from the system.

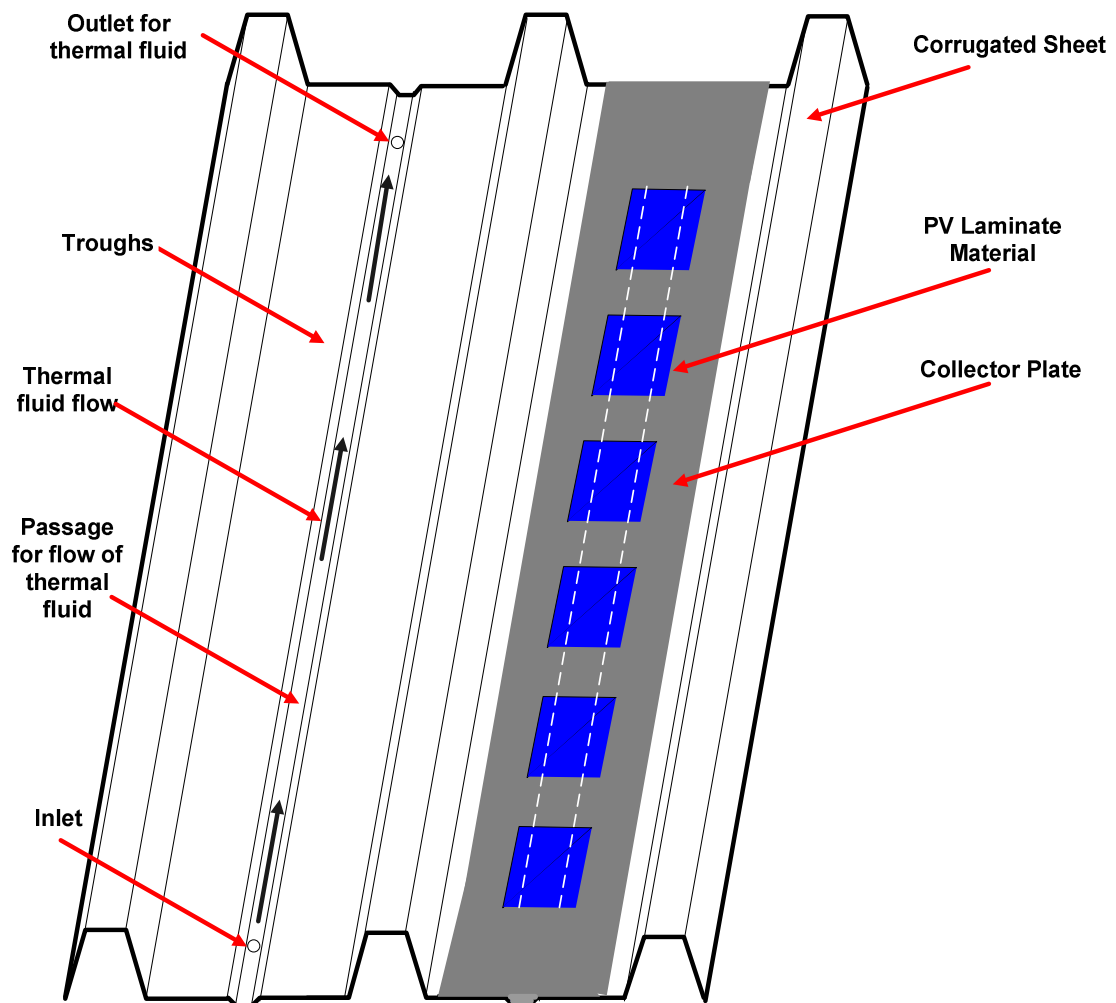


Figure 3.4 Schematic view of BIPVT product.

Manifolds or headers 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. Stud bolt fittings are hollow and carry the thermal fluid from the manifolds to the corrugated sheet (Figure 3.5).

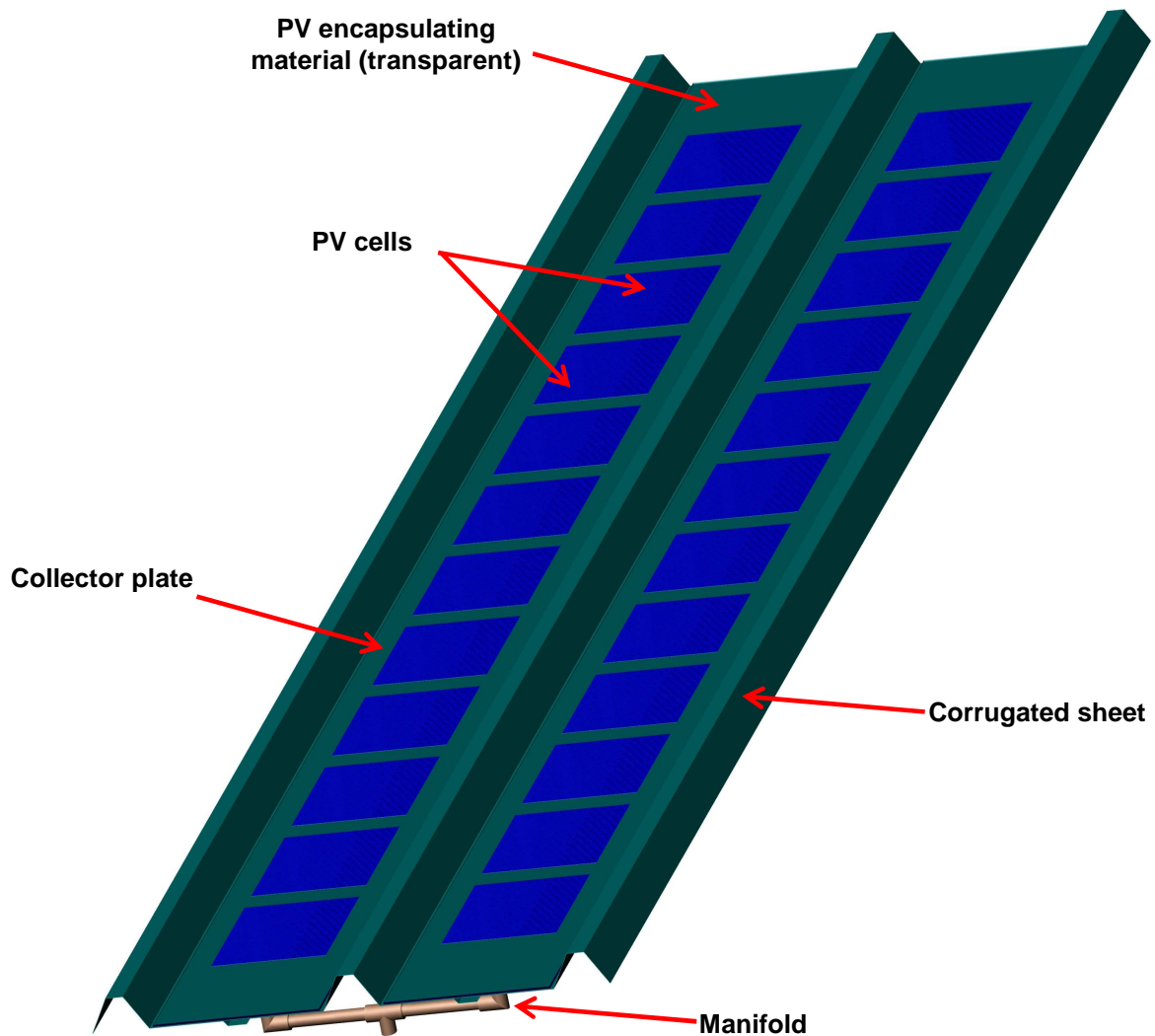


Figure 3.5 An assembled BIPVT panel with all components.

PV laminates used in BIPVT systems comprise glass sheet, EVA, PV strings and EVA layered onto the collector plate and is either glued or pressed together using laminators. This minimises the glass sheet or plastic foil compound used in standard lamination processes. A junction box, cable and connector are used for the PV system electrical connections.

Incident radiation on the BIPVT system is absorbed by the PV laminate which convert 12-17% of the energy into electricity depending on surface PV coverage and cell efficiency. The remainder heats the collector plate which is used to heat the thermal fluid which enters at one end of the BIPVT system through a manifold and leaves at the other end through another manifold. The heat in the thermal fluid is then used for space or water heating (Figure 3.4 and 3.5).

3.3 BIPVT Manufacture

BIPVT manufacturing consists 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 selected for BIPVT manufacture. These are:

Production steps:

1. Corrugating flat metal sheet to form the roofing profile including troughs and central channel.
2. Drilling or 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.
4. Sealing the central channels at each end of the roofing section.
5. Mounting fittings for connecting manifold to the central channels inlets and outlets on the underside of the corrugated sheet.
6. Laminating glass sheet, EVA, PV and EVA onto the collector plate and installing electrical fittings.
7. Sealing the edges between collector plate and corrugated sheet are sealed.
8. Connecting manifolds to the inlet and outlet points.

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.

Manufacturing and quality control steps are shown in Figure 3.6 and summarized in Table 3.1.

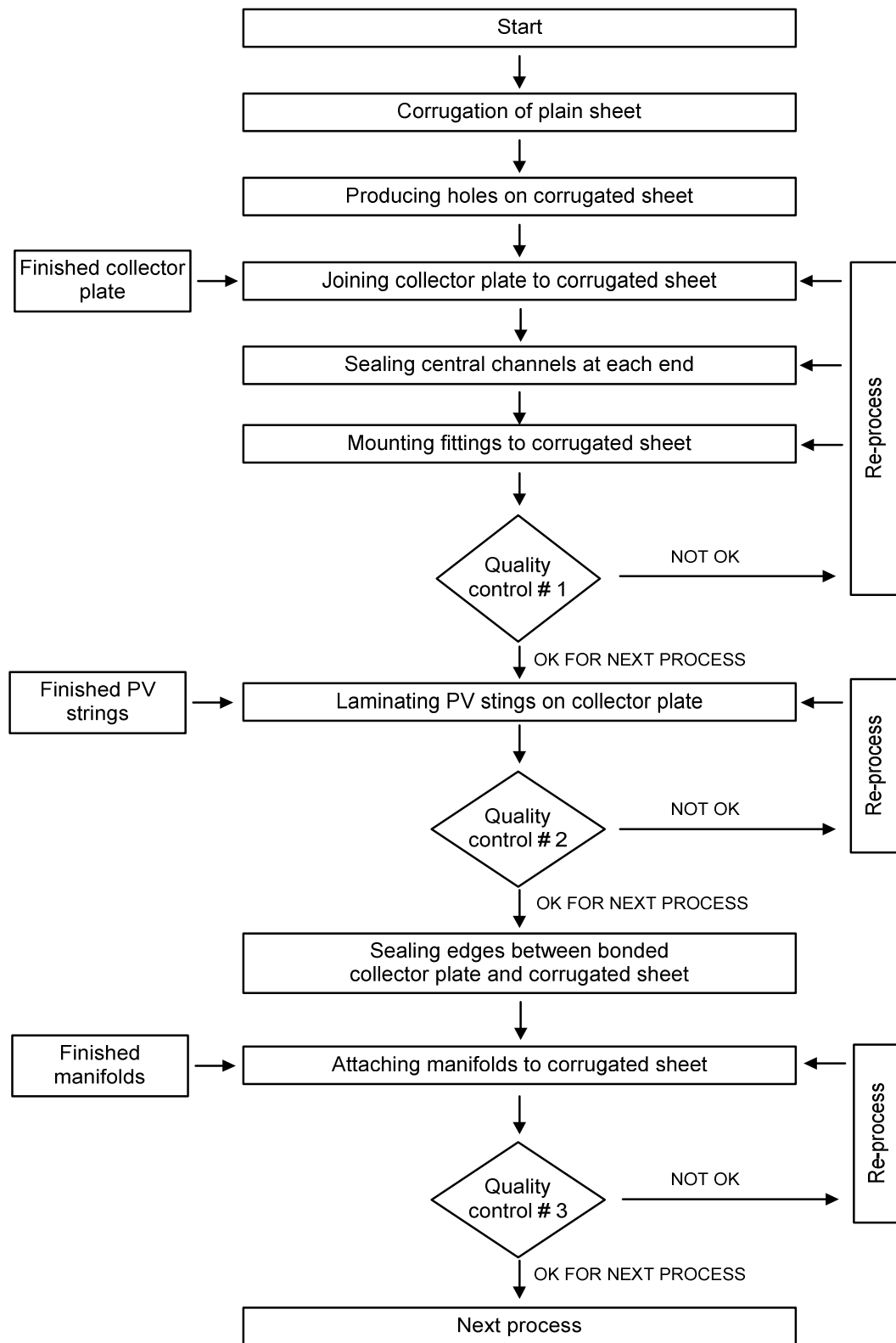


Figure 3.6 General flow chart for manufacturing BIPVT product.

Table 3.1 Operations with functions and details in BIPVT manufacturing.

P= Production operation and Q= Quality operation

Oper. No.	Operation	Function	Details
P1	Corrugation of plain sheet	Generating modified long-run roofing profile	Corrugation comprising crest and troughs along with central channels for thermal fluid flow
P2	Producing holes on central channels	Holes acting as inlet and outlet points for thermal fluid flow through the system	Holes produced at a fixed distance from the ends on central channels act as inlet, outlet and limit thermal fluid flow
P3	Joining collector plate to corrugated sheet	Creating passage for thermal fluid flow and acting as backing plate for PV laminates	Collector plate is bonded to corrugated sheet on trough section along the entire length sealing the central channel
P4	Sealing central channels at each end	Sealing central channels and limiting thermal fluid flow between inlet and outlet points	Fixed distance beyond the inlet and outlet points on central channel is sealed by special inserts
P5	Mounting fittings to corrugated sheet	Facilitating assembly of corrugated sheet with manifolds	Hexagonal nut fittings are joined underneath the corrugated sheet on inlet and outlet points
Q1	Quality control # 1	Monitoring production operation number 3, 4, and 5 results	Water is used as thermal fluid for testing, central channels and inlet and outlet points are checked for proper sealing
P6	Laminating PV strings on collector plate	Transforming the product into a BIPVT product	Finished PV strings are laminated on collector plate using EVA and tedlar for encapsulation
Q2	Quality control # 2	Monitoring production operation number 6 results	Quality and electrical performance of PV lamination is checked
P7	Sealing edges between bonded corrugated sheet and collector plate	Preventing the join from any external fluid flow	Bonded edges across the collector plate and corrugated sheet are sealed by sealants/adhesives
P8	Attaching manifolds to corrugated sheet	Functioning of BIPVT product to generate electricity and thermal energy	Manifolds and corrugated sheet are assembled by mechanical fastening of hexagonal nut and stud bolt fittings. Stud bolts are hollow and thermal fluid flows through them to corrugated sheet
Q3	Quality control # 3	Monitoring production operation number 8 results	Performance of BIPVT product for thermal/electrical properties and also assembly between the corrugated sheet and manifolds is checked. Water is used as thermal fluid for testing.

The manifolds and stud bolts would be removed from the BIPVT after testing to allow for easy BIPVT product stacking and then reassembled when the BIPVT product is installed on location.

In mass production, batch sampling would be used for quality control checks where samples from each batch would be taken and tested. Therefore step 8 in the manufacturing process could be omitted.

A range of manufacturing possibilities were considered for each step in BIPVT production (Table 3.2). These are discussed in detail in the following section.

Table 3.2 Manufacturing possibilities for BIPVT production steps.

Step	Production step	Manufacturing possibilities
1	Corrugating plain sheet	Press-brake forming Roll forming
2	Producing holes on corrugated sheet	Drilling Punching
3 4 5	Joining the collector plate to the corrugated sheet Sealing the central channels at each end Mounting fittings to corrugated sheet	Mechanical fasteners Adhesives Autoclave Welding (Liquid state) MIG TIG Electron beam Welding (Solid state) Resistance seam Friction stir Ultrasonic Brazing/soldering
6	Laminating PV to collector plate and install electrical connections	Laminator Integrated Passing through Autoclave
7	Sealing the edges between the collector plate and corrugated sheet	Adhesives Sealants
8	Assembling manifolds with corrugated sheet	Mechanical fasteners

3.4 Production steps, functions, methods and details

3.4.1 Step 1, corrugation of plain sheet

The roofing profile will be made from Zinalume which is zinc and aluminium coated mild steel and Colorcote which is colour coated Zinalume, supplied by Dimond Ltd.. These are commonly used for roofing products in New Zealand.

Press brake forming and continuous roll forming are two commonly used methods for corrugating flat sheet. Press-brake forming is where pre-cut sheet metal is bent to shape often using a computer numerical controlled (CNC) machine. Press brakes can have beds 7 m or greater in length and are commonly used for batch or mass production. Roll forming is a continuous production method for shaping either pre-cut or long lengths of sheet metal by passing it through a series of shaped rollers to achieve the desired shape [65, 66].

BIPVT roofing profiles will be 6 m in length and it is expected that initially only small volumes of product will be made. Also it is anticipated that there may be minor improvements or changes to the roofing profiles as the product develops. Therefore press-brake forming is the most suitable method as it allows the profile shape to be changed easily by programming the new profile into the CNC machine, compared to roll forming which requires the rollers to be replaced. For longer lengths of BIPVT product, i.e. greater than 6 m and for mass production roll-forming is the best method [65, 66].

3.4.2 Step 2, producing holes on central channels

The central channels need 10 mm diameters holes for the thermal fluid inlet and outlet (Figure 3.7). This can occur before or after the metal sheet used for BIPTVT is corrugated. If the holes are made before corrugation there is a possibility the holes may be misaligned on the central channels after corrugation has taken place due to misalignment of the sheet, therefore the product would need to be discarded. Producing the holes after corrugation seems more sensible as the holes can be correctly aligned with the central channel using a jig.

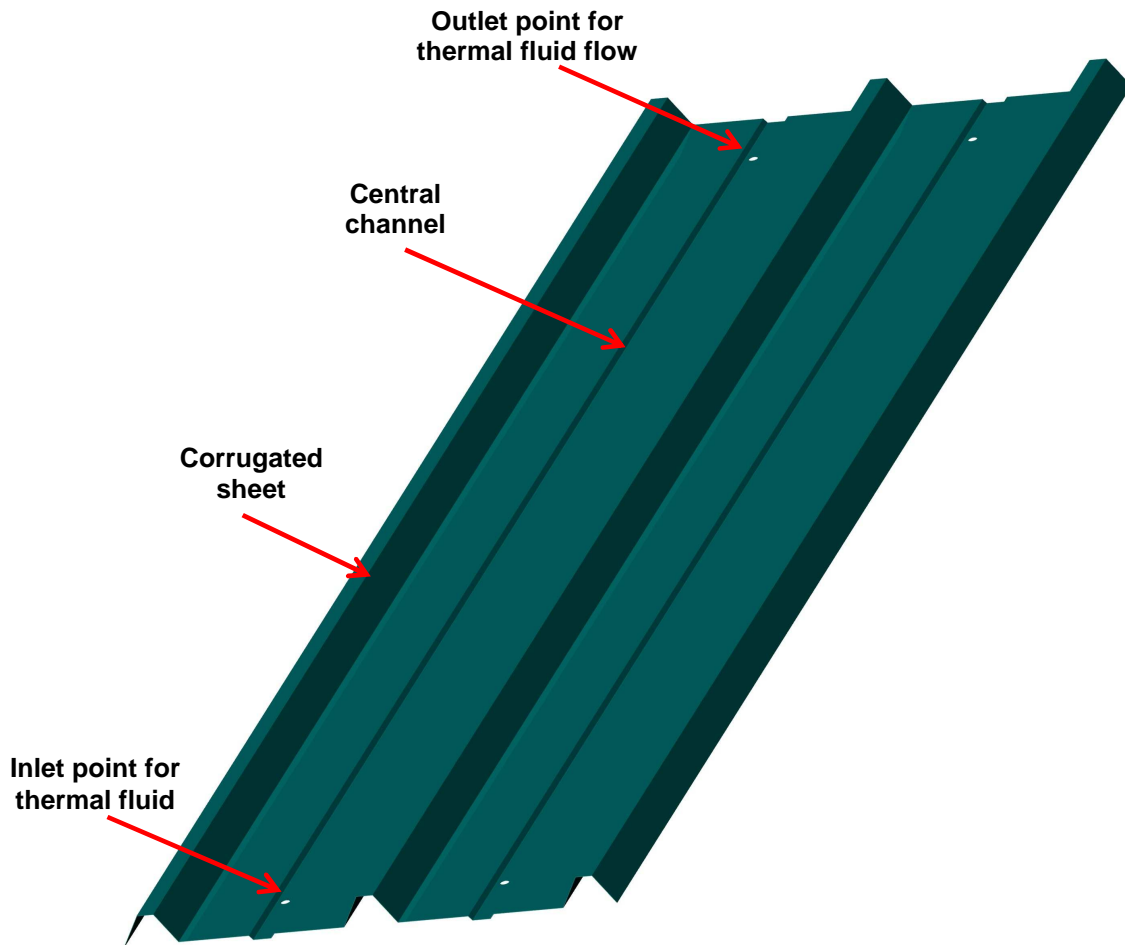


Figure 3.7 Corrugated sheet with inlet and outlet points.

Holes are normally produced in industry using a drill press or hole punch and die [65, 66]. Drilling through a plate produces a burr on the bottom edge of the hole. Punching also creates a burr but also deforms the metal on the top side of the hole because the punch makes a small crater where it enters the material. The burr needs to be removed before any fittings are attached to the plate to ensure a good fit. This can be done using a grinder or sander prior to attaching the fittings. When drilling thin sheet, there is a slight chance the plate can climb up the drill bit. This can be avoided by attaching a spring loaded clamp to the drill press which holds the plate in position as it is being drilled. Punching is very fast and simple compared to drilling. As the sheet is 0.55 -0.70 mm thick deformation and the burr should be small, therefore punching is best method for producing holes.

3.4.3 Step 3, joining the collector plate to corrugated sheet

Joining the collector plate to the corrugated sheet trough sections is an important step. The join should be strong and prevent the collector plate from detaching from the corrugated sheet if the sheet is twisted. Also joining the two forms the central channel for thermal fluid flow, therefore the central channel needs to be sealed to prevent fluid leakage. Mechanical fasteners (such as screws, nuts and bolts, and rivets), adhesives and welding are possibilities for joining the collector plate to the corrugated sheet (Figure 3.8).

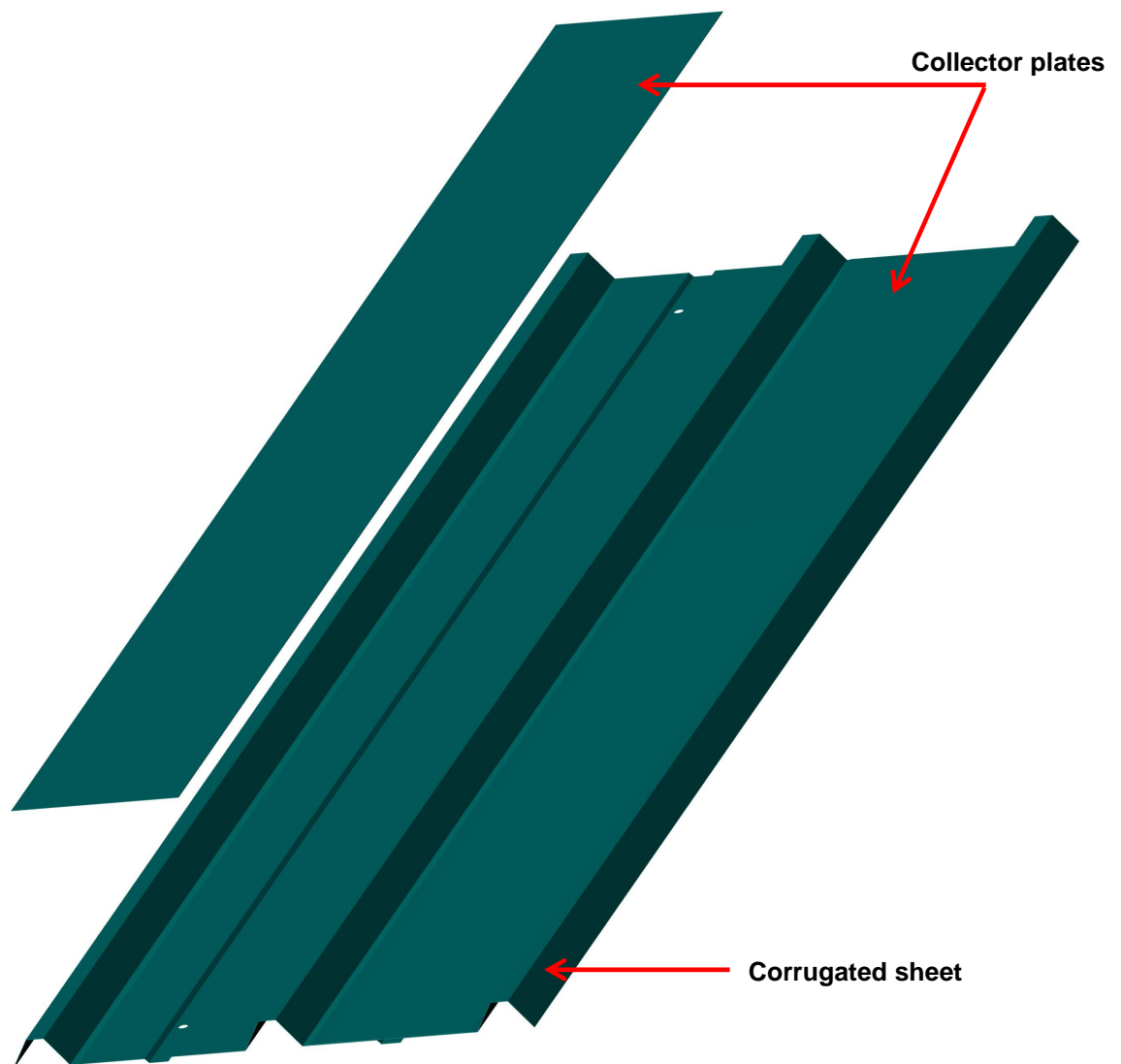


Figure 3.8 Collector plate bonded on corrugated sheet.

Adhesives and welding are mutually exclusive methods for BIPVT manufacture unless adhesives are applied after any welding has been completed when the product is cool. Otherwise product heating from welding may cause adhesive failure.

Mechanical fasteners

Mechanical fasteners need holes drilled or punched [67] in the collector plate and corrugated sheet, which would add additional process steps to the manufacturing. Also, these fastening points and the central channel must be sealed to prevent rainwater leakage through the BIPVT and thermal fluid leakage from the central channel. Therefore mechanical fasteners are not suitable for this step.

Adhesives

Adhesives contain a volatile solvent that evaporates causing the adhesive to solidify bonding the two surfaces together. Adhesives are considered to be one of the best alternatives for joining parts in industry as it eliminates the need to drill or punch holes to fix parts together. They have achieved greater acceptance in manufacturing after World War II, where they were used for assembling load-bearing components in aircrafts [65]. The join between the corrugated sheet and the collector plate is a lap joint, considered the best join for adhesive bonding (Figure 3.9) [68].

Adhesives are available commercially in liquid, paste, solution, emulsion, powder, tape and film form. Bonded joint strength depends on the surface preparation of the mating substrates. The adhesive must wet the surfaces to be joined and form a chemical bond between them. Surface preparation is where the mating surfaces are cleaned and/or chemically treated to facilitate better bonding. Adhesive is applied either manually or automatically to one of the surfaces directly after surface preparation before the treated surfaces dry. Both parts are clamped together to prevent movement of parts relative to each other and so the adhesive has a thickness of around 0.10 mm. Curing occurs at room temperature or higher in an autoclave depending upon the adhesive type [69, 70].

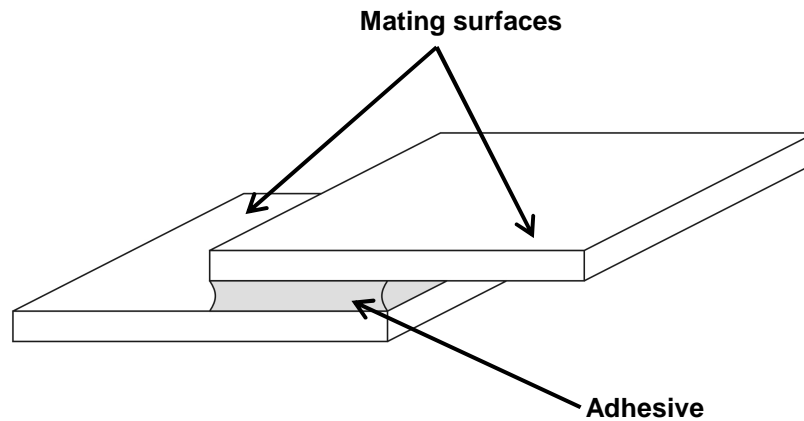


Figure 3.9 Lap joint in adhesive bonding for two workpieces.

Using adhesives allows for low temperature manufacture (up to 200°C in an autoclave) preventing distortion and heat effects that can occur with techniques such as welding. This allows thin materials (<1 mm thickness) and materials of different types to be joined together. Adhesives also double as a sealant which is useful for sealing the central channel between the corrugated sheet and the collector plate. Exterior surface finish is unaffected when adhesives are used as compared to welding metals where a seam and heat affected zone remains [66, 71].

The adhesive bond strength per unit area is not as great as the bond from welding [65]. However the collector plate is not under significant load as only the PV laminate will be attached to it and the adhesive is applied to a large surface area.

Adhesives need time to cure, so some manufacturing processes use an autoclave to decrease curing time by heating the components and extracting the volatile solvents in the adhesive using a vacuum.

For BIPVT, the adhesive needs to be resistant to temperatures from -20°C to 170°C, resistant to moisture and atmospheric/weathering conditions, and bond to steel and aluminium. Adhesives suitable for steel and aluminium include Ms Polymer™, epoxy, silicone based, and acrylic. Silicone based adhesives appeared to be the most suitable because they have good temperature resistance [72].

Autoclaving

Autoclaving is a molding process in which a plastic material is placed on a mold. The plastic is heated in an autoclave, a vacuum applied between the mold and the plastic, and air pressure increased above the plastic forcing the plastic to take the shape of the mold (Figure 3.10). The autoclaves used are large pressure vessels up to 30 m in diameter and 50 m in length [66, 71].

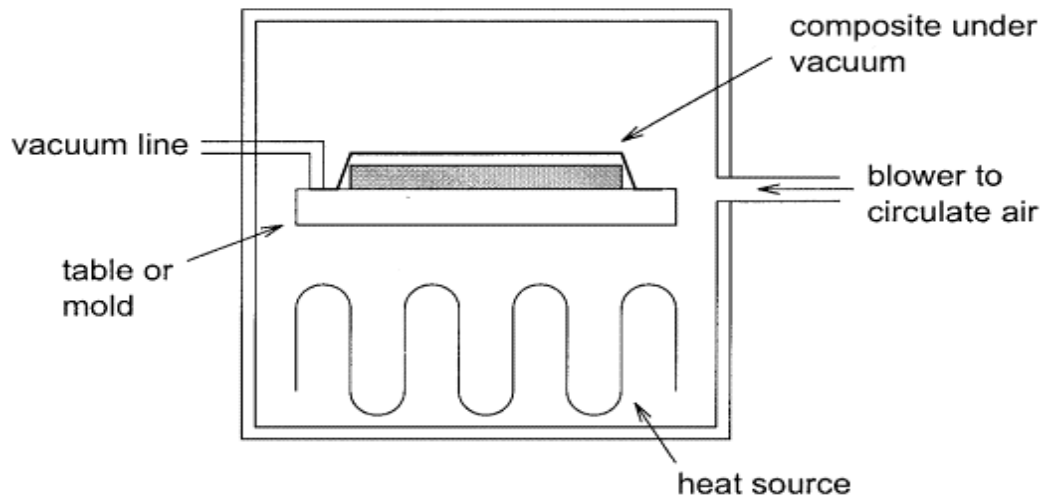


Figure 3.10 Schematic view of an autoclave [71].

A similar process can be used for bonding the collector plate to the corrugated sheet. Using adhesives only a vacuum would be used to remove air from between the surfaces to be joined and heat to decrease adhesive curing time. An autoclave is expensive approximately \$200,000 for a 12m³ system [73] but is fast and used for high volume production [66, 71].

Welding

Welding is where two materials are joined together and creating a seam by melting the mating surfaces or edges together. Welding includes solid and liquid state techniques. Liquid state techniques, such as tungsten inert gas and metal inert gas, use high temperatures to melt the materials where the desired join is to be made and create a large heat affected zone which may cause the material to distort. Electron beam welding, also a liquid state technique, while using high temperatures, is conducted rapidly under a vacuum creating only a small heat affected zone. Solid-state techniques, such as resistance, friction, and ultrasonic

welding, heat the material sufficiently to form a bond without excessive melting. They generate a small heat affected zone and material distortion is reduced. Welding is rapid, the join is high strength and the process can be automated, but specialised techniques such as electron beam, friction stir and ultrasonic welding are more expensive than adhesives. Also any surface coating will need to be removed prior to welding to ensure a clean weld. Resistance seam, ultrasonic, friction stir, and electron beam were selected as possible methods for attaching the collector plate to the corrugated sheet. These techniques are suitable for lap joints, like the join between the collector plate and the corrugated sheet. They are also suitable for medium to high volume production [65-67].

Resistance seam welding is a solid-state welding process in which the materials to be joined are pressed by rollers or cylindrical tips which act as electrodes. An alternating current is passed through the contact point which heats and melts due to the material's electrical resistance. The current is stopped after the mating surfaces have melted and pressure is released after the weld/joint is solidified [66]. When rollers are used, a continuous electric current is used, and the material melting rate determines the speed at which the materials to be welded are passed through the rollers (Figure 3.11). Welding speeds are around 1.8 m/min and equipment capital cost is approximately \$40,000 [65-67].

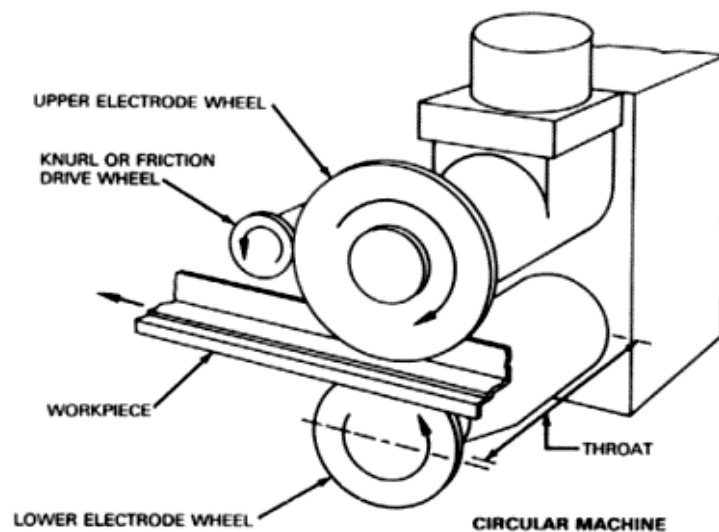


Figure 3.11 Resistance seam welding process [74].

Ultrasonic welding is a solid-state welding process in which the mating surfaces to be joined are vibrated at 10-200 kHz by a transducer. The vibration melts the surfaces and allows them to join together. This process avoids melted material pooling, excessive heating and limits temperature distortion effects [65, 68]. In ultrasonic seam welding, the transducer tip is replaced with rotating disks which runs the length of the material to be welded forming a continuous seam (Figure 3.12). The temperatures generated are lower than other welding processes. Welding speeds are approximately 7 m/min and the equipment capital cost is approximately \$60,000 [65-67]..

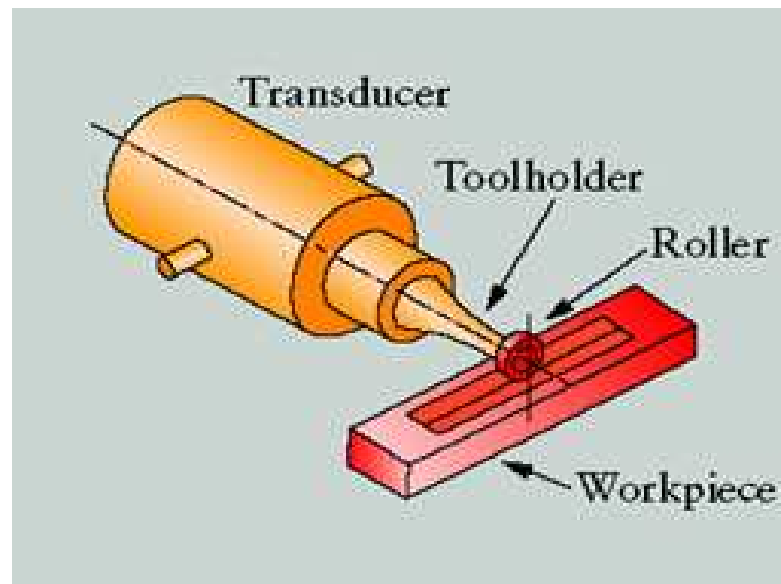


Figure 3.12 Ultrasonic seam welding process [65].

In friction stir welding, a high speed rotating tool is rubbed against the two surfaces to be joined. The rotating tool has a tip which is plunged into the component edges to be joined. The friction melts the material and as the tool moves down the join, the molten metal flows together and fuses as it cools (Figure 3.13). The temperatures are in the range of 230°C to 260°C [65, 67].

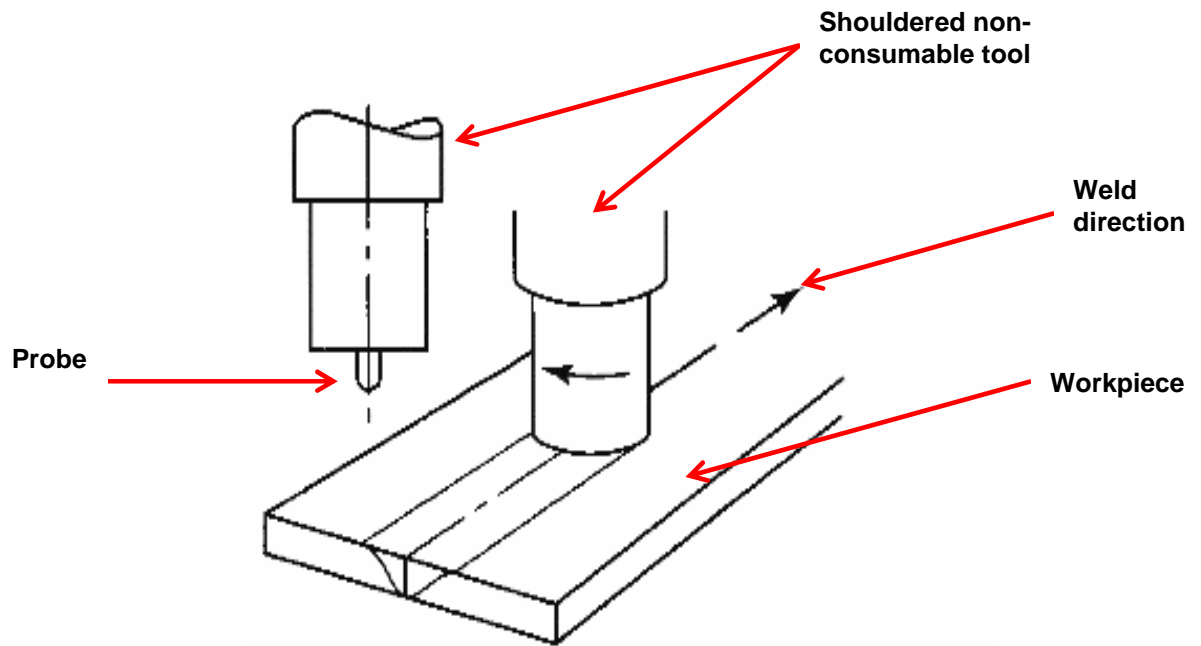


Figure 3.13 Friction stir welding process [69].

This method is suitable for welding aluminium, steel, copper and coated materials. It has the advantages of low heat generation and minimal surface distortion. No shielding gas or surface cleaning is needed. The welding speeds are about 0.5 m/min which is lower than resistance seam, ultrasonic and electron beam welding. Equipment capital costs are approximately \$150,000 [65-67].

Electron beam welding (EBW) is a high-energy process in which high velocity electrons fired in a narrow beam under vacuum at the edges of the two materials to be joined. The electrons heat the material causing the edges to melt and fuse to form a seam (Figure 3.14). Heating depth is determined by the extent of vacuum and the process can be classified as high, medium or no vacuum EBW [65, 67]. This method is a liquid state welding process but has a small heat affected zone because it is very rapid and operates under a vacuum. Welding speeds are up to 12 m/min, higher than previous methods discussed, and high quality welds are obtained. The equipment capital cost is very high, approximately \$250,000 because of the shielding needed to protect against x-ray generated during operation and vacuum requirements [65].

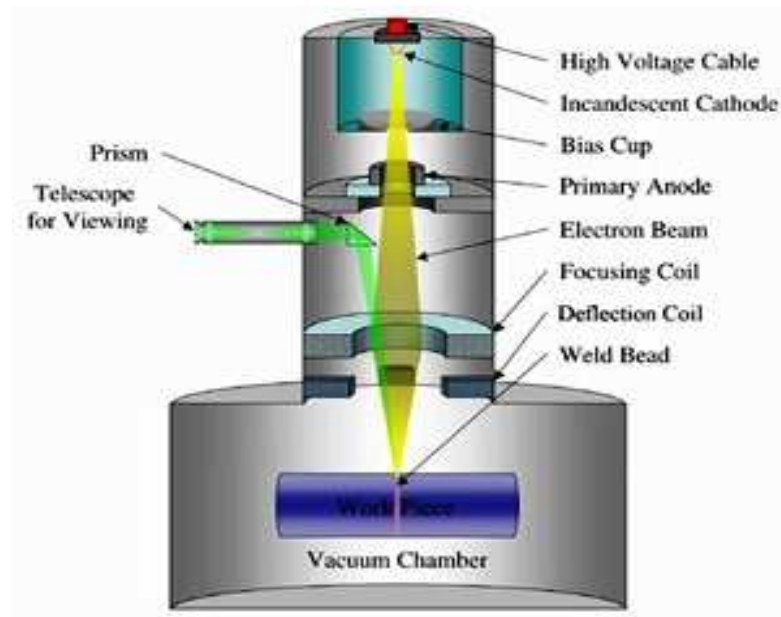


Figure 3.14 Electron beam welding process [65].

A comparison of welding techniques with advantages and disadvantages is shown Tables 3.3 and 3.4. Resistance seam welding was selected as the most suitable method because it has the lowest capital cost and moderate welding speeds and energy consumption. Low capital costs reduce the total investment and payback time for the BIPVT process. It is commonly used as a welding technique for seam joints and less complex than other methods. It does not involve high frequency vibrations as in ultrasonic welding or require shielding and vacuum as in electron beam welding. If electron beam welding was to be used special equipment would be needed in the manufacturing chain to create a sealed vacuum chamber so the beam could operate driving up the capital cost of the manufacturing process.

Table 3.3 Comparison of welding techniques [65-67].

Parameter	Welding techniques			
	RSW	USW	FSW	EBW
Welding speed	1.8 m/min	7 m/min	0.5 m/min	12 m/min
Capital cost	~\$35,000	~\$60,000	~\$150,000	~\$250,000
Type of production	Medium-high	Medium-high	Low-medium	High
Energy consumption	Medium	High	High	Very high

Table 3.4 Welding techniques advantages and disadvantages [65-67].

Method	Advantages	Disadvantages
Resistance seam welding (RSW)	<ul style="list-style-type: none"> • Best suitable for lap joints of thin sheets and plates • Moderate capital equipment cost (\$35,000) • High welding speeds (1.8 m/min) 	<ul style="list-style-type: none"> • Energy consumption varies with type of material • Not suitable for wide variety of materials • surface distortion
Ultrasonic seam welding (USW)	<ul style="list-style-type: none"> • Best for lap welding of thin sheets • Variety of materials can be welded • Low temperatures are evolved • Higher welding speeds (7m/min) 	<ul style="list-style-type: none"> • High capital cost (\$60,000) • High energy consumption • Not suitable for different materials
Friction stir welding (FSW)	<ul style="list-style-type: none"> • Best for lap joints of thin sheets and plates • Suitable for aluminium, copper, steel and other materials • Low heat input and low distortion • No shielding gas, flux or surface cleaning required 	<ul style="list-style-type: none"> • High capital equipment cost (\$150,000) • Lower welding speeds (0.5 m/min) • Energy consumption more for metals other than aluminium
Electron Beam welding (EBW)	<ul style="list-style-type: none"> • Best for lap joints in thin and thick gauges from foil to plate • High welding speeds ~12 m/min • High quality welds are obtained • Best for mass production 	<ul style="list-style-type: none"> • High capital equipment cost (\$250,000) • Process hazardous as X-rays are generated • Vacuum is required for process • Not suitable for job and batch

Brazing and soldering was also considered as a possible method for bonding the collector plate with the corrugated sheet. These are a liquid-solid-state bonding process and the temperature generated is lower than previously mentioned welding processes. In brazing, a filler material is positioned between the components to be joined. The temperature is raised to above 450°C until the filler material melts. After cooling, the filler material bonds the two surfaces together. In soldering, the filler material used is often termed as solder, which melts at lower temperatures than used in brazing. After melting, solder fills the joint by capillary action between components to be joined. Soldering irons or torches are

used as heating sources. These methods are mainly used for soldering electrical components and small metal components but are not typically used for large surfaces [65, 66] such as the collector plate and corrugated sheet in BIPVT product.

3.4.4 Step 4 and 5, sealing central channels at each end and mounting fittings to the corrugated sheet

The central channels are sealed at each end to prevent fluid leakage by slotting in an insert 70 mm long of the same shape as the channel which is 5 mm deep and 20 mm wide (Figure 3.15). Then hexagonal nut fittings are attached to the underside of the central channel to provide mounting points for hollow stud bolts for the thermal fluid inlets and outlets (Figure 3.16).

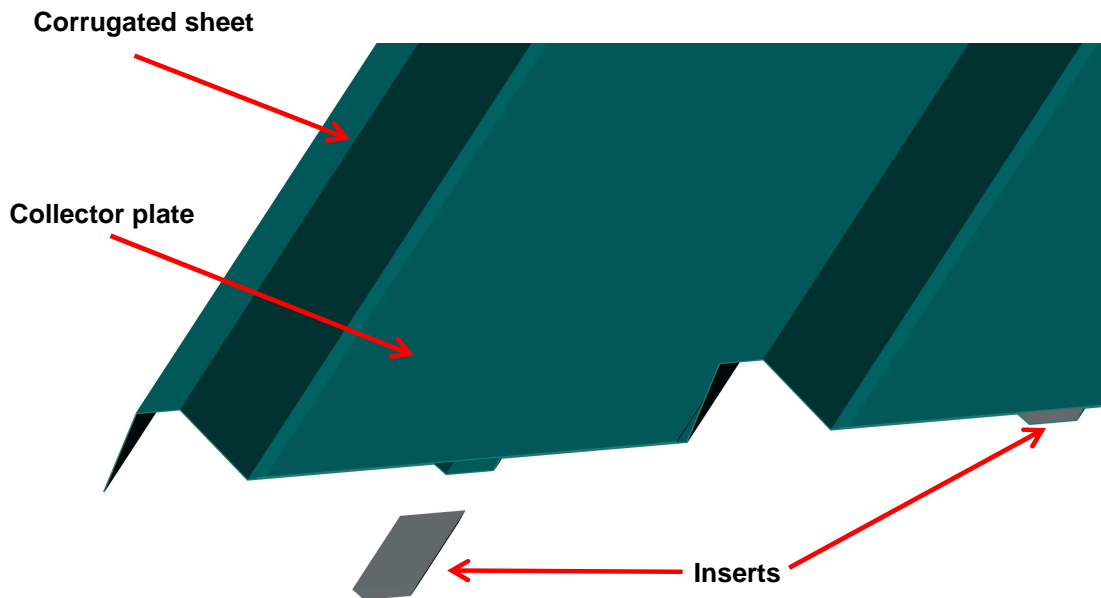


Figure 3.15 Sealing central channels end by inserts.

The inserts can be installed at the same time as the collector plate is being attached if adhesives are used. If the plate is welded to the corrugated sheet, then the inserts need to be installed after the plate is attached. The hexagonal nuts are installed after the inserts have been slotted in place. Brazing, soldering and adhesives are equally suitable methods for these steps (Figure 3.16). However, if adhesives are used for the collector plate or installing the inserts, then brazing or soldering would not be suitable methods because temperatures can approach 400°C which may weaken the adhesives [65, 66].

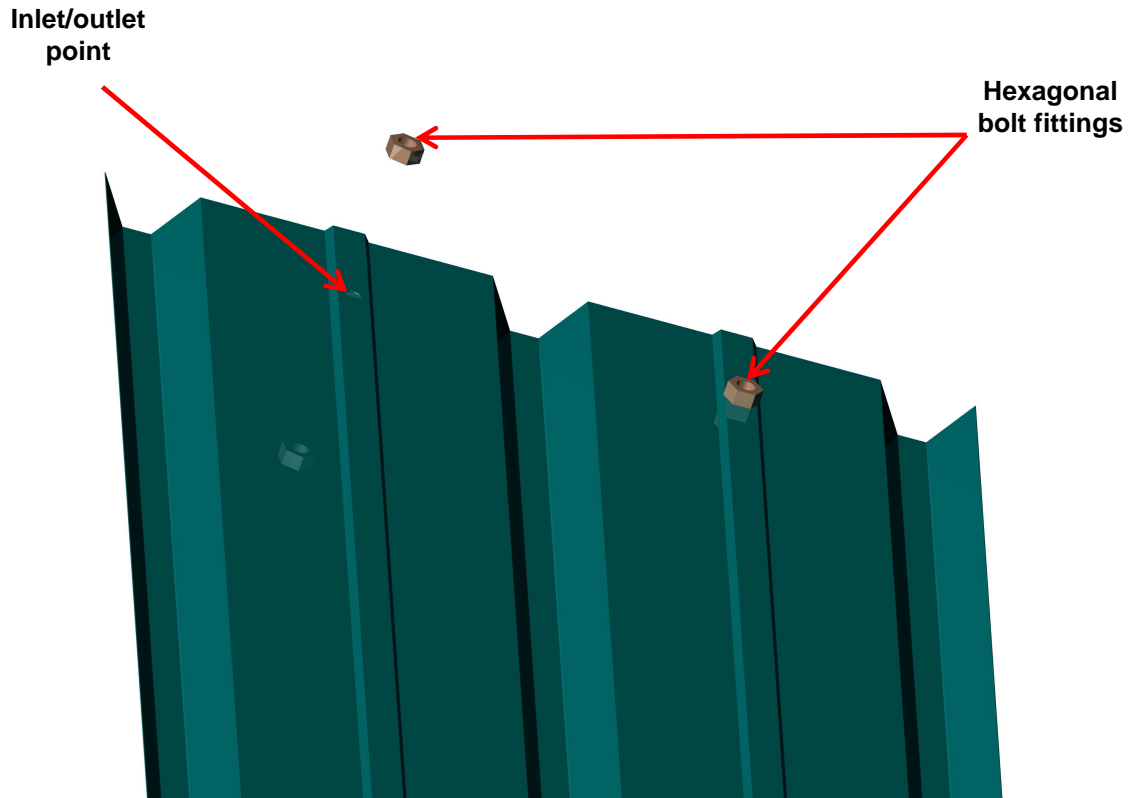


Figure 3.16 Mounting fittings to corrugated sheet underside at inlet and outlet points.

3.4.5 Step 6, lamination of PV strings on collector plate

A vacuum laminator is conventionally used for laminating glass sheet, EVA, PV strings, and EVA on to a backing plate [11, 34]. As the glass sheet, EVA, PV strings, and EVA are layered on to the collector plate, the PV strings are wired to a junction box, so when lamination takes place, the EVA seals around the electrical wires protruding from the PV cells (Figure 3.17). This step could be carried out prior to attaching the collector plate to the corrugated sheet if adhesives were used to join the two. However a load must be applied to the collector plate during attachment to ensure good bonding. The PV cell laminate is delicate and may crack. Therefore it is better to perform lamination after the collector plate has been attached. If welding was used then lamination must occur after the collector plate has been attached because the high temperatures used in welding would destroy the laminate.

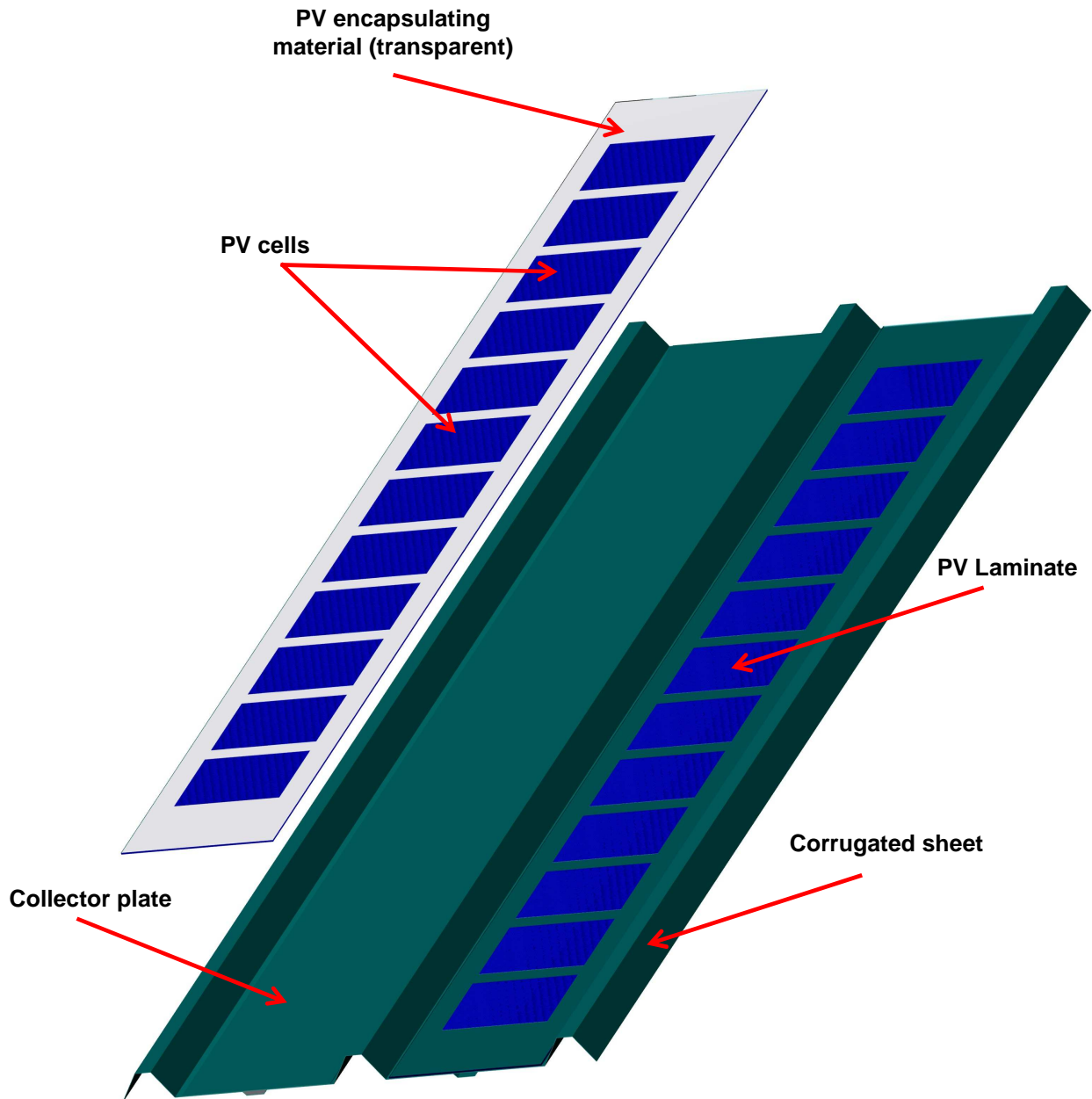


Figure 3.17 Lamination of PV strings on collector plate.

An integrated or passing-through laminator can be used for lamination [11]. Alternatively an autoclave could be used which would potentially allow the lamination to occur at the same time as attaching the collector plate to the corrugated sheet and installing the inserts in the central channels.

In an integrated laminator, heating and cooling cycles are carried out in the same equipment using two methods. The first is Isovolta which uses normal EVA. The laminate (module) is loaded at 90°C and exposed to 10 mbar vacuum. The laminate is heated to 155°C over 10 minutes. During heating the laminate is

compressed to achieve a seal at approximately 120°C. Temperature is held at 150°C for 15 minutes after which it is cooled to 90°C over 10 minutes. The laminator is opened when the laminate has reached 100°C. The total cycle time is approximately 35 minutes [11].

The second integrated lamination method is Springborn which can be used for normal and fast cure EVA. First the laminator plates are pre-heated to 75°C. The laminate is covered in silicon or Teflon foil prior to loading. Three minutes after loading, the laminate base is exposed to 1.3 mbar vacuum. After the laminate reaches 60°C, the laminate is compressed to 1 bar and is heated to 155°C after which curing begins. Curing is 22 minutes for normal EVA at 155°C and 4 minutes for fast cure EVA. After curing, the laminator is opened, cooled to 75°C during which the laminate is unloaded. Total cycle time using normal EVA is approximately 33 minutes and 15 minutes for fast cure EVA [11].

In a passing-through laminator, only the heating cycle and lamination is carried out in the laminator. The laminate is passed from the vacuum laminator to the curing oven and to the cooling zone. The temperature cycles are similar to the integrated laminator process except the laminate is allowed to cool on the conveyor belt or in a separate area. The total cycle time is ten minutes [11].

The Springborn method and fast cure EVA was selected for the BIPVT process because of the fast processing times and rapid curing.

3.4.6 Step 7, sealing the edges between bonded collector plate and corrugated sheet

Adhesives or sealants are used for sealing the edges between the collector plate and corrugated sheet. This step does not have any major impact on the performance of the product but is important for protecting the join between the collector plate and corrugated sheet from rain water which may be acidic and corrosive. The join does not need protection from the thermal fluid however because the fluid will contain additives that prevent it from corroding the join or interacting with the adhesive.

3.4.7 Step 8, attaching manifolds to the corrugated sheet

The manifolds are used to distribute thermal fluid to and from the inlets and outlets on the central channel. Mechanical fastening is the preferred method for this step because it is not permanent [65, 67] and the manifold can be easily removed for packaging after the product has been tested. Hollow stud bolts are used to connect the corrugated sheet and manifolds. These bolts have opposite threads at each end and a square section in the middle and a channel through the axis. The square section and opposite threads allows the bolts to be fixed simultaneously to the manifold and fittings on the corrugated sheet using a spanner. The channel through the axis allows thermal fluid to flow to and from the manifolds to the central channel in the BIPVT.

Attaching the manifolds to the BIPVT was left until last to avoid difficulties in modifying the lamination process to accommodate the manifolds protruding from the underside of the BIPVT (Figure 3.18 and Figure 3.19 A and B).

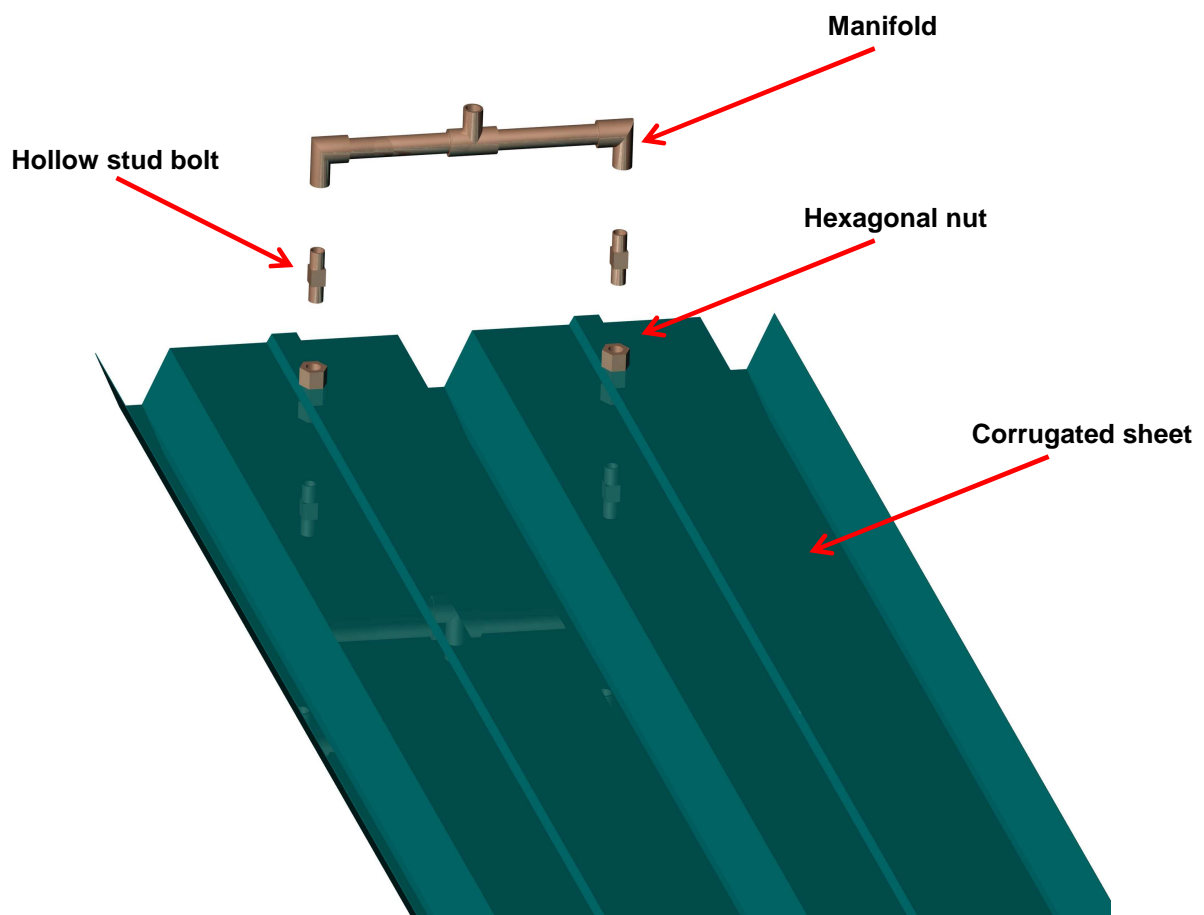
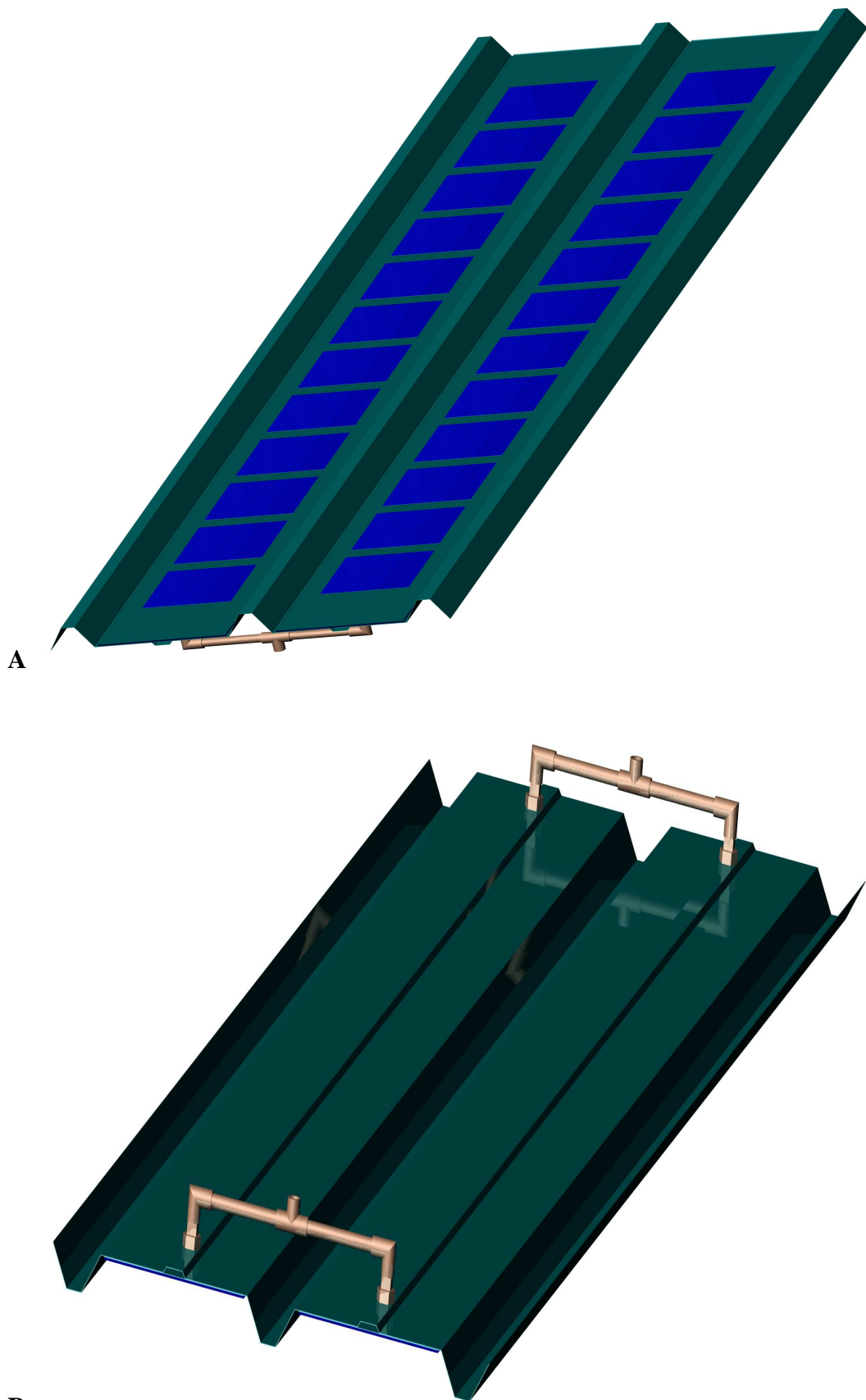


Figure 3.18 Attaching manifolds to the corrugated sheet.



B.

Figure 3.19 A) Front view and B) Underside view of an assembled BIPVT panel.

3.5 Quality steps

After the collector plate has been attached to the corrugated sheet and inserts for the central channel and fittings for the inlets and outlets from the central channel installed, the central channel is checked for fluid leakage from joins between the collector plate and corrugated sheet, from seals at each end of the channel and the inlet and outlet fittings (Quality control # 1) (Figure 3.6). This is carried out by passing fluid under pressure through the central channel through the inlet and outlet points. If leaks are observed, a “NOT OK” quality certification is given and the product is either scrapped or sent for reprocessing depending on where the leaks are found. If no leaks are observed, the product passes and is given an “OK” certificate. It then goes on to the next process step where the PV is laminated to the collector plate.

After the PV cells have been laminated to the collector plate the product is checked for lamination quality and electrical properties (Quality control # 2) (Figure 3.6). The lamination is visually inspected to ensure the EVA has bonded to all components in the laminate and to check for air bubbles and other imperfections. The PV cell laminate electrical properties and efficiency are measured by shining a light at the surface simulating solar radiation of 1000 W/m^2 at a temperature of 25°C . The product then is given a rating based on its light energy to electrical energy conversion efficiency. If there are imperfections in the laminate or the PV cells do not generate electricity then the product is scrapped or sent for reprocessing in which the laminate is removed and lamination repeated.

After the manifolds are installed the stud bolts are checked for leaks and the product is tested for thermal heating and cooling efficiency (Quality control # 3) (Figure 3.6). A thermal fluid is passed through the system at a set inlet temperature while the BIPVT surface is illuminated using the same conditions as when the product is checked previously for electricity production and solar to electrical energy conversion efficiency. The product passes if the thermal fluid extracts heat from the PV cell laminate reducing its temperature when it is exposed to simulated sunlight.

3.6 Identification of manufacturing methodologies

Adhesives, resistance seam welding and autoclaving were identified as the most suitable methods of manufacturing BIPVT. These were categorised based on the method used for joining the collector plate to the corrugated sheet

Using adhesives for BIPVT manufacture has the advantage of allowing the production steps of joining the collector plate to the corrugated sheet and sealing the central channel ends to be achieved in one step. PV cell lamination would occur in a separate step. Production and quality steps for using adhesives are shown in Figure 3.20.

Resistance seam welding has the advantage of being robust, cheap and quick. Brazing and soldering would be used for attaching the inserts and fittings to the central channel and the PV cells would be laminated in separate steps. The production and quality steps for manufacturing BIPVT when resistance seam welding is used is shown in Figure 3.21.

Autoclaving (integrating an autoclave and vacuum laminator into one unit) allows bonding the collector plate to the corrugated sheet, sealing the channel ends, attaching the fittings to occur at the same time as laminating the PV strings and EVA covering to the collector. In this case vacuum would be used to remove air from between the surfaces to be joined and compression to press the laminate together. This has the advantages of reducing production steps, equipment and manufacturing time, eliminating a quality control steps, the need for a vacuum laminator and mechanisms to transfer material from one point to another. It is also suitable for mass production. However if this step fails the product cannot be reprocessed or diverted to another product type as it could be if separate process steps were used as in Table 3.1. Evidence of an integrated autoclave and laminator has not been found during this research. The production steps and quality steps for manufacturing the BIPVT product using an autoclave are shown in Figure 3.22.

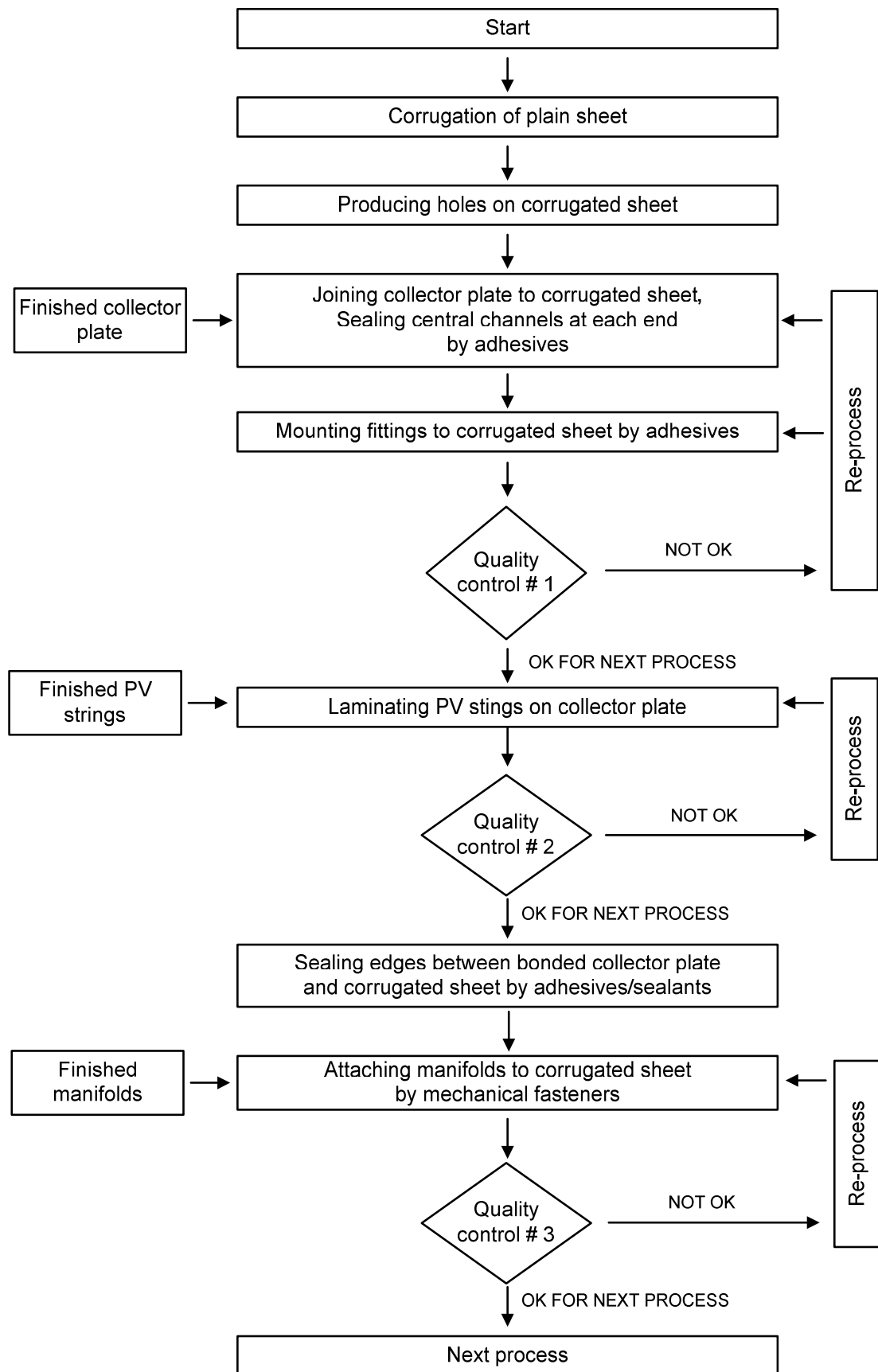


Figure 3.20 Flow chart for manufacturing BIPVT product by adhesives.

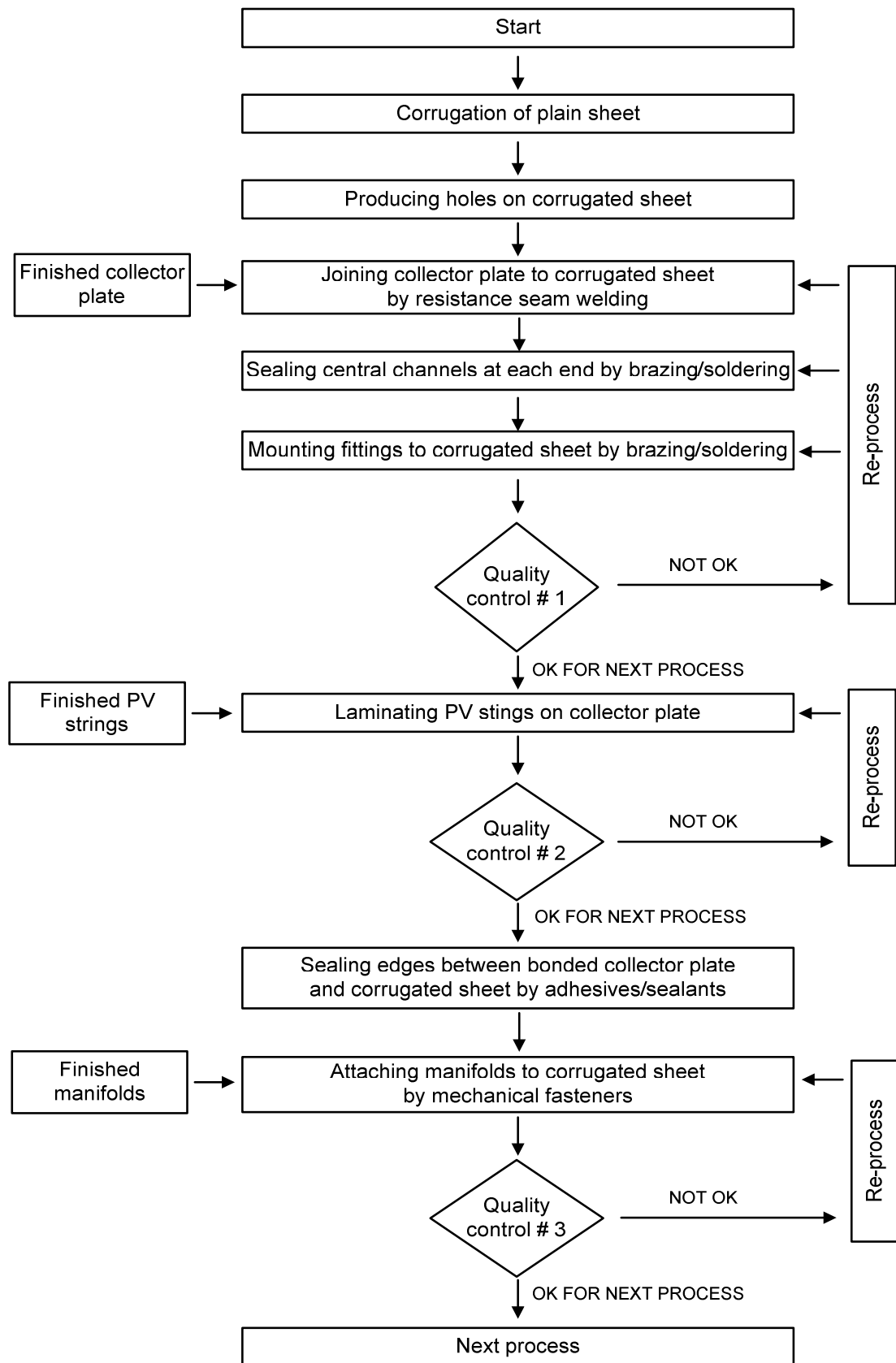


Figure 3.21 Flow chart for manufacturing BIPVT product by resistance seam welding.

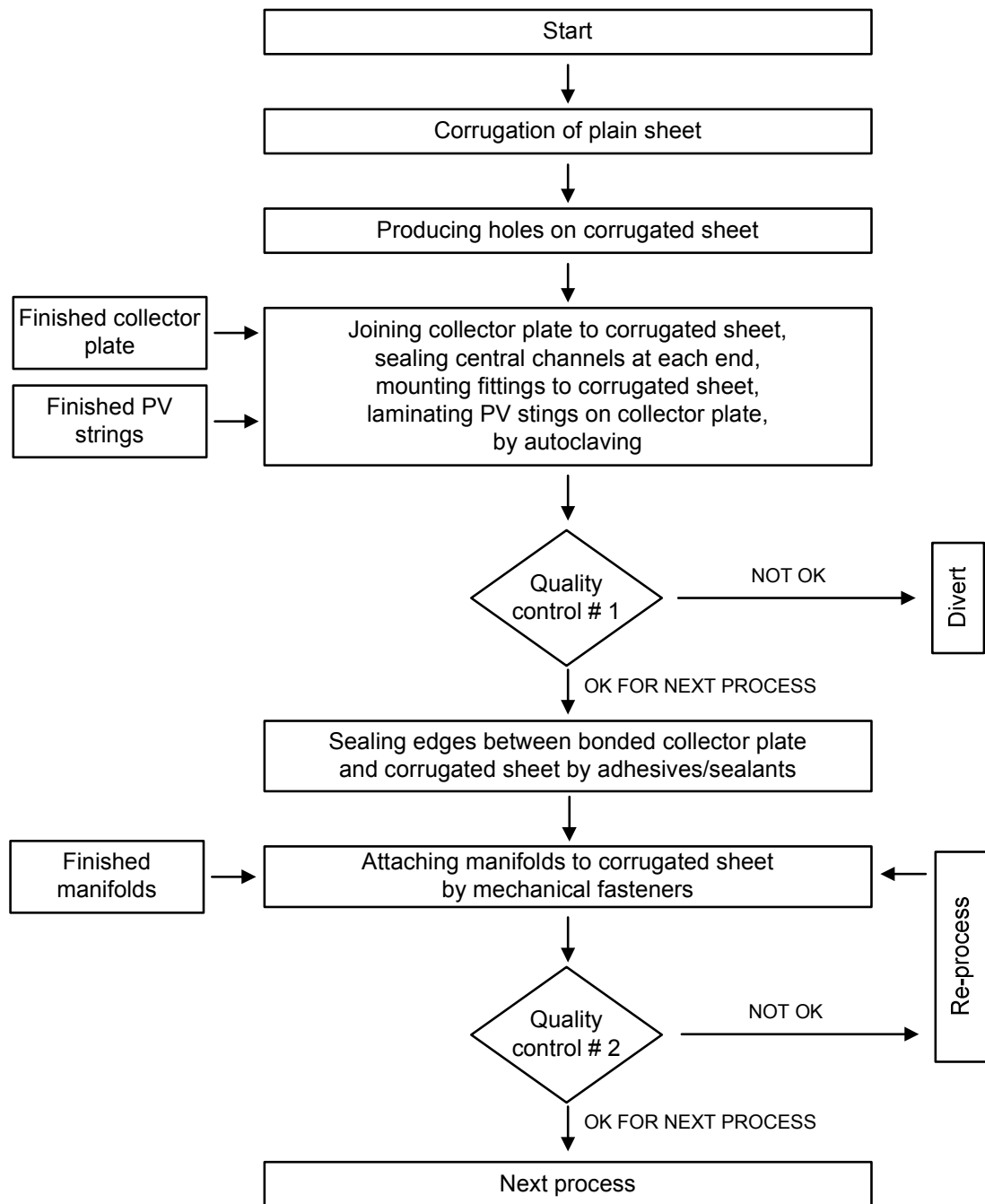


Figure 3.22 Flow chart for manufacturing BIPVT product by autoclaving.

3.7 Material selection

There is no significant change in the collector efficiency and strength and structural properties if either aluminium or steel is used for the BIPVT [75]. However if aluminium was used the surface needs to be coated for cosmetic appearances. Aluminium is typically supplied uncoated whereas steel comes pre-coated with zinc, Zinalume and/or Colorcote so an extra processing step would be needed to coat the aluminium.

The material finalized for the BIPVT product is steel and the brands that can be used are Zinalume and Colorcote.

3.8 Production types

BIPVT production can be categorized according to production volume. Low, medium and large volumes are commonly called jobbing, batch and mass production [67, 76].

3.8.1 Jobbing production

In jobbing production, production volumes, or lot size, are approximately 50-200 units. The production process and layout is designed to allow a number of different products to be produced using the same equipment. Jobbing production typically requires more skilled labour than batch or mass production because product specifications regularly changes and product lines may not be repeated [77, 78]. These lots are produced at once or in intervals. Examples of jobbing include space vehicles, aircraft, special tools and equipment [67, 76].

3.8.2 Batch production

In batch production, volumes are typically around 200-10,000 units depending on product size and complexity. A batch process will produce several different product types using the same equipment and processing may be batch or continuous depending on production volume [67, 78]. An example of batch production is limited edition high performance car manufacture.

3.8.3 Mass production

In mass production, high volumes of products (10,000 or more) are continuously produced using specialised, highly optimised and rapid process lines [67, 76]. Large capital investment is required for special machinery and the process is tailored to maximize machine utilisation [78]. The plant layout is fixed according to the flow of material through the production operations [67]. The plant may be fully automated or employ low skilled labour which man specific stations in the production line. Special conveyors and transfer devices are used to facilitate rapid material and component flow through the process [76]. Examples of mass production include steel processing, soft drinks and pharmaceutical manufacture [67, 76].

3.8.4 BIPVT production

BIPVT production can be defined according to production volume using the above definitions. Custom built BIPVT panels for specific jobs would fall under the jobbing category and require a highly flexible manufacturing process. Standard types of BIPVT panels of volumes between 200-10,000 panels per year would fall under batch production. Batch production would cover low to medium volumes (<50,000 panels per year). Greater than 50,000 panels per year is considered high production (Table 3.5).

Table 3.5 Volume, area, type of production and system for BIPVT product.

Volume	Area* in m ²	Type of production	Production system
<10,000	33,840	Low	Job
20,000	67,680	Low-Medium	Batch
30,000	101,520	Medium	Batch
40,000	135,360	Medium	Batch
>50,000	169,200	High	Mass

* Area for a BIPVT panel is 3.384 m² (6 m long by 0.564 m wide)

3.9 Built-to-order BIPVT panels

Roofing products can be custom built in different profiles, materials and sizes according to customer needs, making them easy to install on site. BIPVT panels would also need to be manufactured to customer needs to cater for different roofing lengths, material types, % PV coverage, and position of manifolds and inlet and outlet points.

For a fixed set-up in a mass production facility custom manufacturing can be achieved using integrated systems with a common database shared by all the departments in the company. For a BIPVT product, the customer requirements are accepted by the marketing department after consultation with the installation department. Sale orders, with product specifications, are entered into the integrated system database which generates a 'Sales Order' number for product tracking.

The sales order is received by the operations department and passed onto production planning control (PPC), quality control (QC) and production departments (Figure 3.23). The QC department specifies the operating parameters for each production step during product manufacture to achieve product specifications in the sales order. A production plan is issued by PPC to the production department containing detailed specifications set by the QC department for BIPVT processing. After each production step a bar code with the sales order number is pasted on the product and the product is passed on for the next stage of production. Machining parameters can be checked by scanning the barcode or entering the sales order number into the integrated database. QC checks the product after each major production step to ensure the product meets the specifications on the sales order.

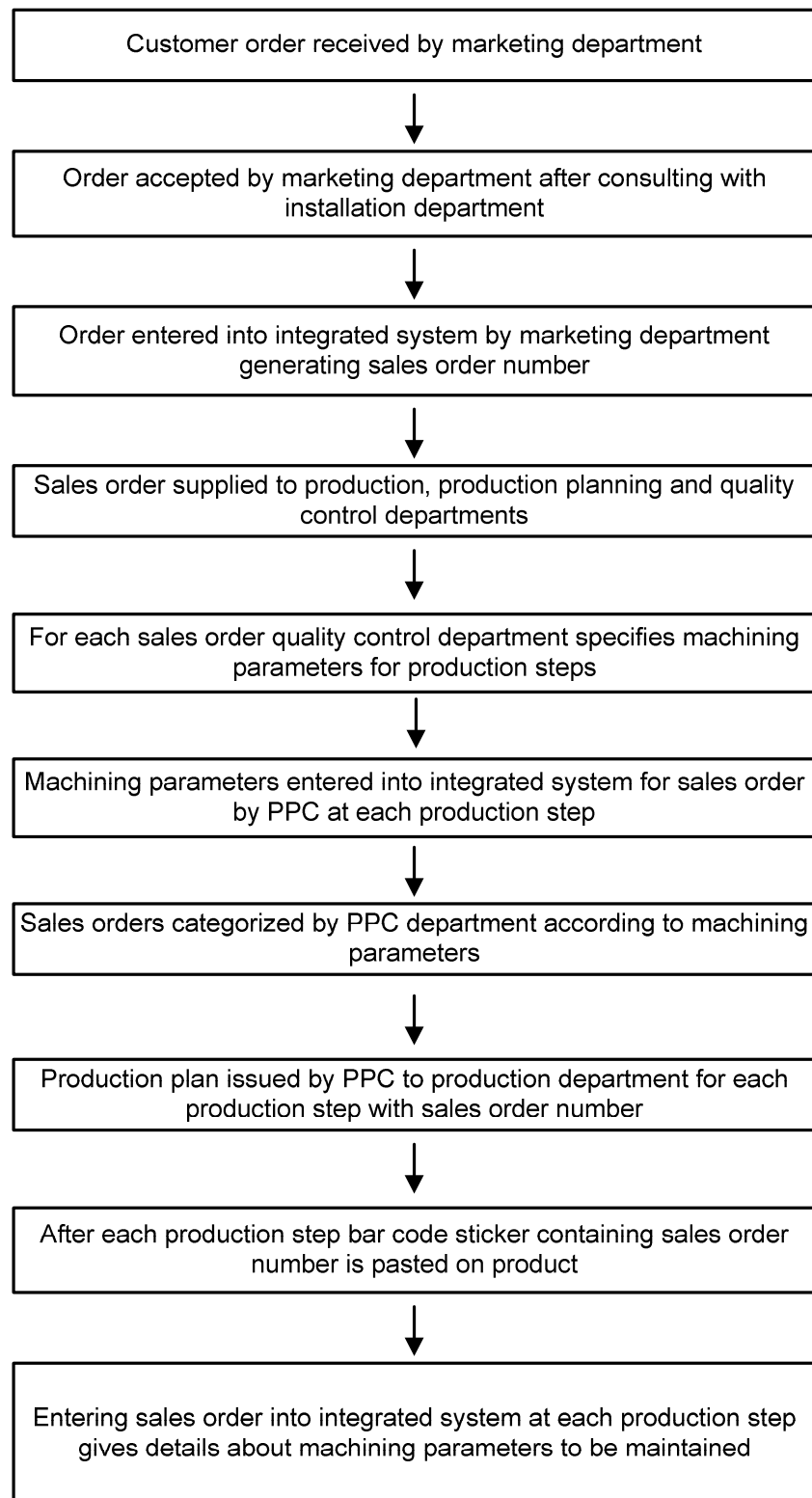


Figure 3.23 Flow chart for custom built BIPVT orders.

Chapter 4 Prototype production and evaluation

4.1 Introduction

Two BIPVT prototypes were constructed from aluminium and Colorcote using silicone based adhesives. After several attempts a successful prototype was built from Colorcote, the method used is described in following section. Resistance seam welding was also attempted by an Australian company for constructing a prototype. Findings from building the prototypes are discussed.

4.2 Prototype construction and testing

Colorcote corrugated sheet (2 m long by 0.56 m wide and 0.55 mm thick) and two collector plates (2 m long by 0.18 m and 0.55 mm thick), fabricated from galvanized steel with acrylic black coating, was supplied by Dimond Ltd.. The dimensions and profile of the corrugated sheet are shown in Figure 4.1.

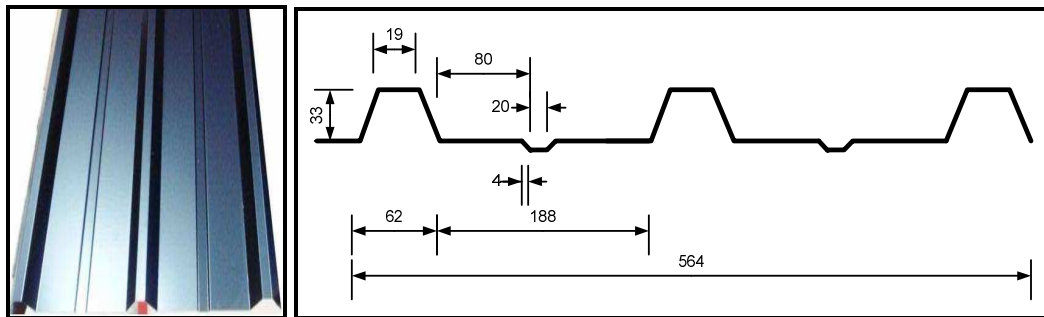


Figure 4.1 Modified corrugated roofing profile (All dimensions are in mm).

Two 10 mm diameter holes for fluid inlets and outlets were drilled in each central channel on the corrugated sheet 90 mm from each end of the sheet using a hand held drill (Makita made). Two additional holes, 5 mm in diameter (Figure 4.2) were drilled in the corrugated sheet crests, the first 10 mm and the second 1 m from the end of the sheet, for electrical cables. Any burrs around the holes were removed using 40 grit sand paper.

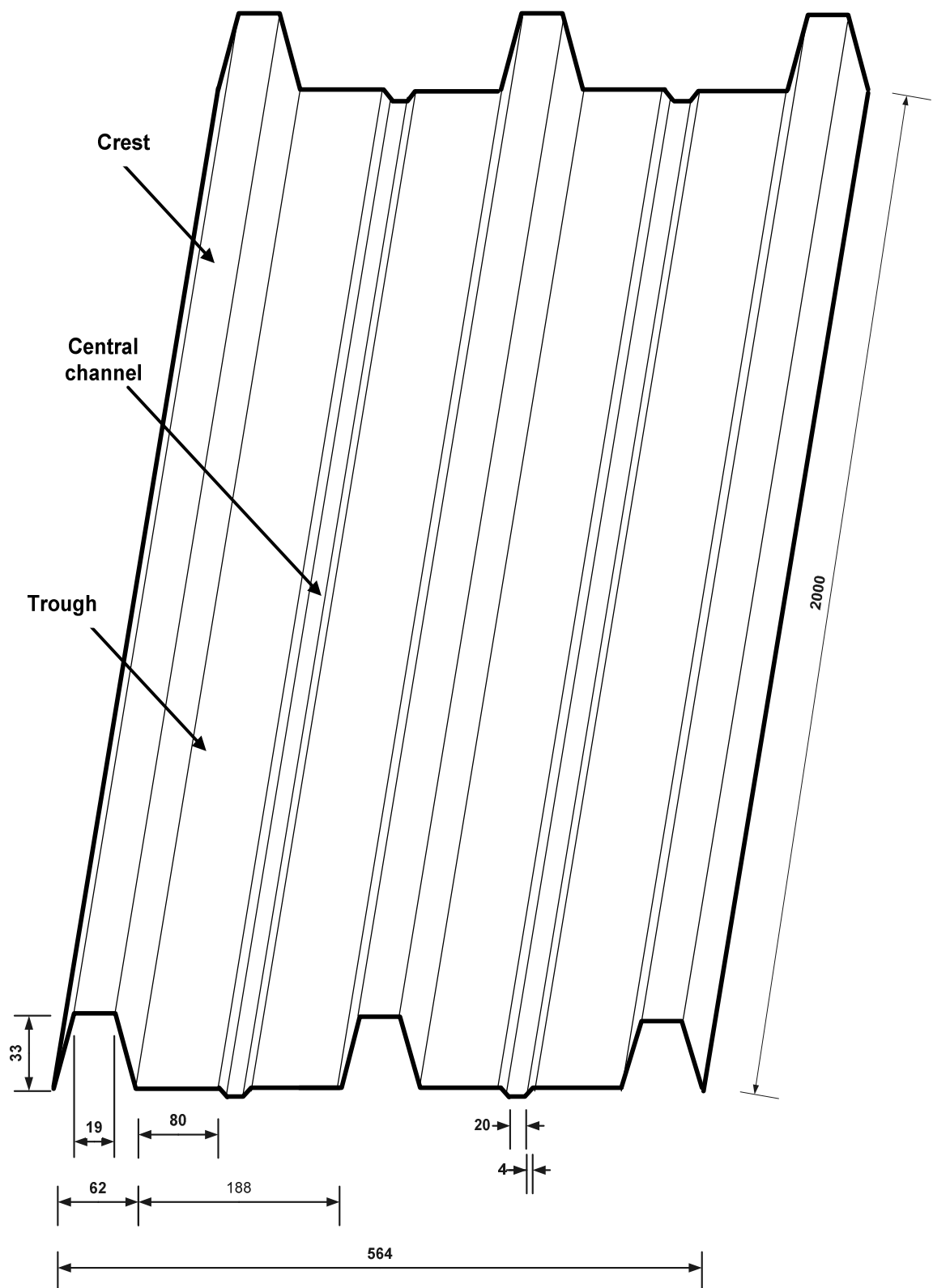


Figure 4.2 Corrugated sheet dimensions used for prototypes (All dimensions are in mm).

Mild steel connector pipes, 70 mm long, 10 mm ID and 12 mm OD with a 22 mm diameter and 1 mm thick flange (Figure 4.3), were soldered to the inlet and outlet points under the corrugated sheet (Figure 4.4) using acetylene torch.

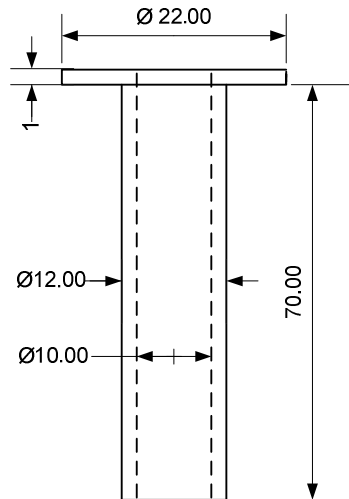


Figure 4.3 Connector pipe (All dimensions are in mm).

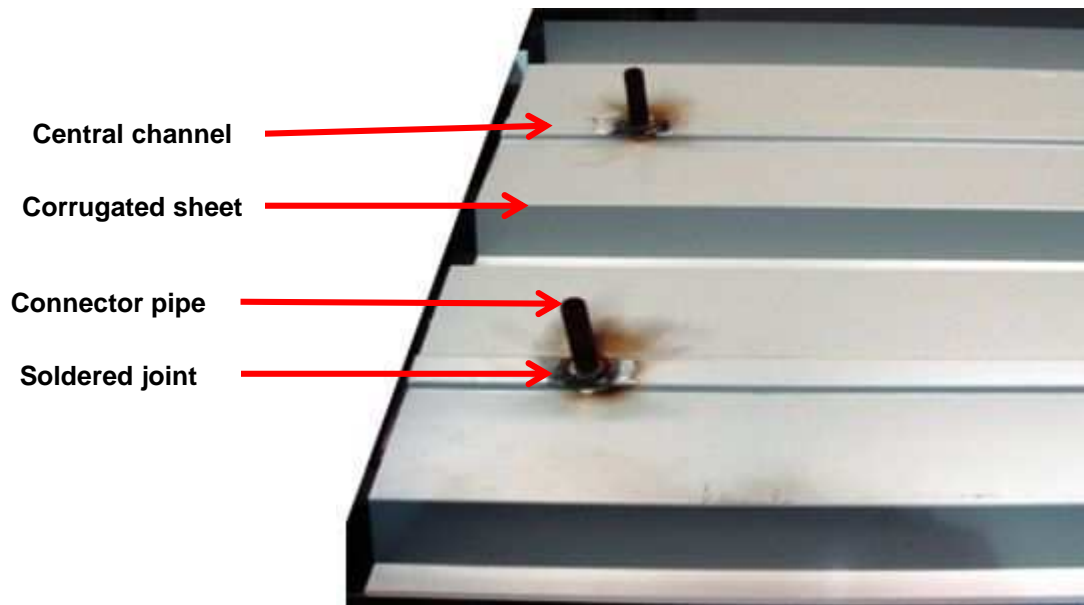


Figure 4.4 Connector pipes soldered to inlet and outlet points underside the corrugated sheet.

Before soldering, the primer and galvanised coating were removed from the area around the inlet and outlet holes using sand paper to ensure good bonding between the connector pipe and corrugated sheet.

After the connector pipes were soldered to the corrugated sheet, the holes on the top side of the sheet were blocked off and water poured into the pipes to check for leaks around the joint.

After testing the corrugated sheet was mounted on four hollow mild steel square sectioned pipes (80 mm by 80 mm by 2 m long and 5 mm thick) to protect the connector pipes. The central channels in the corrugated sheet sat between the pipes.

All surfaces of the corrugated sheet that were to have adhesives applied to were cleaned with a cloth. A bead of Silicon based adhesive (Dow Corning 732 TM) was applied to the length of the sheet in the centre of each trough either side of the central channel and to the ends of the central channels. 70 mm long, 20 mm wide and 5 mm thick inserts were glued to each end of the central channels. A bead of adhesive was then run along each end of the trough and over the insert in the central channel. The collector plate was placed on the trough section covering the central channel and inserts and a load of 100 kg was evenly applied over the plate. Excess adhesive was wiped off using a cloth. This was repeated for the second trough. The adhesive was allowed to cure at room temperature over three days, after which the weights were removed. The finished product is shown in Figure 4.5.



Figure 4.5 Prototype comprising corrugated sheet with collector plate made from Colorcote steel.

The product was tested to check if the central channels were completely sealed by attaching mains water supply to one of the connector pipes and letting water flow through the channel and out the other connector pipe. The pressure was slowly increased until the flow rate through the central channel was 2 l/s. After

confirming that there was no leakage, the corrugated sheet was tilted to 30°, the same inclination used for roofing on houses, and the test repeated.

Polycrystalline PV cells (125 mm by 125 mm, 0.5 V, 2 A) were soldered together at their contact points to form 2 PV strings, 5 cells long. Electrical cable was attached to the ends of the PV strings. As mentioned in Section 3.4, EVA is used as the encapsulating material for laminating PV cells in a vacuum laminator. However no vacuum laminators are currently installed in New Zealand, so PV encapsulation for the BIPVT prototypes was carried out using resin. Degassed transparent resin (100 ml volume used), prepared from vinyl ester resin was spread on the collector plate so it formed a layer 2 mm thick, by 1 m long and 180 mm wide. Stops were used at each end of the collector plate to prevent to resin from flowing over the edges. The PV strings were pressed into the top of the resin while it was still wet using a wooden spatula. The electrical cables were passed through the holes in the crests running along each side of the collector plate. Another layer of resin (100 ml) was then evenly spread over the PV strings. The resin was allowed to set over 24 hours at room temperature.

After the resin cured, the resin was visually inspected to ensure the PV cells were encapsulated (Figure 4.6). PV cell electrical performance was checked by using eight 500 W halogen bulbs positioned 50 cm above the two PV strings. The electrical cables from the PV strings were connected to multi meters (Digitor Q1467, 20MΩ, 10A max) to measure the current and voltage across the system.

The BIPVT prototype was then connected to the mains water supply and water pumped through the central channels to check for leaks. Hosepipes were connected to the ends of connector pipes and tap water was passed through the system. The product was tested for measuring electrical and thermal properties by running a flow of 2 l/s for 2 hours under the illumination of eight 500 W halogen lights using a digital thermometer with thermocouples connected to the connector pipes at the entry point of water and exit point in the corrugated sheet. Thermally tempered glass for glazing purpose was positioned on top of panel resting on the crests of corrugated sheet. The crests of the sheet were covered by sticking tape which facilitates the glass to rest on top of it. After glazing the thermal and

electrical properties was measured (the conditions were the same as that for unglazed system).

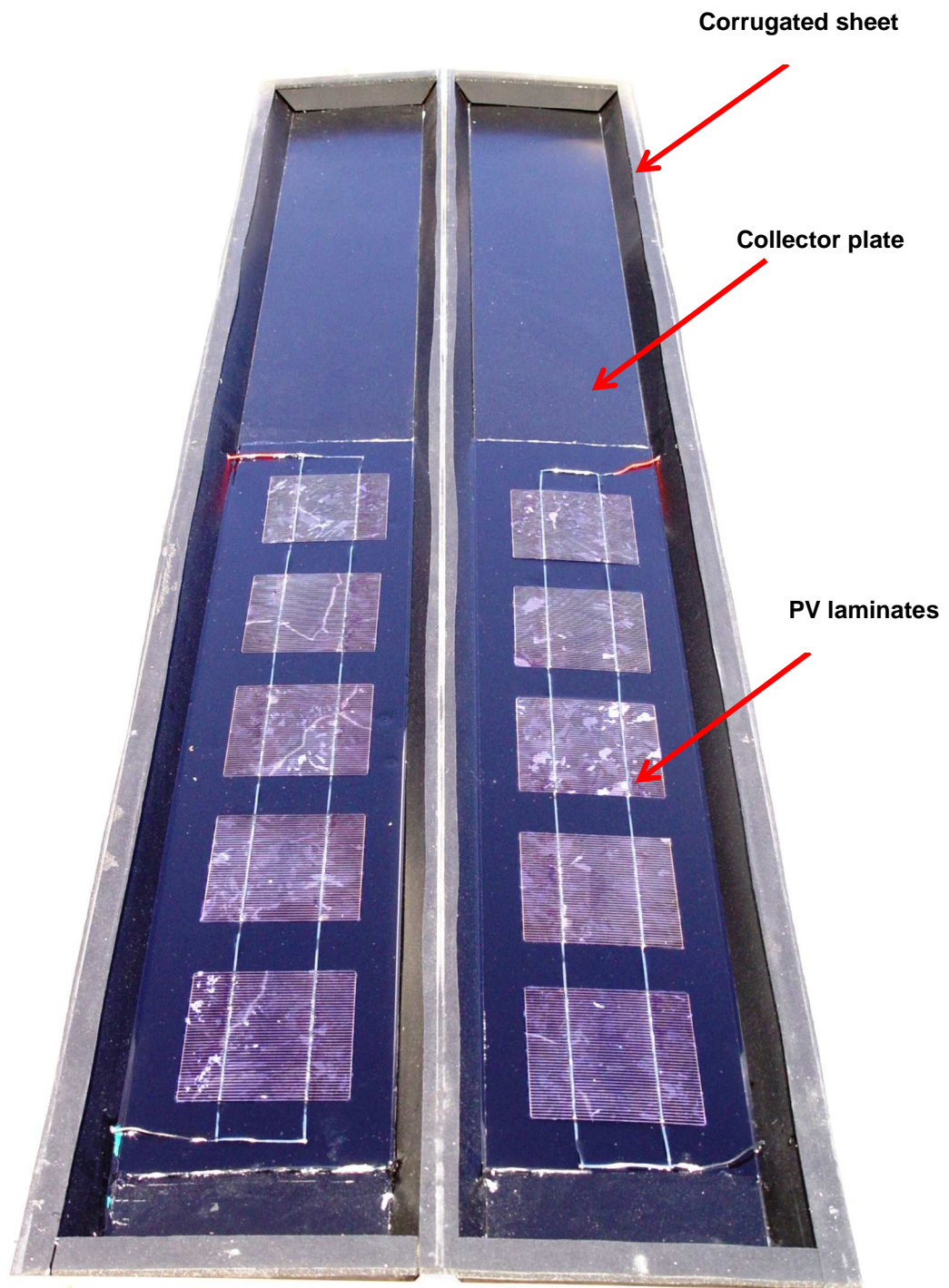


Figure 4.6 Unglazed BIPVT Colorcote prototype produced using adhesives.

4.3 Findings from prototype construction

4.3.1 Aluminium BIPVT

Several aluminium prototypes were built and were tested for leaks prior to bonding the PV strings to the collector plate. It was found the central channels were not sealed completely with leaks observed between collector plate and corrugated sheet and from the central channel ends. It was thought the poor sealing was due to incomplete curing of the silicon, and poor contact between the bonded surfaces. This was due to excessive silicon being applied to the bonding surface, uneven load distribution on the collector plate resulting in regions of poor contact between bonded surfaces and non-uniform silicon distribution, and the corrugated sheet not being mounted in a flat fixture which also contributed uneven load distribution. The aluminium BIPVT was discarded.

4.3.2 Colorcote BIPVT

A Colorcote BIPVT was built, this time mounting the panel on a fixture and evenly distributing the load across the collector plates. In addition less adhesive was applied to the bonding surfaces. No leaks were observed when the BIPVT was tested showing that manufacturing issues had been solved. PV strings were then laminated to the collector plate surface. When tested for electricity and hot water generation, it was found the BIPVT proof of concept worked successfully. Detailed testing will be conducted by another student.

4.3.3 Zincalume BIPVT

A seam welding specialist in Australia was asked to weld the collector plate to a corrugated sheet, both made from Zincalume. The product showed surface distortion which they stated occurred because of the low current used during welding (Figure 4.7 A and B). Therefore the welding speed and current used needs to be refined for Zincalume to avoid surface distortion. The method was not tried using Colorcote because a working prototype had already been manufactured in the lab using adhesives. Resistance seam welding would need to

be trialled using Colorcote to verify that it is a suitable method for bonding the collector plate to the corrugated sheet.

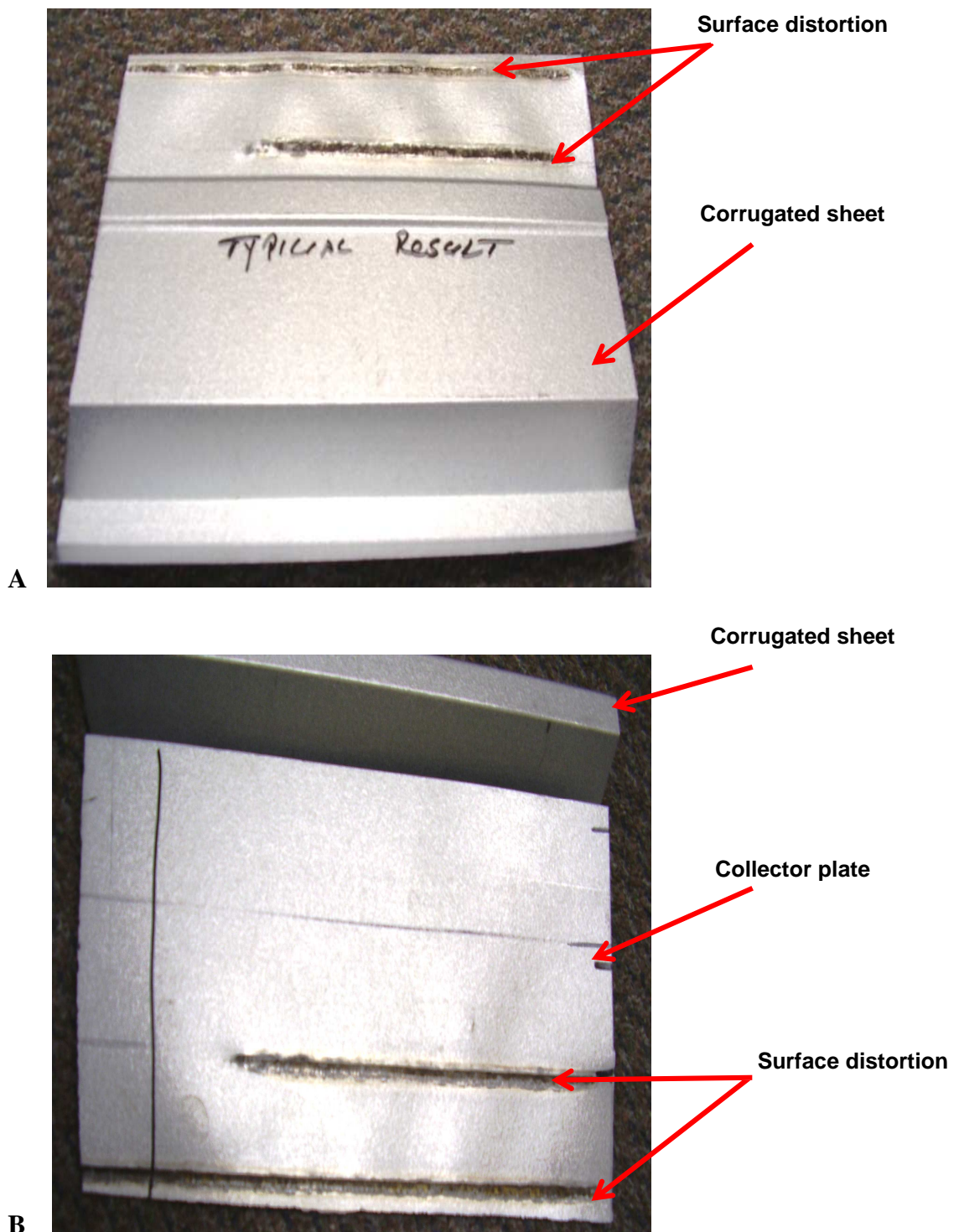


Figure 4.7 (A) Underside view and (B) Top view of surface distortion from resistance seam welding of Zincalume corrugated sheet and collector plate.

Chapter 5 Economic analysis and discussion

5.1 Introduction

From Chapter three, adhesives (ADH), resistance seam welding (RSW), and autoclaving (ATC) were chosen as the three methods considered most viable for manufacturing BIPVT. In this chapter the manufacturing costs for unglazed Colorcote steel BIPVT production using the three methodologies were analysed and discussed in terms of capital, material and operating costs, net profit and capital investment payback time. Different processing conditions were explored such as operating hours, production volume, equipment utilization and equipment optimisation. The effect of BIPVT market price and glazed and unglazed Zinalume and Colorcote material costs on payback time was investigated. Production volumes considered were for the domestic and export market. A case study incorporating ADH in a roofing manufacturing company was also examined. Costs associated with quality control steps in the analysis were neglected because their contribution to the operating and material costs would not be significant.

5.2 Capital costs

Capital costs for BIPVT production using resistance seam welding, adhesives and autoclaving methodologies were obtained by finding or estimating the equipment purchase costs and multiplying the costs by a Lang factor of 3.06 [79] (Table 5.1). The Lang factor takes into account installation, building and utility costs, as well as factory start up and contractor fees. Cost estimations using Lang factors and estimated equipment costs have an error of -30% to +60% [80]. Details about the different factors are given in Appendix 5. The installed manufacturing equipment has a fixed production capacity (Table 5.3) so more equipment must be installed if the production volume increases above the production capacity. Each process step can process 1 BIPVT panel at a time except for autoclaving which can process 3 panels at time.

Table 5.1 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	\$250,000	\$250,000
2	Punching holes on corrugated sheet	\$10,000	\$10,000	\$10,000
3	Joining collector plate with corrugated sheet	\$33,500	\$80,000	\$600,000
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	\$400,000	
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

The press-brake cost was obtained from Dimond Ltd., New Zealand approximately as NZ\$250,000. The punching machine cost was assumed to be \$10,000. The equipment cost for bonding corrugated sheet to the collector plate and sealing the central channel ends using adhesives was estimated to be \$33,500 (Loctite, New Zealand). Resistance seam welding and cleaning equipment was approximately \$80,000 (Resistance Seam Welding specialist, Australia) (Table 5.1)

A PV laminator costs approximately \$400,000, and production volume is between 25,000 to 45,000 modules per year (PV areas 2.74 m²) [11, 81]. This was based on a lamination process which includes equipment for sorting PV cells, tabbing, testing PV strings, lamination, and assembling the PV string laminates, a total cost of NZ\$2.4 million (Spire Corporation, USA) [81]. For the proposed BIPVT process, production volume is 5,000 to 90,000 panels per year with two laminated PV modules (180 mm wide by 6 m long, total PV area at 44% coverage 0.75 m²) per panel, so a total of 10,000 to 180,000 PV modules are needed. Currently no

laminators produce PV modules 6 m in length, but Meier Group (Germany) have stated they are able to produce laminators capable of manufacturing 6 m PV laminates. Laminator cost estimates are based on the lowest laminate production volume of 25,000 per year.

It was assumed that the autoclave made for manufacturing BIPVT would combine a vacuum laminator and an autoclave integrated into one unit. A 12 m³ vacuum autoclave that can process three BIPVT panels was valued at \$200,000 [73]. Lamination equipment included inside the autoclave was based on \$400,000 given previously. The total equipment cost was estimated to be \$600,000.

Any manual processes using custom built equipment such as steps 4, 5, 7 and 8 in Table 5.1 was assumed to be \$5,000 each, which included working space and tooling.

5.3 Process times and production capacity

Process times for each BIPVT production step are given in Table 5.2. Press brake cycle times were obtained from Dimond Ltd., adhesive applying equipments were obtained from Loctite, resistance seam welding (welding speed of 1.8 m/min, 24 m total weld length for one panel), autoclaving and laminator cycle times were given Chapter 3, section 3.4.3. For steps 2, 4, 5, 7, and 8, the process times were estimated from building the prototype and taking into account that skilled labourers would be carrying out the operations. The slowest production steps 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. RSW had the slowest panel cycle time of 62.5 minutes due to it having more process steps than ADH (42.5 minutes) and ATC. ATC had fastest process cycle time of 32.5 minutes (Table 5.2).

Table 5.2 Process times for each BIPVT production step.

Operation no.	Production step	Time per panel (minutes)		
		ADH	RSW	ATC
1	Corrugation of plain sheet by press-brake	2	2	2
2	Producing holes on corrugated sheet by punching	2.5	2.5	2.5
3	Joining collector plate to corrugated sheet	10	18	20*
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	15	
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

* The cycle time for autoclaving is more than lamination as more steps are processed in single set-up.

Process times for each BIPVT production step were then converted to production rates in panels per minute (Table 5.3). 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 overall had the greater process throughput and for an operating time of 1,920 hrs (8 hour per day, 5 days per week for 48 weeks) in a year could produce 17,280 panels.

Table 5.3 Process times in terms of panels per minute.

Operation No.	Production step	Panels per minute		
		ADH	RSW	ATC
1	Corrugation of plain sheet by press-brake	0.50	0.50	0.50
2	Producing holes on corrugated sheet by punching	0.40	0.40	0.40
3	Joining collector plate to corrugated sheet	0.10	0.06	0.15*
4	Sealing central channels at each end		0.20	
5	Mounting fittings to the corrugated sheet	0.20	0.20	
6	Lamination of PV strings on collector plate	0.07	0.07	
7	Sealing the edges between bonded corrugated sheet and collector plate	0.25	0.25	0.25
8	Attaching manifolds to corrugated sheet	0.25	0.25	0.25
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
Area of panels produced (m²)		25,989	21,658	58,476

*The autoclave can process three panels every 20 minutes.

Production capacity can be increased 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. This is discussed in more detail in Section 5.9.

5.4 Materials costs

The component costs for the BIPVT (glazed and unglazed) product including PV laminates are shown in Table 5.4. Component costs were estimated from Rawlinsons New Zealand Construction Handbook [82] for roofing and polycarbonate sheet, fittings costs from EDL [83, 84] and Summitracing (APC) [83, 84], and manifolds from Micometals [85] New Zealand. Corrugated sheet and collector plate (roofing material) made from Zinalume and Colorcote steel was \$48.50/m² and \$67.50/m² respectively. Polycarbonate sheet was \$40/m². The cost estimated for the nuts and custom built hollow stud bolts was \$10 per set and \$15 for the copper tubing and fittings for each manifold.

The typical PV module for a BIPVT panel of 3.384 m² (0.564m x 6m) has a PV area of 1.50 m² which is evenly spread across two collector plates. For each collector plate the PV lamination area is 0.75 m². On each collector plate, up to 36 mono or poly-crystalline 150 x 150 mm cells can be attached. Each cell generates a maximum of 3W, therefore each BIPVT can generate approximately 200 W. PV cell prices, including materials for lamination, are \$3/W estimated from the current module and retail price [86], therefore the materials for PV lamination including the cells is \$600 per panel.

Table 5.4 Component costs for BIPVT (glazed and unglazed) made from Zinalume and Colorcote steel.

Component	Qty.	Unglazed		Glazed	
		Zinalume	Colorcote	Zinalume	Colorcote
Corrugated sheet	3.384 m ²	\$164	\$228	\$164	\$228
Collector plate	2.16 m ²	\$105	\$146	\$105	\$146
PV laminates (total)	1.49 m ²	\$600	\$600	\$600	\$600
Nuts and hollow stud bolts	4	\$40	\$40	\$40	\$40
Copper tubes for manifolds	0.6 m	\$30	\$30	\$30	\$30
Polycarbonate sheet	3 m ²			\$120	\$120
Consumables		\$6	\$6	\$6	\$6
Total material cost per panel		\$945	\$1,050	\$1,065	\$1,170

Unglazed BIPVT made from Zinalume had the lowest component costs. However process economics were based on Colorcote because it is more commonly used in New Zealand and a working prototype had been successfully made from that material.

5.5 Labour, machine and energy costs

Labour costs were calculated by multiplying the manual labour needed to produce a panel (Table 5.2) by the hourly pay rate. In New Zealand the average pay rate for a fitter and turner is \$20 per hour [87]. Overheads were included at 100% of the hourly pay rate which covers administrative costs. Labour costs are shown in

Table 5.5. Machine operating costs per year were estimated at 10% of the equipment purchase cost. This includes cost of consumables such as hydraulic fluid for the press-brake, repairs, and maintenance (Table 5.5). This was then multiplied by the number of shifts operating each day to reflect the increased equipment use if the operation was to be run over, for example, 3x8 hour shifts per day instead of 1x8 hour shift per day.

Equipment energy consumption costs per year were not known so it was estimated to be 1% of the total equipment purchase cost. This was multiplied by a factor to account for expected energy demand by each methodology: 1 for adhesives, 2 for resistance seam welding and 4 for autoclaving. This was then multiplied by the number of shifts operating each day. Autoclaving was expected to use the most energy as it requires a 12 m³ chamber to be heated to 175°C to cure each panel under vacuum. Approximate energy costs are shown in Table 5.5.

Table 5.5 Cost per panel including labour, machine and energy for Colorcote unglazed BIPVT.

Parameter	Production system		
	ADH	RSW	ATC
Total equipment cost (TEC)	\$708,500	\$760,000	\$870,000
Panels per year for 1920 hrs operating time (N)	7680	6400	17280
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.

ATC had the lowest labour costs per panel because it had the lowest number of process steps. It also had the lowest operating cost per panel because it had 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 were 2.6, 3.7 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. If only BIT was considered without PV then the operating cost per panel would have been approximately \$500, therefore ways of reducing PV costs should be investigated.

5.6 Economic analysis

Net profit per year and payback time were calculated for unglazed Colorcote BIPVT using the capital cost, revenue and operating costs per year and depreciation (Table 5.6). Each panel was assumed to have a market value of \$1,400, a mark-up of approximately 1.3. The production equipment life time was 5 years and depreciated 20% each year. It was assumed that each process would be operating at 100% production capacity and that all panels produced each year would be sold.

Gross profit before tax was calculated by subtracting the total operating costs per year from the revenue per year. Corporate tax in New Zealand is 33% and is taken from the company's gross profit. Net profit includes any tax write-offs from depreciation. Gross margin was obtained by dividing gross profit after tax by revenue before tax. Return on investment was calculated by net profit per year by the capital investment. Payback time in years was obtained by dividing the capital investment by the net profit per year, assuming that all products manufactured could be sold.

RSW generated the lowest net profit per year of \$1.75 million and had a payback time of 1.3 years (Table 5.6). ATC despite having the greater capital investment had the lowest payback time (7-8 months) and return on investment due it having the greatest net profit of \$4.25 million per year due to it having the greatest

production capacity. ADH came second because it had the lowest capital cost and second highest production capacity.

Table 5.6 BIPVT payback period, net profit analysis for production systems using unglazed Colorcote material.

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 1920 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

5.7 Payback time with production volume

Process payback time was investigated for ADH, RSW and ATC for 1,920, 3,840, and 5,760 operating hours per year for different unglazed Colorcote BIPVT production volumes. BIPVT product was sold at \$1,400 per panel. Additional production lines were included when production volume was higher than installed capacity. This is reflected in the crests for each plot in Figures 5.1, 5.2, and 5.3. As production volume approached installed production capacity (shown as machine utilisation in Figure 5.4), payback time decreased until additional equipment was installed. Minimum payback times for 1,920 hrs process in Figure 5.1 are the same as in Table 5.6 when machine utilisation approaches 100%.

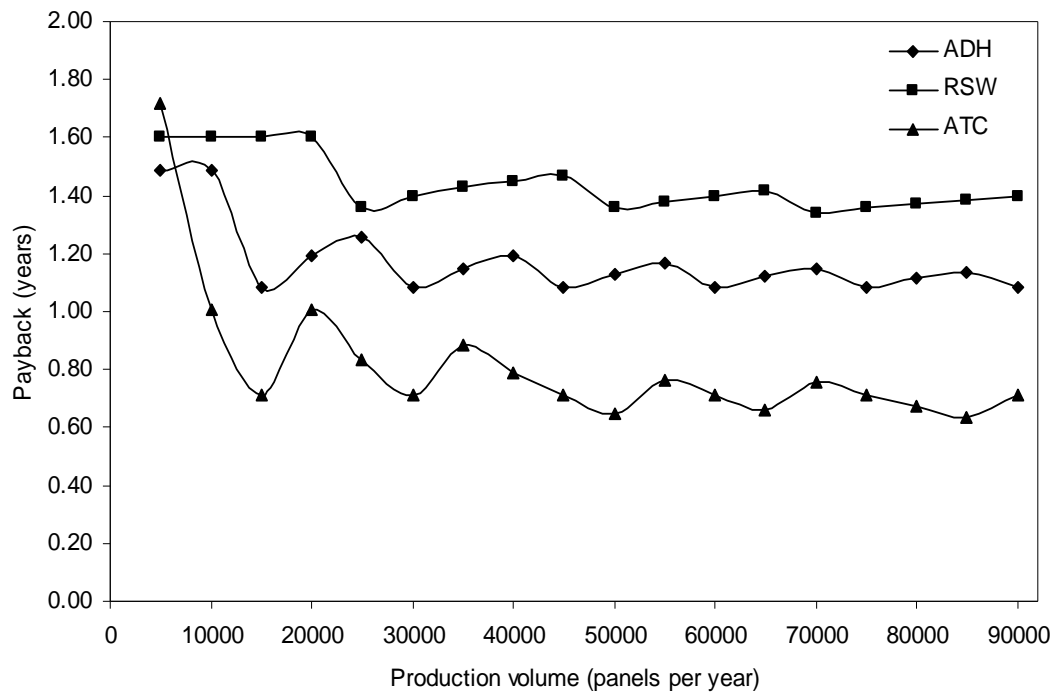


Figure 5.1 Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/year). Appendix 1.A.

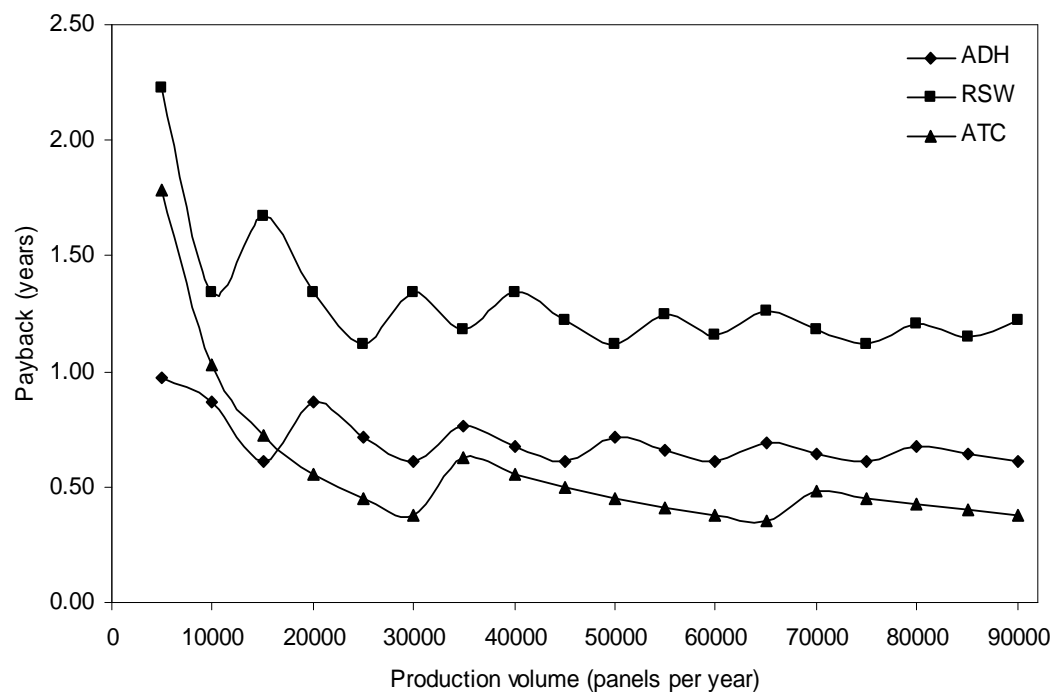


Figure 5.2 Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 3,840 hours production time (16 hours/day, 5 days/week at 48 weeks/year). (Appendix 1.B.)

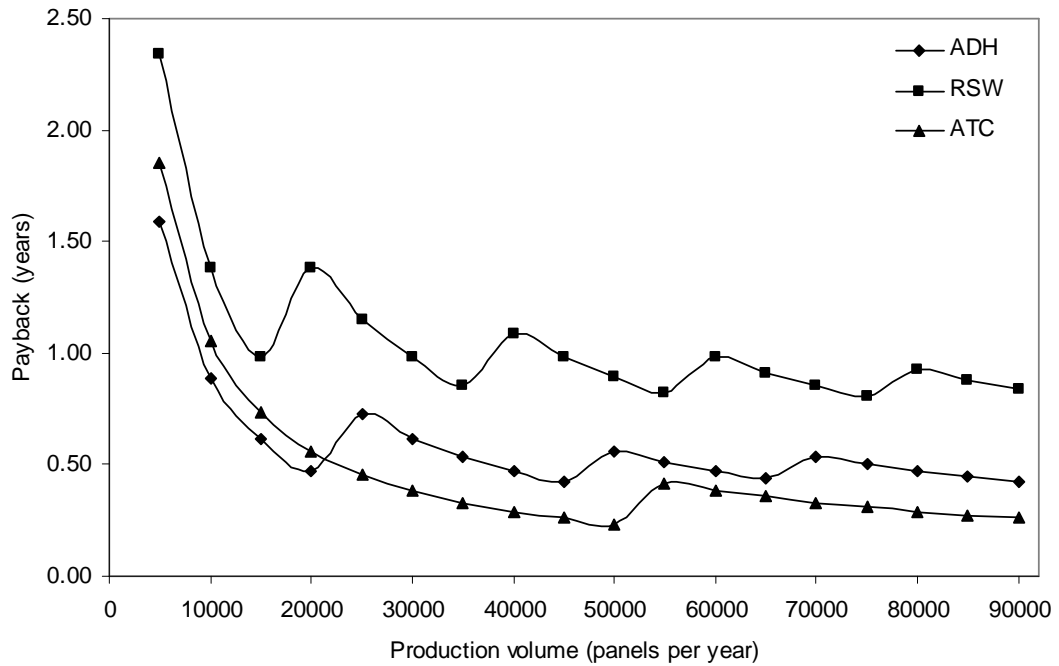


Figure 5.3 Payback time vs production volume for unglazed Colorcote BIPVT with ADH, RSW and ATC system operating 5,760 hours production time (24 hours/day, 5 days/week at 48 weeks/year). (Appendix 1.C.)

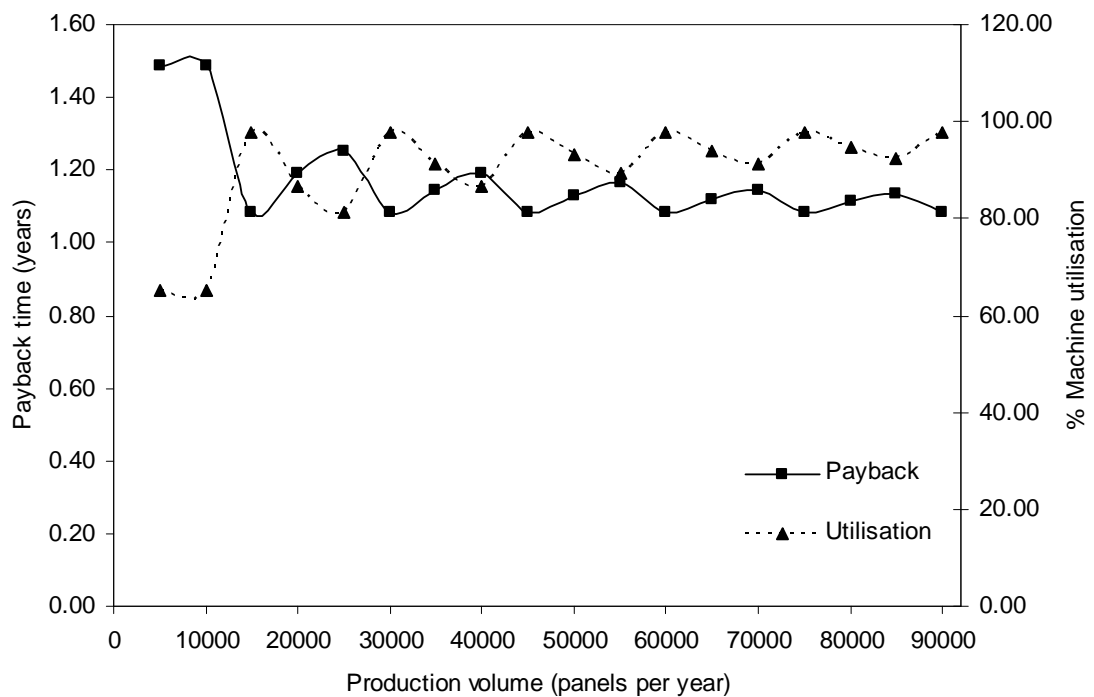


Figure 5.4 Payback time and machine utilisation vs production volume for unglazed Colorcote BIPVT with ADH system operating 1,920 hrs production time (8 hours/days, 5 days/week at 48 weeks/year). (Appendix 1.D.)

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 (Figure 5.3). Therefore rather than increasing 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.

Payback time versus production volume was also explored for unglazed and glazed Colorcote and Zincalume BIPVT (material costs shown in Table 5.4), all at 140% mark-up on material costs. As material cost increased, payback time increased showing that to reduce operating costs and payback it was better to have lower material costs (Figure 5.5).

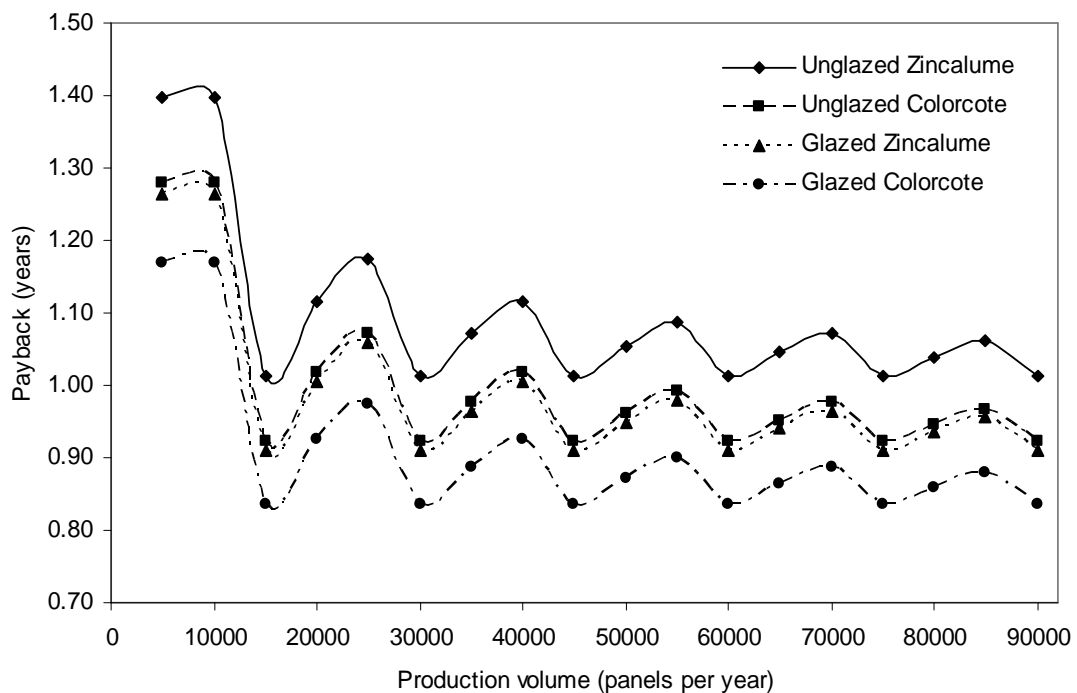


Figure 5.5 Payback time vs production volume for unglazed and glazed Colorcote and Zincalume BIPVT with ADH system operating 1,920 hrs production time (8 hrs/d, 5 d/wk at 48 wks/yr). (Appendix 1.E.)

5.8 Payback time vs market value

Payback times were obtained for set BIPVT market prices for production volumes between 5000 to 90,000 panels per year. BIPVT prices ranged from \$1,100 to

\$1,800. Lower prices could not be used because the process became unprofitable as the operating costs per panel ranged between \$1089 to \$1101. Where the operating costs were \$1101, the process was still profitable because revenue was being generated from equipment depreciation.

Payback times were analysed for one 8-hr shift per day for 5 days per week for 48 weeks per year. These payback times were averaged for each panel price and displayed for ADH, RSW, and ATC in Figures 5.6, 5.7A, and 5.7B. Payback time decreased with increasing panel price asymptoting towards zero. Variation in payback time for each panel price was observed with change in production volume (error bars in Figures 5.6, 5.7A, and 5.7B). Least variation was seen with RSW as the 5,000 panel step changes in production volume were within 89% of production capacity of an installed production line (6,340 panels per line per year) (Figure 5.7A). Maximum variation was observed with ATC because starting production was 5,000 panels, less than one third of installed capacity (17,120 panels per production line per year) (Figure 5.7B).

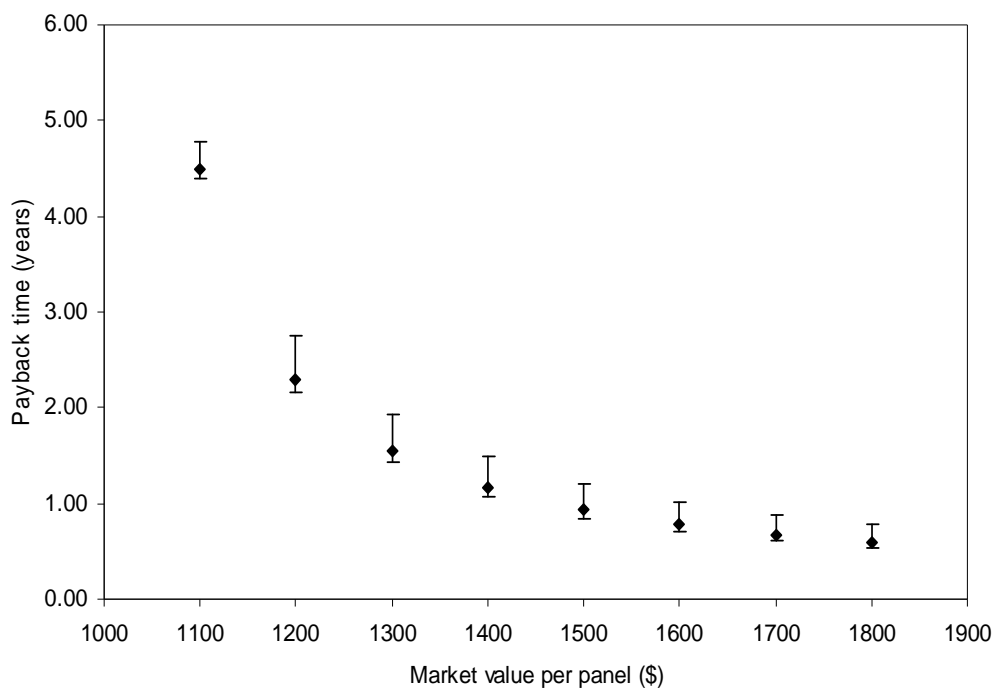


Figure 5.6 Average payback time vs market value per panel for unglazed Colorcote BIPVT using ADH system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/year) for 5,000 to 90,000 panels per year. (Appendix 2.A.)

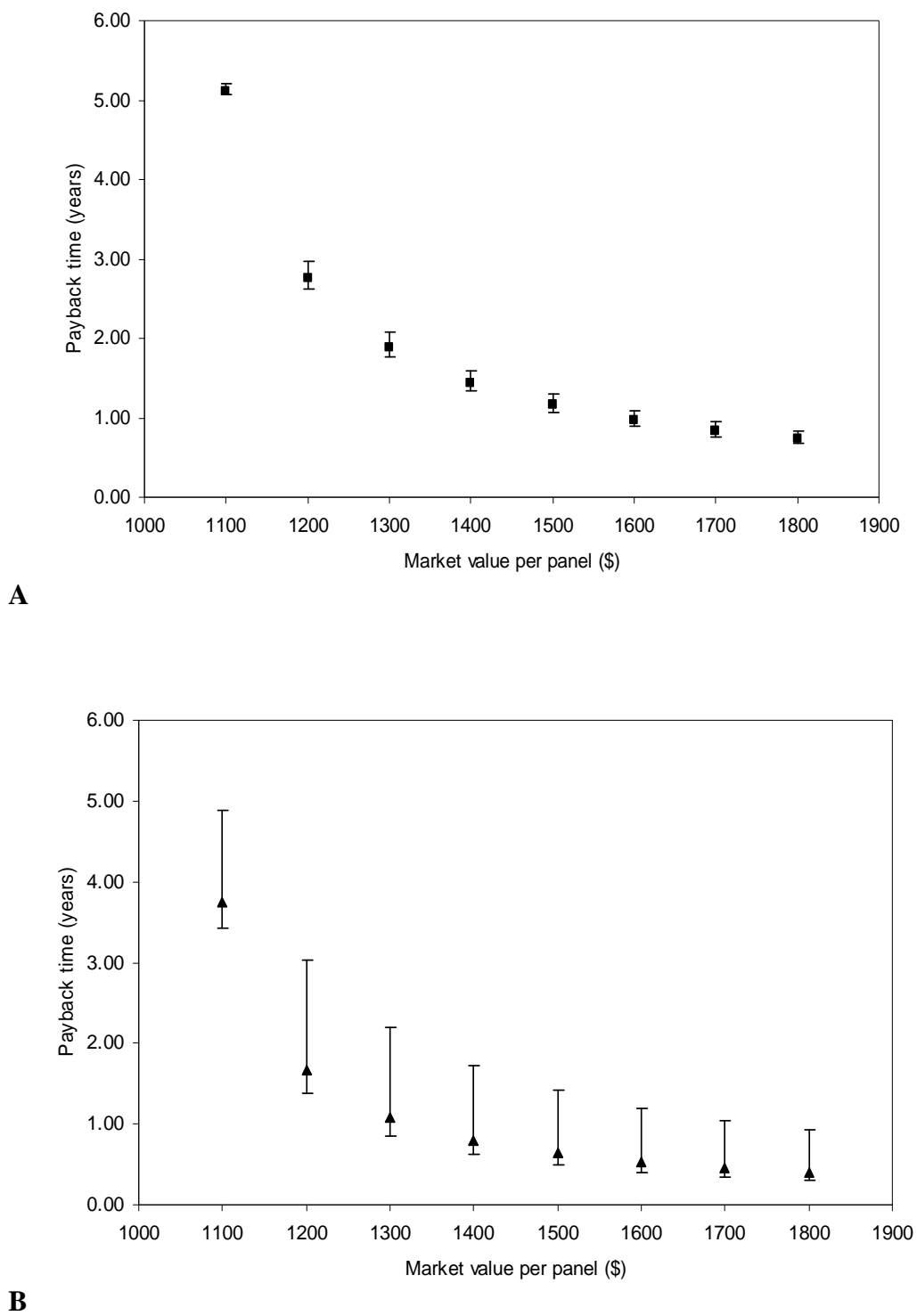


Figure 5.7 Average payback time vs market value per panel for unglazed Colorcote BIPVT using A) RSW and B) ATC system operating 1,920 hours production time (8 hours/day, 5 days/week at 48 weeks/yr) for 5,000 to 90,000 panels per year. (Appendix 2.B and 2.C.)

5.9 Process optimisation to increase throughput

As an alternative to installing additional production lines individual production step throughputs at rate limiting steps can be increased by installing additional equipment to increase overall process throughput. ADH was used as an example for process optimisation (Table 5.7). The slowest step in ADH is PV lamination at 0.07 panels per minute. Installing 6 PV lamination units allows the PV lamination throughput to be almost equal to the throughput for the corrugation step. The next slowest step is bonding the collector plate to the corrugated sheet at 0.1 panels per minute. Throughput for this step was increased by installing 4 units. Optimisation increased the total number of panels produced over 5,760 operating hours (3 shifts per day, 5 days a week and 48 weeks a year) from 23,040 to 138,240 panels per year by increase throughput from 0.07 to 0.40 panels per minute (Table 5.7). In comparison, the unoptimised process needed 6 production lines to equal the production volume per year of the optimised process.

Table 5.7 Comparison of individual process step throughput for unoptimised (unoptd.*) and optimised (optd.*)ADH BIPVT prod. Values based on Table 5.3.

Production step	Panels processed/step		Panels/min	
	Unoptd.*	Optd.*	Unoptd.*	Optd.*
Corrugation of plain sheet	1	1	0.50	0.50
Producing holes on corrugated sheet	1	1	0.40	0.40
Joining collector plate to corrugated sheet	1	4	0.10	0.40
Mounting fittings to the corrugated sheet	1	2	0.20	0.40
Lamination of PV strings on collector plate	1	6	0.07	0.40
Sealing the edges between bonded corrugated sheet and collector plate	1	2	0.25	0.50
Attaching manifolds to corrugated sheet	1	2	0.25	0.50
Process throughput (panels/min) based on slowest step			0.07	0.40
Panels per year per production line for 5,760 hrs operating time			23,040	138,240
Number of equipment lines needed			6	1
Panels per year installed capacity			138,240	138,240

Process optimisation reduced ADH production capital costs by approximately \$4.4 million (Table 5.8), by only installing additional equipment where necessary rather than installing new production lines. There was little difference in the operating costs per year and net profit per year between the unoptimised and optimised systems, but the payback time was reduced from 4.8 to 3.3 months for the optimised process (Table 5.9).

Table 5.8 Capital costs for unoptimised and optimised ADH BIPVT production.

Production step	Equipment cost	
	Unoptimised	Optimised
Corrugation of plain sheet by press-brake	\$250,000	\$250,000
Producing holes on corrugated sheet by punching	\$10,000	\$10,000
Joining collector plate to corrugated sheet	\$33,500	\$134,000
Mount fittings on corrugated sheet	\$5,000	\$10,000
Lamination of PV strings on collector plate	\$400,000	\$2,400,000
Sealing the bonded edges between collector plate and corrugated sheet	\$5,000	\$10,000
Attaching manifolds with the corrugated sheet	\$5,000	\$10,000
Production line equipment cost	\$708,500	\$2,824,000
Production lines needed	6	1
Total equipment cost (TEC)	\$4,251,000	\$2,824,000
Capital investment (TEC x Lang factor 3.06)	\$13,008,060	\$8,641,440

ATC and RSW was also optimised, and similar results were found except that only a ~\$0.8 million reduction in capital cost could be achieved for ATC with payback time being reduced from 0.23 to 0.19 years (Appendix 3). This was due to the high capital cost of the autoclave and high throughput of the process. Approximately \$3.4 million reduction in capital cost was achieved for RSW with payback time being reduced from 0.54 to 0.39 years (Appendix 4).

Table 5.9 Comparison of individual process step throughput for unoptimised and optimised ADH BIPVT production.

Parameter	Production system (ADH)	
	Unoptimised	Optimised
Total equipment cost (TEC)	\$4,251,000	\$2,824,000
Capital investment (CI = TEC x Lang factor 3.06)	\$13,008,060	\$8,641,440
Depreciation (20%) (DC=0.20xCI)	\$2,601,612	\$1,728,288
Panels per year for 5760 hrs operating time (N)	13,8240	138,240
Labour per panel (min)	0.71	0.71
Labour cost per min (including overhead) (LC)	\$28	\$28
Labour cost per year (A=LC x N)	\$3,916,800	\$3,916,800
Machine operating cost per year (B = 10% of TEC)	\$1,275,300	\$847,200
Equipment energy consumption per year (C=1% of TEC x factor*)	\$42,510	\$28,240
Material cost per panel Colorcote (Unglazed) (MP)	\$1,050	\$1,050
Material cost per year (D=MP x N))	\$145,152,000	\$145,152,000
Total operating costs per year (TO = A+B+C+D)	\$150,386,610	\$149,944,240
Cost per panel (CP = TO/N)	\$1,088	\$1,085
Market value per panel (MV)	\$1,400	\$1,400
Revenue before tax (RT = MV x N)	\$193,536,000	\$193,536,000
Gross profit before tax (GP = RT – TO)	\$43,149,390	\$43,591,760
Gross profit after tax (33%) (GPT = GP x 0.67)	\$28,910,091	\$29,206,479
Net profit per year (NP = GPT + DC)	\$31,511,703	\$30,934,767
Gross margin (GM = GPT/RT)	14.94%	15.09%
Return on investment (ROI = NP/CI)	242%	358%
Payback time (years) (PT = CI/NP)	0.41	0.28

5.10 Dimond scenario

BIPVT production system for ADH system was analysed as a case study with a long-run roofing manufacturing company Dimond Ltd., Auckland. The analysis was carried out for 1,920 operating hours per year producing 7,680 panels.

Dimond Ltd. has a CNC operated press-brake for producing corrugated roofing profiles. A CNC operated press-brake can process a single corrugated sheet for a BIPVT panel in two minutes, including set up time. The press brake if operated continuously can produce up to 172,800 sheets over 5,760 hours a year (Table 5.26). Maximum BIPVT production for 5,760 hours a year for ADH, RSW and ATC systems is 23,040; 19,200 and 51,840 panels respectively. Press-brake utilisation would be approximately 13% to 30% (Table 5.10) of the total process operating time. The press-brake can be operated independently of the other process steps in BIPVT production; therefore it would be free from 87% to 70% of the time for other jobs. If the corrugated sheets were stacked the press brake would only need to operate for 5-12 hours per week (for BIPVT production running over 1,920 hours a year) to produce sufficient panels to supply the BIPVT process.

Table 5.10 Press brake utilisation for panels produced in a year.

System/ equipment	Panels produced per year			% Press brake utilisation
	1,920 hours	3,840 hours	5,760 hours	
ADH	7,680	15,360	23,040	13%
RSW	6,400	12,800	19,200	11%
ATC	17,280	34,560	51,840	30%
Press-brake	57,600	115,200	172,800	100%

5.10.1 Economic analysis for case study

Two scenarios were considered in the case study. Scenario I was producing 7,680 panels per year without a laminator and scenario II was with laminator. In scenario I, all the production steps remained the same as the standard production system (Table 5.2) except that pre-made PV laminated modules are bonded on collector plate using silicone based adhesives. The cost of PV laminates was calculated on the basis of price/Wp. The current market price for mono crystalline PV module price is about \$US 4.30/Wp [86] . The power generated by BIPVT panel is about 200 W and the total price for PV laminates is calculated about \$NZ1074. For bonding the PV laminates to the collector plate it was assumed similar equipment to bonding the collector plate with the corrugated sheet was used. The time required for bonding the laminate was assumed to be same as joining the collector plate with corrugated sheet.

In scenario II, the PV lamination was conducted in a vacuum laminator in a similar way as that of standard production system discussed in Section 5.7. PV material cost was the same as that of a standard production system.

The capital costs for the standard process and scenarios I and II are shown in Table 5.11. The time required for each production step along with panels per minute are compared to the standard process in Tables 5.12 and 5.13. Labour, machine and energy costs for all three systems are tabulated in Table 5.14.

In scenario I, excluding the PV laminator means only \$282,000 needs to be invested in capital costs for the BIPVT process (Table 5.11). However, the materials costs are \$500 greater than the standard process or scenario II. For equivalent production volumes of 7,680 panel per year and same panel market value, scenario I only generates \$800,000 net profit a year (Table 5.15) because the operating costs are almost \$4 million dollars greater than the other two scenarios (Tables 5.13, 5.14). After 5 years operation scenario I would only generate a \$3.5 million surplus compared to \$15 million for the other two scenarios (Table 5.16). A laminator is therefore essential in the long term to keep material costs low and keep margins high.

Table 5.11 BIPVT capital cost comparison.

Production step	Equipment costs		
	Standard	Scenario I	Scenario II
Corrugation of plain sheet by press-brake	\$250,000	\$0	\$0
Producing holes on corrugated sheet by punching	\$10,000	\$10,000	\$10,000
Joining collector plate to corrugated sheet	\$33,500	\$33,500	\$33,500
Mount fittings on corrugated sheet	\$5,000	\$5,000	\$5,000
Lamination of PV strings on collector plate	\$400,000	\$33,500*	\$400,000
Sealing the bonded edges between collector plate and corrugated sheet	\$5,000	\$5,000	\$5,000
Attaching manifolds with the corrugated sheet	\$5,000	\$5,000	\$5,000
Production line equipment cost	\$708,500	\$92,000	\$458,500
Total equipment cost (TEC)	\$708,500	\$92,000	\$458,500
Capital Investment (CI=TEC x 3.06)	\$2,168,010	\$281,520	\$1,403,010

*Pre made PV laminates are used in this scenario so only equipment needed for bonding the laminates onto the collector is needed.

Table 5.12 Process time comparison for each BIPVT production step.

Production step	Time per panel (minutes)		
	Standard	Scenario I	Scenario II
Corrugation of plain sheet by press-brake	2	2	2
Producing holes on corrugated sheet by punching	2.5	2.5	2.5
Joining collector plate to corrugated sheet	10	10	10
Mount fittings on corrugated sheet	5	5	5
Lamination of PV strings on collector plate	15	10	15
Sealing the bonded edges between collector plate and corrugated sheet	4	4	4
Attaching manifolds with the corrugated sheet	4	4	4
Total labour per panel (min)	42.5	37.5	42.5
Rest time in cycle (min)	5	5	5
Total cycle time (min)	47.5	42.5	47.5

Table 5.13 Process time comparison in terms of panels per minute.

Production step	Time per panel (minutes)		
	Standard	Scenario I	Scenario II
Corrugation of plain sheet by press-brake	0.50	0.50	0.50
Producing holes on corrugated sheet by punching	0.40	0.40	0.40
Joining collector plate to corrugated sheet	0.10	0.10	0.10
Mount fittings on corrugated sheet	0.20	0.20	0.20
Lamination of PV strings on collector plate	0.07	0.10	0.07
Sealing the bonded edges between collector plate and corrugated sheet	0.25	0.25	0.25
Attaching manifolds with the corrugated sheet	0.25	0.25	0.25
Process throughput(panels/min) based on slowest step	0.07	0.10	0.07
Panels per year for 1,920 operating hours	7,680	11,520	7,680
Total area for panels produced (m²)	25,989	38,984	25,989

Table 5.14 Comparison of cost per panel including labour, machine and energy for all three scenarios.

ADH system	Production system		
	Standard	Scenario I	Scenario II
Total equipment cost (TEC)	\$2,168,010	\$281,520	\$1,403,010
Panels per year for 1920 hrs operating time (N)	7,680	7,680	7,680
Labour per panel (min)	42.5	37.5	42.5
Labour cost per min (including overhead) (LC)	\$28	\$25	\$28
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	\$3,420	\$7,085
Material cost per panel Colorcote (Unglazed) (MP)	\$1,050	\$1,524	\$1,050
Material cost per year (D=MP x N))	\$8,064,000	\$11,704,320	\$8,064,000
Total operating costs per year (TO = A+B+C+D)	\$8,359,535	\$11,933,940	\$8,359,535
Cost per panel (CP = TO/N)	\$1,088	\$1,554	\$1,088

Table 5.15 Comparison of payback, net profit analysis for all three systems.

Production step	Production system		
	Standard	Scenario I	Scenario II
Capital investment (CI)	\$2,168,010	\$531,520	\$1,653,010
Deprecation (DC = 20% of CI)	\$433,602	\$106,304	\$330,602
Panels produced per year for 1,920 hrs operating time (N)	7,680	7,680	7,680
Area of produced panels (m ²)	25,989	25,989	25,989
Total operating costs per year (TO)	\$8,359,535	\$11,933,940	\$8,359,535
Cost per panel (CP = TO/N)	\$1,088	\$1,554	\$1,088
Market value per panel (MV)	\$1,700	\$1,700	\$1,700
Market value per m ²	\$502	\$502	\$502
Revenue before tax (RT = MV x N)	\$13,056,000	\$13,056,000	\$13,056,000
Gross profit before tax (GP = RT – TO)	\$4,696,465	\$1,122,060	\$4,696,465
Gross profit after tax (33%) (GPT = GP x 0.67)	\$3,146,632	\$751,780	\$3,146,632
Net profit per year (NP = GPT + DC)	\$3,580,234	\$858,084	\$3,477,234
Gross margin (GM = GPT/RT)	24.10%	5.76%	24.10%
Return on investment (ROI = NP/CI)	165%	161%	210%
Payback time (years) (PT = CI/NP)	0.61	0.62	0.48

Table 5.16 Net savings per year comparison.

Net savings per year	Standard	Scenario I	Scenario II
Year 1 (Y1 = CI - NPY)	\$1,412,224	\$326,564	\$1,824,224
Year 2 (Y2 = Y1 + NPY)	\$4,992,457	\$1,184,648	\$5,301,457
Year 3 (Y3 = Y2 + NPY)	\$8,572,691	\$2,042,733	\$8,778,691
Year 4 (Y4 = Y3 + NPY)	\$12,152,924	\$2,900,817	\$12,255,924
Year 5 (Y5 = Y4 + NPY)	\$15,733,158	\$3,758,901	\$15,733,158
Year 6 (Y6 = Y5 + GPT)	\$18,879,789	\$4,510,681	\$18,879,789
Year 7 (Y7 = Y6 + GPT)	\$22,026,421	\$5,262,461	\$22,026,421

5.10.2 Conclusions from case study

Installing a low volume BIPVT production facility into Dimond's existing could potentially generate an additional \$3.5 million per year in profit for a process that produces 7,680 panels a year. Payback time for the capital investment would be just over half a year making BIPVT an attractive possibility. However a PV laminator would need to be installed to keep operating costs low, otherwise 75% of the profits would be lost to covering the PV laminate costs.

5.11 Potential Market

Currently in New Zealand, 22,000 homes are being built each year [88]. If 10% of these homes were equipped with on average 1.5 BIPVT panels, approximately 3,300 panels would need to be produced each year, which equates to 11,160 m². In terms of PV capacity, about 660 KW/year as each panel can generate 200 W. If all the new homes were equipped with 1-2 BIPVT panels, for example through Government initiatives 33,000 panels would be needed each year, which is 111,600 m², about 6.6 MW per year. BIPVT installation in 10% of new homes would exceed the SHW association target of 10,000 m² SHW systems installed per year and almost double the current growth of PV systems. Being a roofing product which avoids the problems of installing PV and solar thermal systems separately, BIPVT may be an attractive possibility. If the industry and commercial building were also considered in New Zealand, the potential market would be much greater. If the Australian market was also considered, where solar thermal and PV markets are greater than New Zealand, then BIPVT would be a strong commercial possibility.

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

Building integrated photovoltaic thermal (BIPVT) production systems were investigated to develop an economic and viable method for BIPVT manufacture. BIPVT is based on long-run metal roofing and is currently being developed at the University of Waikato in partnership with Dimond Ltd, a long-run roof product manufacturer. The concept consists of a CNC folded metal roofing sheet with a central channel and a collector plate bonded to the roofing sheet to create a sealed channel for thermal fluid flow. PV laminates are bonded to the collector plate and inlet and outlet manifolds attached for thermal fluid distribution. When exposed to solar radiation the system generates heat and electricity for domestic and industry use.

BIPVT manufacturing methods were investigated for creating the sealed channel for thermal fluid flow. 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 20,000 BIPVT panels per year as it has greater production capacity and lower capital investment payback time than ADH and RSW. ATC had a payback time of 0.26 years for 90,000 BIPVT panels per year at a 40% mark up. However ATC has several technical challenges that need to be overcome whereas ADH and RSW are proven production methods. ADH is more suitable for low production volumes below 20,000 panels per year as it has a low capital cost compared to RSW and ATC and can be readily optimised when increased production is required. Cost savings can be achieved by reducing material costs as they were 95% of the total operating costs for all methods. ADH and RSW could be readily optimised to increase production at lower capital expenditure by installing additional equipment at production bottlenecks rather than installing new production lines. ATC could not be as readily optimised as it has high production capacities.

Installing a low volume ADH BIPVT production facility into Dimond Ltd. could potentially generate an additional \$3.5 million per year in profit, for a process that produces 7,680 panels a year. Payback time for the capital investment including a PV laminator would be just over half a year making BIPVT an attractive possibility.

6.2 Recommendations

Silicone based adhesives could be investigated as a replacement for EVA for lamination and bonding the collector plate to the corrugated sheet in glazed BIPVT as stagnation temperatures in these products are greater than the melting temperature of EVA.

Roll forming is suggested for roofing sheet corrugation along with roll bonding of collector plate with corrugated sheet for higher BIPVT production volumes.

The possibility of using custom built processing equipment for BIPVT production to reduce capital costs instead of purchasing equipment such as resistance seam welders and laminators could be researched.

Combining an autoclave and laminator into one process unit for BIPVT production has never been done in practice. It would be worthwhile developing such a system as it combines several process steps into one operation.

Sealing the central channel ends in the BIPVT product could be removed from BIPVT manufacture by using roll punching or die punching to form the central channel in the corrugated sheets, instead of having the central channel run to the ends of the sheet.

A resistance seam welded BIPVT prototype should be manufactured for comparison to the existing prototype and tested for weld strength and product robustness. This methodology needs to be refined to avoid surface distortion when joining the collector plate to the corrugated sheet.

Alternative methods for bonding the collector plate to the corrugated sheet such as ultrasonic seam welding could be investigated further to overcome surface distortion generated by resistance seam welding.

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Appendix 1

Appendix 1 contains the payback time verses production volume for ADH, RSW and ATC systems operating over 1,920, 3,840 and 5,760 hours production time and producing 5,000 to 90,000 BIPVT panels per year with a market value of \$1,400 per panel for Unglazed Colorcote. It also includes machine utilization for ADH system operating 1,920 hours per year.

Table 1.A Payback time vs production volume for ADH, RSW and ATC systems operating 1,920 hours (8 hours/day, 5 days/week at 48 weeks/year) production time with a market value of \$1,400 per panel for Unglazed Colorcote BIPVT. (Ref. Figure 5.1)

Production volume	Market value per panel	Payback time for production system		
		ADH	RSW	ATC
5,000	\$1,400	1.49	1.60	1.72
10,000	\$1,400	1.49	1.60	1.00
15,000	\$1,400	1.09	1.60	0.71
20,000	\$1,400	1.19	1.60	1.00
25,000	\$1,400	1.25	1.36	0.83
30,000	\$1,400	1.09	1.40	0.71
35,000	\$1,400	1.15	1.43	0.88
40,000	\$1,400	1.19	1.45	0.79
45,000	\$1,400	1.09	1.47	0.71
50,000	\$1,400	1.13	1.36	0.65
55,000	\$1,400	1.16	1.38	0.77
60,000	\$1,400	1.09	1.40	0.71
65,000	\$1,400	1.12	1.42	0.66
70,000	\$1,400	1.15	1.34	0.75
75,000	\$1,400	1.09	1.36	0.71
80,000	\$1,400	1.11	1.37	0.67
85,000	\$1,400	1.14	1.39	0.64
90,000	\$1,400	1.09	1.40	0.71

Table 1.B Payback time vs production volume for ADH, RSW and ATC systems operating 3,840 hours (16 hours/day, 5 days/week at 48 weeks/year) production time per year with market value of \$1,400 per panel for Unglazed Colorcote BIPVT. (Ref. Figure 5.2)

Production volume	Market value per panel	Payback time for production system		
		ADH	RSW	ATC
5,000	\$1,400	0.98	2.23	1.78
10,000	\$1,400	0.87	1.34	1.03
15,000	\$1,400	0.61	1.68	0.72
20,000	\$1,400	0.87	1.34	0.56
25,000	\$1,400	0.72	1.12	0.45
30,000	\$1,400	0.61	1.34	0.38
35,000	\$1,400	0.76	1.18	0.63
40,000	\$1,400	0.68	1.34	0.56
45,000	\$1,400	0.61	1.22	0.50
50,000	\$1,400	0.72	1.12	0.45
55,000	\$1,400	0.66	1.24	0.41
60,000	\$1,400	0.61	1.16	0.38
65,000	\$1,400	0.69	1.26	0.35
70,000	\$1,400	0.65	1.18	0.48
75,000	\$1,400	0.61	1.12	0.45
80,000	\$1,400	0.68	1.20	0.43
85,000	\$1,400	0.64	1.15	0.40
90,000	\$1,400	0.61	1.22	0.38

Table 1.C Payback time vs. production volume for ADH, RSW and ATC systems operating for 5,760 hours (24 hours/day, 5 days/week at 48 weeks/year) production time per year with market value of \$1,400 per panel for Unglazed Colorcote BIPVT. (Ref. Figure 5.3)

Production volume	Market value per panel	Payback time for production system		
		ADH	RSW	ATC
5,000	\$1,400	1.59	2.34	1.86
10,000	\$1,400	0.89	1.38	1.05
15,000	\$1,400	0.62	0.98	0.73
20,000	\$1,400	0.47	1.38	0.56
25,000	\$1,400	0.73	1.15	0.46
30,000	\$1,400	0.62	0.98	0.38
35,000	\$1,400	0.53	0.86	0.33
40,000	\$1,400	0.47	1.09	0.29
45,000	\$1,400	0.42	0.98	0.26
50,000	\$1,400	0.56	0.89	0.23
55,000	\$1,400	0.51	0.82	0.42
60,000	\$1,400	0.47	0.98	0.38
65,000	\$1,400	0.44	0.91	0.36
70,000	\$1,400	0.53	0.86	0.33
75,000	\$1,400	0.50	0.80	0.31
80,000	\$1,400	0.47	0.93	0.29
85,000	\$1,400	0.45	0.88	0.27
90,000	\$1,400	0.42	0.83	0.26

Table 1.D Payback time and machine utilisation for unglazed Colorcote BIPVT production volume by ADH system for 1,920 hours (8 hours/day, 5 days/week at 48 weeks/year) production time. (Ref. Figure 5.4)

Production volume	Market value per panel	Payback time	Machine utilization
5,000	\$1,400	1.49	65%
10,000	\$1,400	1.49	65%
15,000	\$1,400	1.09	98%
20,000	\$1,400	1.19	87%
25,000	\$1,400	1.25	81%
30,000	\$1,400	1.09	98%
35,000	\$1,400	1.15	91%
40,000	\$1,400	1.19	87%
45,000	\$1,400	1.09	98%
50,000	\$1,400	1.13	93%
55,000	\$1,400	1.16	90%
60,000	\$1,400	1.09	98%
65,000	\$1,400	1.12	94%
70,000	\$1,400	1.15	91%
75,000	\$1,400	1.09	98%
80,000	\$1,400	1.11	95%
85,000	\$1,400	1.14	92%
90,000	\$1,400	1.09	98%

Table 1.E Payback time vs production volume for unglazed and glazed Zinalume and Colorcote using ADH system for 1,920 hours (8 hours/day, 5 days/week at 48 weeks/year) production time for production of 5,000 to 90,000 panels per year with a market value of 140% over material cost per panel. (Ref. Figure 5.5)

Production volume	Unglazed Zinalume			Unglazed Colorcote			Glazed Zinalume			Glazed Colorcote		
	MC/P*	MV/P*	PBT*	MC/P	MV/P	PBT	MC/P	MV/P	PBT	MC/P	MV/P	PBT
5,000	\$945	\$1,323	1.40	\$1,050	\$1,470	1.28	\$1,065	\$1,491	1.27	\$1,170	\$1,638	1.17
10,000	\$945	\$1,323	1.40	\$1,050	\$1,470	1.28	\$1,065	\$1,491	1.27	\$1,170	\$1,638	1.17
15,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84
20,000	\$945	\$1,323	1.12	\$1,050	\$1,470	1.02	\$1,065	\$1,491	1.00	\$1,170	\$1,638	0.92
25,000	\$945	\$1,323	1.17	\$1,050	\$1,470	1.07	\$1,065	\$1,491	1.06	\$1,170	\$1,638	0.98
30,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84
35,000	\$945	\$1,323	1.07	\$1,050	\$1,470	0.98	\$1,065	\$1,491	0.97	\$1,170	\$1,638	0.89
40,000	\$945	\$1,323	1.12	\$1,050	\$1,470	1.02	\$1,065	\$1,491	1.00	\$1,170	\$1,638	0.92
45,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84
50,000	\$945	\$1,323	1.06	\$1,050	\$1,470	0.96	\$1,065	\$1,491	0.95	\$1,170	\$1,638	0.87
55,000	\$945	\$1,323	1.09	\$1,050	\$1,470	0.99	\$1,065	\$1,491	0.98	\$1,170	\$1,638	0.90
60,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84
65,000	\$945	\$1,323	1.05	\$1,050	\$1,470	0.95	\$1,065	\$1,491	0.94	\$1,170	\$1,638	0.86
70,000	\$945	\$1,323	1.07	\$1,050	\$1,470	0.98	\$1,065	\$1,491	0.97	\$1,170	\$1,638	0.89
75,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84
80,000	\$945	\$1,323	1.04	\$1,050	\$1,470	0.95	\$1,065	\$1,491	0.93	\$1,170	\$1,638	0.86
85,000	\$945	\$1,323	1.06	\$1,050	\$1,470	0.97	\$1,065	\$1,491	0.96	\$1,170	\$1,638	0.88
90,000	\$945	\$1,323	1.01	\$1,050	\$1,470	0.92	\$1,065	\$1,491	0.91	\$1,170	\$1,638	0.84

MC/P*: Material cost per panel, MV/P*: market value per panel, PBT*: Payback time (years)

Appendix 2

Appendix 2 comprises average payback time ADH, RSW and ATC systems operating over 1,920 hours and producing 5,000 to 90,000 BIPVT panels per year with market value from \$1,100 to \$1,800 per panel for Unglazed Colorcote.

Table 2.A Average payback time vs market value per panel for unglazed Colorcote by ADH system for 1,920 hrs production time for producing 5,000 to 90,000 panels per year. (Refer Figure 5.6)

Production volume	Material cost/panel	Operating cost/panel	Market value per panel and payback time (years)							
			\$1,100	\$1,200	\$1,300	\$1,400	\$1,500	\$1,600	\$1,700	\$1,800
5,000	\$1,050	\$1,094	4.78	2.75	1.93	1.49	1.21	1.02	0.88	0.77
10,000	\$1,050	\$1,094	4.78	2.75	1.93	1.49	1.21	1.02	0.88	0.77
15,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
20,000	\$1,050	\$1,090	4.53	2.34	1.58	1.19	0.96	0.80	0.69	0.60
25,000	\$1,050	\$1,091	4.59	2.43	1.66	1.25	1.01	0.84	0.73	0.64
30,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
35,000	\$1,050	\$1,089	4.49	2.28	1.53	1.15	0.92	0.77	0.66	0.58
40,000	\$1,050	\$1,090	4.53	2.34	1.58	1.19	0.96	0.80	0.69	0.60
45,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
50,000	\$1,050	\$1,089	4.47	2.25	1.50	1.13	0.90	0.75	0.65	0.57
55,000	\$1,050	\$1,090	4.51	2.30	1.55	1.16	0.93	0.78	0.67	0.59
60,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
65,000	\$1,050	\$1,089	4.46	2.23	1.49	1.12	0.90	0.75	0.64	0.56
70,000	\$1,050	\$1,089	4.49	2.28	1.53	1.15	0.92	0.77	0.66	0.58
75,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
80,000	\$1,050	\$1,089	4.45	2.23	1.48	1.11	0.89	0.74	0.64	0.56
85,000	\$1,050	\$1,089	4.48	2.26	1.51	1.14	0.91	0.76	0.65	0.57
90,000	\$1,050	\$1,089	4.42	2.18	1.45	1.09	0.87	0.72	0.62	0.54
Average			4.50	2.30	1.55	1.17	0.93	0.78	0.67	0.59
Maximum			4.78	2.75	1.93	1.49	1.21	1.02	0.88	0.77
Minimum			4.40	2.15	1.42	1.06	0.85	0.71	0.61	0.53
+			0.28	0.45	0.38	0.32	0.27	0.24	0.21	0.19
-			0.10	0.15	0.12	0.10	0.09	0.07	0.06	0.06

Table 2.B Average payback time vs market value per panel for unglazed Colorcote RSW for 1,920 hours production time for producing 5,000 to 90,000 panels per year. (Ref: Figure 5.7A)

Production Volume	Material cost/panel	Operating cost/panel	Market value per panel and payback time (years)							
			\$1,100	\$1,200	\$1,300	\$1,400	\$1,500	\$1,600	\$1,700	\$1,800
5,000	\$1,050	\$1,105	5.20	2.97	2.08	1.60	1.30	1.10	0.95	0.83
10,000	\$1,050	\$1,105	5.20	2.97	2.08	1.60	1.30	1.10	0.95	0.83
15,000	\$1,050	\$1,105	5.20	2.97	2.08	1.60	1.30	1.10	0.95	0.83
20,000	\$1,050	\$1,105	5.20	2.97	2.08	1.60	1.30	1.10	0.95	0.83
25,000	\$1,050	\$1,102	5.07	2.65	1.79	1.36	1.09	0.91	0.78	0.69
30,000	\$1,050	\$1,102	5.10	2.71	1.85	1.40	1.13	0.94	0.81	0.71
35,000	\$1,050	\$1,103	5.11	2.75	1.88	1.43	1.15	0.97	0.83	0.73
40,000	\$1,050	\$1,103	5.12	2.78	1.91	1.45	1.17	0.98	0.85	0.74
45,000	\$1,050	\$1,103	5.13	2.80	1.93	1.47	1.19	0.99	0.86	0.75
50,000	\$1,050	\$1,102	5.07	2.65	1.79	1.36	1.09	0.91	0.78	0.69
55,000	\$1,050	\$1,102	5.09	2.68	1.82	1.38	1.11	0.93	0.80	0.70
60,000	\$1,050	\$1,102	5.10	2.71	1.85	1.40	1.13	0.94	0.81	0.71
65,000	\$1,050	\$1,102	5.11	2.73	1.86	1.42	1.14	0.96	0.82	0.72
70,000	\$1,050	\$1,101	5.06	2.63	1.77	1.34	1.07	0.90	0.77	0.68
75,000	\$1,050	\$1,102	5.07	2.65	1.79	1.36	1.09	0.91	0.78	0.69
80,000	\$1,050	\$1,102	5.08	2.67	1.81	1.37	1.10	0.92	0.79	0.70
85,000	\$1,050	\$1,102	5.09	2.69	1.83	1.39	1.12	0.93	0.80	0.70
90,000	\$1,050	\$1,102	5.10	2.71	1.85	1.40	1.13	0.94	0.81	0.71
Average			5.11	2.75	1.89	1.43	1.16	0.97	0.83	0.73
Maximum			5.20	2.97	2.08	1.60	1.30	1.10	0.95	0.83
Minimum			5.06	2.62	1.77	1.33	1.07	0.89	0.77	0.67
+			0.08	0.22	0.20	0.17	0.14	0.13	0.11	0.10
-			0.05	0.14	0.12	0.10	0.09	0.08	0.07	0.06

Table 2.C Average payback time vs market value per panel for unglazed Colorcote BIPVT for ATC production system operating 1,920 hours production time for producing 5,000 to 90,000 panels per year. (Ref. Figure 5.7B)

Production Volume	Material cost/panel	Operating cost/panel	Market value per panel and payback time (years)							
			\$1,100	\$1,200	\$1,300	\$1,400	\$1,500	\$1,600	\$1,700	\$1,800
5,000	\$1,050	\$1,096	4.88	3.02	2.19	1.72	1.41	1.20	1.04	0.92
10,000	\$1,050	\$1,084	4.16	2.03	1.34	1.00	0.80	0.67	0.57	0.50
15,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
20,000	\$1,050	\$1,084	4.16	2.03	1.34	1.00	0.80	0.67	0.57	0.50
25,000	\$1,050	\$1,081	3.87	1.74	1.13	0.83	0.66	0.55	0.47	0.41
30,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
35,000	\$1,050	\$1,082	3.96	1.83	1.19	0.88	0.70	0.58	0.50	0.43
40,000	\$1,050	\$1,081	3.78	1.67	1.07	0.79	0.62	0.51	0.44	0.38
45,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
50,000	\$1,050	\$1,079	3.47	1.41	0.89	0.65	0.51	0.42	0.36	0.31
55,000	\$1,050	\$1,081	3.74	1.63	1.04	0.77	0.61	0.50	0.43	0.37
60,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
65,000	\$1,050	\$1,079	3.51	1.44	0.91	0.66	0.52	0.43	0.37	0.32
70,000	\$1,050	\$1,080	3.72	1.61	1.03	0.75	0.60	0.49	0.42	0.37
75,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
80,000	\$1,050	\$1,079	3.53	1.46	0.92	0.67	0.53	0.44	0.37	0.32
85,000	\$1,050	\$1,079	3.44	1.39	0.87	0.64	0.50	0.41	0.35	0.30
90,000	\$1,050	\$1,080	3.62	1.53	0.97	0.71	0.56	0.46	0.39	0.34
Average			3.75	1.67	1.08	0.80	0.64	0.53	0.45	0.39
Maximum			4.88	3.02	2.19	1.72	1.41	1.20	1.04	0.92
Minimum			3.42	1.37	0.86	0.63	0.49	0.41	0.34	0.30
+			1.12	1.35	1.11	0.91	0.77	0.67	0.59	0.53
-			0.34	0.30	0.22	0.18	0.15	0.12	0.11	0.09

Appendix 3

Appendix 3 includes the optimisation of ATC production system operating 5,760 production hours per year and shows comparison of individual process step throughput, capital costs, net profit and payback time for unoptimised and optimised ATC production systems.

Table 3.A Comparison of individual process step throughput for optimised and unoptimised ATC BIPVT production system operating 5,760 hours per year.

Production step (ATC)	Panels processed/step		Panels/min	
	Unoptd.*	Optd.*	Unoptd.*	Optd.*
Corrugation of plain sheet	1	1	0.50	0.50
Producing holes on corrugated sheet	1	1	0.40	0.40
Joining collector plate to corrugated sheet, sealing central channels end, mounting fittings and lamination of PV strings	3	6	0.15	0.30
Sealing the edges between bonded corrugated sheet and collector plate	1	2	0.25	0.50
Attaching manifolds to corrugated sheet	1	2	0.25	0.50
Process throughput (panels/min) based on slowest step			0.15	0.30
Panels per year per production line for 5760 hrs operating time			51,840	103,680
Number of equipment lines needed			2	1
Panels per year installed capacity			103,680	103,680

Unoptd:* Unoptimised, *Optd.*:* optimised

Table 3.B Capital cost comparison for optimised and unoptimised ATC production system operating 5,760 hours per year.

Production step (ATC)	Equipment cost	
	Unoptd.*	Optd.*
Corrugation of plain sheet by press-brake	\$250,000	\$250,000
Producing holes on corrugated sheet by punching	\$10,000	\$10,000
Joining collector plate to corrugated sheet, sealing central channels end, mounting fittings and lamination of PV strings	\$600,000	\$1,200,000
Sealing the bonded edges between collector plate and corrugated sheet	\$5,000	\$10,000
Attaching manifolds with the corrugated sheet	\$5,000	\$10,000
Production line equipment cost	\$870,000	\$1,480,000
Total equipment cost (TEC)	\$1,740,000	\$1,480,000
Capital investment (TEC x Lang factor 3.06)	\$5,324,400	\$4,528,800

Unoptd.: Unoptimised, Optd.*: optimised*

Table 3.C Net profit, payback time and return on investment comparison for unoptimised and optimised ATC production system operating 5,760 hours per year.

ATC	Production system	
	Unoptimised	Optimised
Total equipment cost (TEC)	\$1,740,000	\$1,480,000
Capital investment (CI = TEC x Lang factor 3.06)	\$5,324,400	\$4,528,800
Depreciation (20%) (DC=0.20xCI)	\$1,064,880	\$905,760
Panels per year for 5760 hrs operating time (N)	103,680	103,680
Labour per panel (min)	32.5	32.5
Labour cost per min (including overhead) (LC)	\$22	\$22
Labour cost per year (A=LC x N)	\$2,246,400	\$2,246,400
Machine operating cost per year (B = 10% of TEC)	\$522,000	\$444,000
Equipment energy consumption per year (C=1% of TEC x factor*)	\$69,600	\$59,200
Material cost per panel Colorcote (Unglazed) (MP)	\$1,050	\$1,050
Material cost per year (D=MP x N))	\$108,864,000	\$108,864,000
Total operating costs per year (TO = A+B+C+D)	\$111,702,000	\$111,613,600
Cost per panel (CP = TO/N)	\$1,077	\$1,077
Market value per panel (MV)	\$1,400	\$1,400
Revenue before tax (RT = MV x N)	\$145,152,000	\$145,152,000
Gross profit before tax (GP = RT – TO)	\$33,450,000	\$33,538,400
Gross profit after tax (33%) (GPT = GP x 0.67)	\$22,411,500	\$22,470,728
Net profit per year (NP = GPT + DC)	\$23,476,380	\$23,376,488
Gross margin (GM = GPT/RT)	15%	15%
Return on investment (ROI = NP/CI)	441%	516%
Payback time (years) (PT = CI/NP)	0.23	0.19

Appendix 4

Appendix 4 includes the optimisation of RSW production systems operating 5,760 production hours per year. Comparison of individual process step throughput, capital costs, net profit and payback time for optimised and unoptimised systems for RSW are shown in the optimisation.

Table 4.A Comparison of individual process step throughput for unoptimised and optimised RSW production system operating 5,760 hours per year.

Production step (RSW)	Panels Processed/step		Panels/min	
	Unoptd.	Optd.	Unoptd.	Optd.
Corrugation of plain sheet	1	1	0.50	0.50
Producing holes on corrugated sheet	1	1	0.40	0.40
Joining collector plate to corrugated sheet	1	5	0.06	0.28
Sealing central channels at each end	1	2	0.20	0.40
Mounting fittings to the corrugated sheet	1	2	0.20	0.40
Lamination of PV strings on collector plate	1	5	0.07	0.33
Sealing the edges between bonded corrugated sheet and collector plate	1	2	0.25	0.50
Attaching manifolds to corrugated sheet	1	2	0.25	0.50
Process throughput (panels/min) based on slowest step			0.06	0.28
Panels per year per production line for 5760 hrs operating time			19,200	96,000
Number of equipment lines needed			5	1
Panels per year installed capacity			96,000	96,000

Unoptd:* Unoptimised, *Optd.*:* optimised

Table 4.B Capital cost comparison for unoptimised and optimised RSW production system operating 5,760 hours per year.

Production step (RSW)	Equipment cost	
	Unopt.*	Optd.*
Corrugation of plain sheet by press-brake	\$250,000	\$250,000
Producing holes on corrugated sheet by punching	\$10,000	\$10,000
Joining collector plate to corrugated sheet	\$80,000	\$400,000
Sealing central channel ends	\$5,000	\$10,000
Mount fittings on corrugated sheet	\$5,000	\$10,000
Lamination of PV strings on collector plate	\$400,000	\$2,000,000
Sealing the bonded edges between collector plate and corrugated sheet	\$5,000	\$10,000
Attaching manifolds with the corrugated sheet	\$5,000	\$10,000
Production line equipment cost	\$760,000	\$2,700,000
Total equipment cost (TEC)	\$3,800,000	\$2,700,000
Capital investment (TEC x Lang factor 3.06)	\$11,628,000	\$8,262,000

Unoptd.: Unoptimised, Optd.*: optimised*

Table 4.C Comparison of net profit, payback time and return on investment for unoptimised and optimised RSW production system operating 5,760 hours per year.

RSW	Production system	
	Unoptimised	Optimised
Total equipment cost (TEC)	\$3,800,000	\$2,700,000
Capital investment (CI = TEC x Lang factor 3.06)	\$11,628,000	\$8,262,000
Depreciation (20%) (DC=0.20xCI)	\$2,325,600	\$1,652,400
Panels per year for 5760 hrs operating time (N)	96,000	96,000
Labour per panel (min)	0.93	0.93
Labour cost per min (including overhead) (LC)	\$37	\$37
Labour cost per year (A=LC x N)	\$3,552,000	\$3,552,000
Machine operating cost per year (B = 10% of TEC)	\$1,140,000	\$810,000
Equipment energy consumption per year (C=1% of TEC x factor*)	\$76,000	\$54,000
Material cost per panel Colorcote (Unglazed) (MP)	\$1,050	\$1,050
Material cost per year (D=MP x N))	\$100,800,000	\$100,800,000
Total operating costs per year (TO = A+B+C+D)	\$105,568,000	\$105,216,000
Cost per panel (CP = TO/N)	\$1,100	\$1,096
Market value per panel (MV)	\$1,400	\$1,400
Revenue before tax (RT = MV x N)	\$134,400,000	\$134,400,000
Gross profit before tax (GP = RT – TO)	\$28,832,000	\$29,184,000
Gross profit after tax (33%) (GPT = GP x 0.67)	\$19,317,440	\$19,553,280
Net profit per year (NP = GPT + DC)	\$21,643,040	\$21,205,680
Gross margin (GM = GPT/RT)	14.37%	14.55%
Return on investment (ROI = NP/CI)	186%	257%
Payback time (years) (PT = CI/NP)	0.54	0.39

Appendix 5

Table 5.A Lang factors in detail for solid, fluid and combination processing plants.

Category	Solids processing	Solid-fluid processing	Fluid processing
Equipment (delivered)	1	1	1
Equipment, Installation	0.19-0.23	0.39-0.43	0.76
Piping	0.07-0.23	0.30-0.39	0.33
Structural foundations	-	-	0.28
Electrical	0.13-0.25	0.08-0.17	0.09
Instruments	0.03-0.12	0.13	0.13
Battery-limits building and service	0.33-0.50	0.26-0.35	0.45
Excavation and site preparation	0.03-0.18	0.08-0.22	-
Auxiliaries	0.14-0.30	0.48-0.55	included
Total physical Plant	2.37	2.97	3.04
Field expenses	0.10-0.12	0.35-0.43	
Engineering	-	0.35-0.43	0.41
Direct plans costs	2.48	3.73	3.45
Contractor's fees, overhead, profit	0.30-0.33	0.09-0.17	0.17
Contingency	0.26	0.39	0.36
Total fixed-capital investment	3.06	4.27	3.98

Appendix 6

Table 6.A Production method advantages and disadvantages [65, 66, 68].

Method/ equipment	Advantages	Disadvantages
Press-brake forming	<ul style="list-style-type: none"> Tooling is simple Varieties of parts and shapes are produced Process can be automated for low-cost 	<ul style="list-style-type: none"> Speed lower than roll-forming Length of the bed is fixed
Roll forming	<ul style="list-style-type: none"> Sheet produced in thickness range of 0.125 – 20 mm High forming speeds about 1.5 m/s Suitable for mass production Length of products is more than press brakes 	<ul style="list-style-type: none"> Less number of parts and components are produced in single set up High cost of tooling and set-up
Using Adhesives	<ul style="list-style-type: none"> Lower temperatures generate during joining process Joining of dissimilar metals and thin gauges Sealing, insulating, and preventing electrochemical corrosion of dissimilar metals Exterior surfaces of bonded components remain smooth and unaffected No distortion of bonded surfaces as operating temperatures during process are from room temperature to 200°C 	<ul style="list-style-type: none"> Strength of the bond per unit area is limited Service temperature range is limited Time for bonding process can be long Surface preparation is crucial for strength of bond and needs great care Reliability is limited as degradation of bonds occur due to environmental conditions
Welding	<ul style="list-style-type: none"> High strength joint Process can be automated Quick and energy efficient process 	<ul style="list-style-type: none"> Joint cannot be dismantled High initial cost Surface distortion
Brazing/ Soldering	<ul style="list-style-type: none"> Less surface distortion than welding Joining of dissimilar metals and thin gauges No expensive equipment required Joints produced are fast and at low cost 	<ul style="list-style-type: none"> Strength of joint lower than welding Within dissimilar metal joints galvanic action can occur Environmental operating temperatures are limited
Mechanical fastening	<ul style="list-style-type: none"> Dissimilar metals of different gauges are easily joined Joints are easily dismantled and assembled with simple tools 	<ul style="list-style-type: none"> Failure of the mechanical fasteners at joint due to localized stresses Within dissimilar metal joints galvanic action can occur Joint preparation is required