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**DESIGN OF
BUILDING INTEGRATED
PHOTOVOLTAIC PRODUCT
FOR
LONG RUN METAL ROOFING**

A thesis
submitted in partial fulfillment
of the requirements for the degree

of

Master of Engineering

at

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by

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Abstract

In this study an innovative concept for a building integrated photovoltaic (BIPV) product was generated and verified at the University of Waikato in partnership with Dimond Roofing. The concept is based on a new principle which consists of laminating solar cells directly to a COLORSTEEL substrate, with a thin polymer cover, and folding this post-lamination into a profile which is capable of mating with standard long run metal roofing profiles.

There were two major unknowns associated with the new concept which needed to be verified. Firstly, the suitability of laminating directly onto COLORSTEEL was in question as this material has not been used for this purpose before. More importantly, it was unsure whether the laminate would withstand the folding process without causing damage to the cells or other laminate materials.

The issue of laminating to COLORSTEEL was addressed experimentally by producing small scale COLORSTEEL-EVA laminates. T peel tests were performed on samples from two different laminates - one which consisted of COLORSTEEL which had not undergone any kind of surface treatment, and another which was subjected to flame treatment to increase its surface energy. The flame treated sample exhibited a 7 fold increase in adhesion strength over the untreated sample, with average adhesion values of 56 N/cm, which is comparable to proven materials currently used in commercial quality photovoltaic modules. Untreated COLORSTEEL is not suitable for PV laminates. Further optimization of the treatment and lamination processes is likely to produce laminates with even greater adhesion strengths.

Subsequently, it was necessary to fabricate equipment to replicate the commercial lamination process in order to produce laminates of high quality. These laminates were then folded on a hand brake to determine the feasibility of forming them into shapes capable of mating with existing metal roofing profiles. Folds were able to be started very close to the edge of the cell, even as close as 1 mm, without affecting the performance of the laminate, or causing any damage to the cell or laminate materials.

This study was successful in designing an innovative BIPV product with huge potential to succeed in today's market. It was shown that the product is worth further investigation, therefore it is recommended that larger scale prototypes are produced and subjected to a range of testing.

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Nomenclature

<i>a-Si</i>	Amorphous Silicon	<i>mc-Si</i>	Monocrystalline Silicon
<i>AUD</i>	Australian Dollars	<i>NZD</i>	New Zealand Dollar
<i>BIPV</i>	Building Integrated Photovoltaics	<i>pc-Si</i>	Polycrystalline Silicon
<i>BIPVT</i>	Building Integrated Photovoltaic Thermal	<i>PECVD</i>	Plasma Enhanced Chemical Vapour Deposition
<i>BIT</i>	Building Integrated Thermal	<i>PV</i>	Photovoltaic
<i>CdTe</i>	Cadmium Telluride	<i>QD</i>	Quantum Dot
<i>CIGS</i>	Copper Indium Gallium Diselenide	<i>REC</i>	Renewable Energy Credit
<i>CSG</i>	Crystalline Silicon on Glass	<i>RET</i>	Renewable Energy Target
<i>c-Si</i>	Crystalline silicon	<i>TCO</i>	Transparent Conductive Oxide
<i>DSSC</i>	Dye-sensitised Solar Cell	<i>TFSC</i>	Thin Film Solar Cell
<i>EU</i>	European Union	<i>TFSC</i>	Thin Film Solar Cell
<i>FiT</i>	Feed in Tarrif	<i>UoW</i>	University of Waikato
<i>ITC</i>	Investment Tax Credit	<i>USD</i>	US dollars
<i>kWh</i>	Kilowatt Hour	<i>VHF</i>	Very High Frequency
<i>kW_p</i>	Peak Kilowatt	<i>W_p</i>	Peak Watt

Chapter 1: Introduction

1.1 Overview

The need to establish a more sustainable energy infrastructure has arisen due to concerns associated with the use of traditional energy sources, including increasing costs, security of supply, and environmental issues. Current fuel sources are being consumed at a rate which is unsustainable (in particular fossil fuels), additionally, these fuels produce significant emissions of global warming gasses. International pressure to reduce the consumption of such fuels has been applied in the form of the Kyoto Protocol, and the recent Copenhagen summit meeting.

Adoption of renewable energy technology is gaining impetus worldwide, with interest in wind energy, biomass, hydropower, and photovoltaic (PV) technologies. PV is by far the fastest growing energy and most abundant energy source, and, unlike other renewables, is well suited to the built environment.

This chapter provides a basic overview on solar energy and building integrated photovoltaics (BIPV), followed by background on solar work already performed at the University of Waikato (UoW). Finally, the objective of the thesis is stated, and an outline of the thesis structure is presented.

1.2 Solar Energy

Solar energy is so abundant that enough solar energy falls on the earth in one hour to more than meet the world's entire annual energy demands¹. There is significant potential to offset the use of conventional fuels if even a small portion of this energy is able to be harnessed.

The energy from the sun is typically utilised in two forms - solar thermal and photovoltaic (PV). Solar thermal technology is concerned with converting solar radiation into useful heat to produce hot water, which is then usually consumed as utility on site. PV technology converts the solar radiation directly into electricity, which can then be stored, fed back into the grid, or consumed locally. PV is well

suited to the built environment, particularly so because it does not require additional real estate, and can be installed on rooftops.

If the electrical power demand of many countries is to be supplemented by the use of PV, it is necessary to integrate such systems into the building envelope. This is essential in many countries such as Japan, Britain and Germany, where there is a huge pressure on land use and building's surfaces offer relatively free areas².

1.3 Building Integrated Photovoltaics

Unlike traditional PV systems, building integrated PV (BIPV) systems are integrated *into* the building structure, rather than an additional added *onto* the building. By providing a streamlined solution, BIPV systems deliver a vast improvement on visual appeal over traditional installations, which can be bulky and obtrusive, as illustrated in Figure 1. The image on the left shows an example of a typical PV installation, while a BIPV alternative called Sunslate, produced by Atlantis Energy Systems, is pictured on the right. The conventional installation is clearly visible as an addition to the roof, whereas it is difficult to even tell that the roof on the right is actually generating electricity - only a slight change in tile colour is noticeable where it switches to standard tiles near the edge of the roof.



Figure 1 - An example of a typical PV installation (left), and a BIPV alternative (right)

BIPV products are commonly integrated into a number of building elements, including roofs, windows, facades and skylights. Architecturally, such products can be applied in different contexts - they can be almost invisible for little visual impact, or they can add to, or determine the architectural image, in some cases leading to new architectural concepts³. BIPV will become more and more a

standard component of buildings, and therefore a higher proportion of the costs of the mechanical structure will be associated with the building itself⁴.

Several advantages can be expected for BIPV systems when compared to ground based PV power plants⁵:

- Improved aesthetics giving a greater acceptance with end users and architects
- Cost savings due to combined functions
- No high value land is necessary
- No separate support structure is required
- Electricity is generated at the point of use, avoiding transmission and distribution losses

Similar to BIPV, building integrated thermal (BIT) solutions are possible, where water channels are integrated into the roofline, which heat water to a useful temperature. BIT and BIPV can be combined into one total solution to utilise a greater proportion of solar energy, offering both heating and power generation, called building integrated photovoltaic thermal (BIPVT). Such systems have been proven to increase the electricity output by providing cooling to the PV cells, which degrade in efficiency as the operating temperature is increased⁶.

1.4 Solar research at the UoW

There has been significant research into a range of aspects associated with building integrated solar products at the UoW, with a focus on BIT and more recently BIPVT. The solar product range is being developed in partnership with Dimond Roofing Ltd, the largest manufacturer of metal roofing in New Zealand (NZ), which is a division of Fletcher Building Ltd, the largest listed company in NZ.

A BIT concept in which water channels are integrated into long run metal roofing at the manufacture stage has been investigated thoroughly. The BIT concept is aesthetically unobtrusive, and difficult to differentiate visually from standard

metal roofing. It is installed in the same way as traditional metal roofing. Figure 2 illustrates the principle of construction of the BIT product.

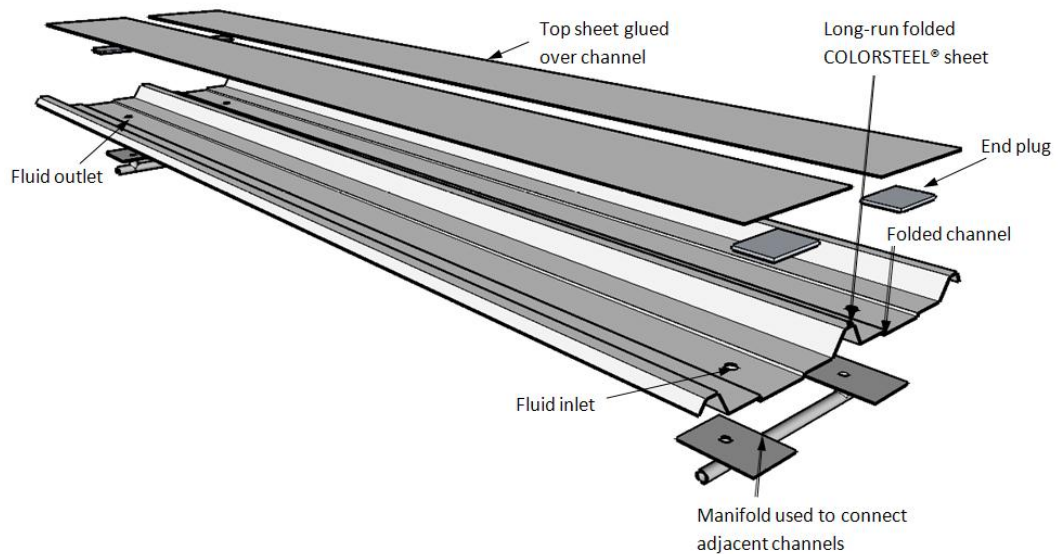


Figure 2 - Principal of operation of BIT product developed at the UoW

Prototypes and two demonstration sites have been completed, which have provided proof of concept. One is a small scale research rig, and the other is a larger scale roof used to heat the dive pool at the UoW, which is pictured below in Figure 3. There is ongoing research and development into the BIT product by the Solar Energy Research Group (SERG) at the UoW.

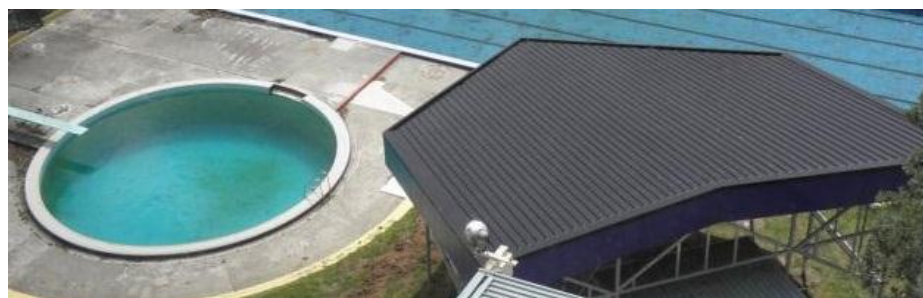


Figure 3 - BIT roof used to heat the dive pool at the UoW

The concept was later adapted to incorporate PV technology, where polycrystalline solar cells are laminated directly to the top sheet pictured in Figure 2, to produce a BIPVT product. The PV laminate is bonded to the troughed roofing profile using an adhesive. A prototype has been constructed and tested by Anderson, 2009⁷.

There has been recent interest in developing a BIPV product which is likely to be the first solar product to be put to the market. This is due to the simplicity of BIPV when compared to BIT and BIPVT, which still require a degree of research to solve issues associated with the integrated water channels. Additionally, the PV market has been booming recently, so it is expected that it would be relatively easy to penetrate a BIPV product into the market.

1.5 Thesis Objective

Recently, work has been conducted at the UoW in partnership with Dimond Roofing to develop a range of solar products integrated into long run metal roofing. The aim of this thesis is to present an innovative design for a BIPV product to Dimond Roofing, which could be introduced into the current market to diversify the range of products offered by Dimond.

The scope of the project will be limited to:

- Long run metal roofing
- Photovoltaics only, with no thermal
- PV technologies which are readily available
- Designs which can be incorporated into existing profiles, and do not infringe heavily on aesthetics

1.6 Thesis Outline

This thesis will follow the progression of the design of the BIPV product. Chapter 2 presents a review of the current market around the world, identifying areas of opportunity. Chapter 3 then reviews photovoltaic technologies, focusing on module construction and materials.

Chapter 4 is concerned with the design of the BIPV product, from problem analysis through to detailed design. Experiments are devised in Chapter 5 to verify unknowns associated with the innovative design. Following this, a discussion the work undertaken is provided in Chapter 6, and the product design is evaluated. Finally, conclusions and recommendations are then presented in Chapter 7.

Chapter 2: Market Review

2.1 Introduction

The first chapter provided an insight into the advantages of solar energy and BIPV systems, and demonstrated that the product is worthy of further investigation. As the product will be designed in the context of the current economic climate, it is necessary to determine that there exists sufficient market demand to justify pursuing the product idea.

The first section presents a brief review outlining the major features of the market which are expected to influence the success of the BIPV product. Following this, the uptake of (BI)PV technology on a global scale is reviewed, and regions of interest are identified. An overview of the metal roofing market in New Zealand and Australia is then presented. Existing BIPV products are then reviewed, before conclusions and recommendations are presented.

2.2 Factors Influencing the Uptake of (BI)PV Technology

The uptake and acceptance of PV technology varies considerably around the world, making it important to understand what is actually driving the market. This means the product can be targeted at the market(s) where it is likely to achieve the greatest success.

The PV market is likely to thrive in regions where the government is motivated to reduce their carbon emissions and create a more sustainable energy infrastructure. Recently, many governments have called for an increase in the installed capacity of renewable power, in order to meet renewable energy targets (RETs) set for the future. The renewable energy sector is driven by these targets, with a growing focus in PV technologies. In order to encourage the uptake of renewable technology, many governments now offer cash based incentives for such installations. Cash incentives help offset the high capital cost of photovoltaic systems, and make the systems more economically attractive to install. Cash incentives typically come in the form of:

- Feed-in tariffs (FiTs) - producers of PV energy are given a monetary payment based on the amount of power generated by the system

- Installation subsidies– a subsidy is provided to offset a proportion of the high initial cost of the system
- Tax credits

FiT programs appear to be the most significant force driving the market, as proven by the success of the German market, which experienced substantial growth in the years following the introduction of the scheme to become by far the largest market in the world. FiTs are offered in two forms, Net and Gross, of which Gross is the favourable model:

- Net– the PV system owner is paid only for *surplus* energy they produce, per kWh.
- Gross - the PV system owner is paid for *every* kWh of electricity they produce.

Additionally, regions receiving high levels of solar radiation will receive an increased energy benefit from installing PV, and therefore a more significant reduction of the reliance in fossil fuels.

2.3 Current PV Market around the World

The preceding section identified government support schemes as the most significant force driving the PV market. There are varying levels of support provided by different governments, ranging from none at all, to strong FiT schemes which can actually make the system profitable for the owner. As such the uptake of PV technology varies significantly around the world.

This section reviews the PV market around the world, and identifies regions which are favourable to the uptake of BIPV technology. The NZ and Australian markets are then reviewed, followed by other regions of interest, including Europe and the United States.

2.3.1 Global Overview

The cumulative installed photovoltaic capacity has grown to around 22 GW at the end of 2009, experiencing a compounding annual growth rate (CAGR) of around

35% over the last decade. Figure 4 shows the global cumulative installed PV capacity since 2000^{8,9}.

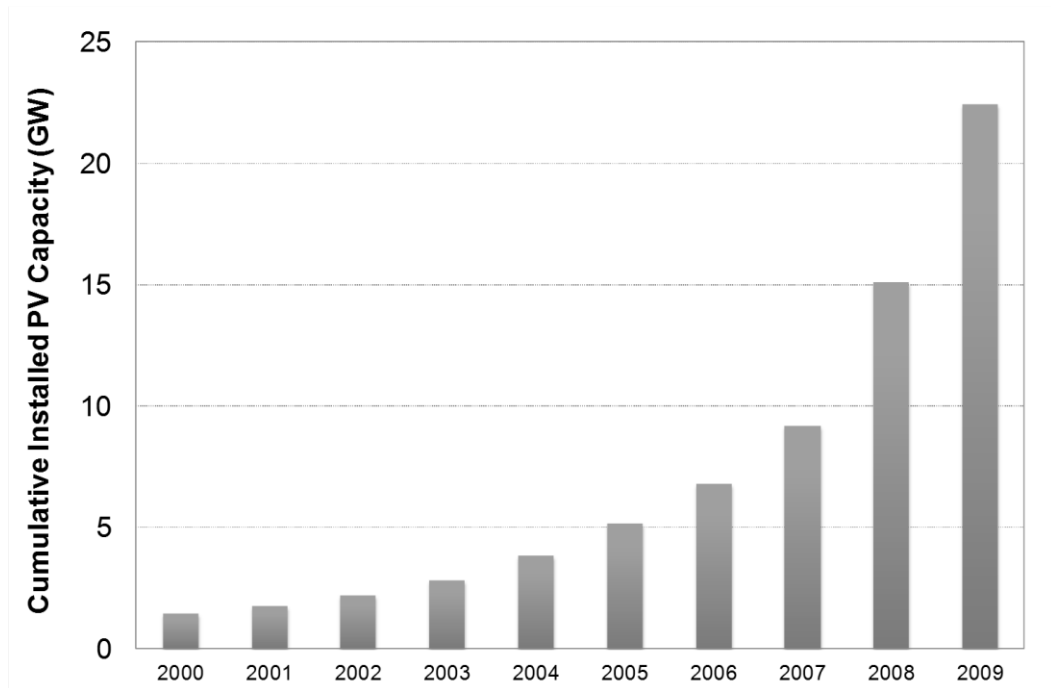


Figure 4 - Global Cumulative Installed PV Capacity^{8, 9}

Global PV installations reached a record high of 7.3 GW in 2009, with the industry generating 38.5 billion USD in global revenues⁹. Germany continued high growth in 2009, and was the top country, accounting for over half of the world market. Germany was followed by Italy, Japan, and the US, in order of decreasing market share. Figure 5 shows how the share of the world demand was distributed in 2009¹⁰.

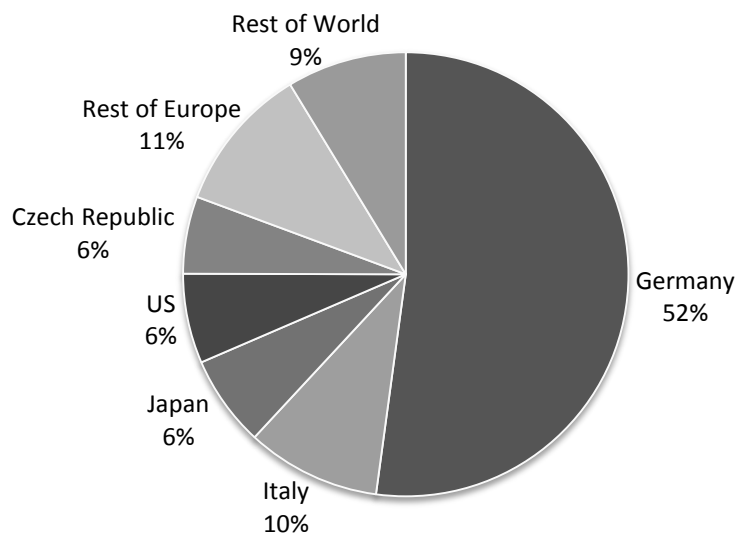


Figure 5 - Share of PV market in 2009

The majority of worldwide installed PV capacity has been grid connected since about 1999, reaching 94% in 2008, with 97% of new installations being grid connected¹¹. The trend towards grid connected systems has come as a result of support from incentives for such systems in the top global markets.

There are four end-use sectors with distinct markets for PV:

1. Residential systems - typically up to 20 kW systems on individual homes.
2. Commercial systems - typically up to 1 MW systems for commercial office buildings, schools, hospitals, and retail
3. Utility scale systems - starting at 1 MW, mounted on buildings or directly on the ground
4. Off-grid applications -varying sizes

2.3.2 BIPV Overview

With relatively low market size and penetration, the BIPV market holds large potential globally, and will soon experience a market growth as intense as the growth of the traditional PV market¹², however, currently BIPV installations remain limited. Assuming 1% of installations in Europe are BIPV, and 10% in the US, the global BIPV market stood at approximately 115 MW in 2009¹³.

There are two main domains of the BIPV market - low cost standardised BIPV products for the private housing and industrial market, and high cost customised BIPV for high rise buildings, office buildings and public buildings¹². Previously, the public market has been important in spreading the visibility and awareness of BIPV through large showcase projects, although its market share is decreasing due to the high growth rate of residential and commercial installations.

The majority of BIPV projects are installed on roofs, accounting for approximately 71% of installations, as shown in Figure 6, with most being integrated into flat roofs. Domestic and commercial roofs hold the largest potential market in the developed world for BIPV².

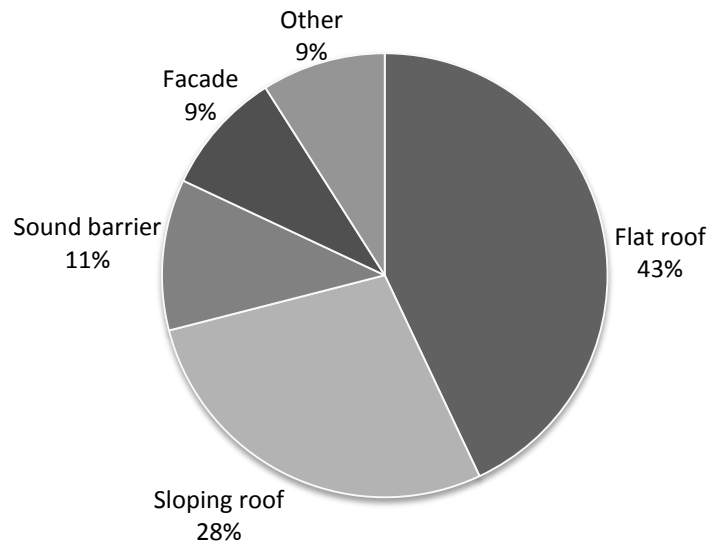


Figure 6 - BIPV projects by type from 400 PV projects⁵

There are certain barriers to the uptake of BIPV, such as a lack of awareness of the economic viability of the investment in BIPV, and also there are not many standardised mass produced PV products that are easily integrated into buildings¹³. PV has been proven to be an aesthetically neutral or visually attractive element when integrated with architecture, although many BIPV systems display few architectural qualities, as many architects have never thought about using PV as a means of architectural expression. As property developers see a building as a means of generating a return on their investment, in order to encourage them to apply PV, it must be presented as neutrally as possible with regard to aesthetics and costs³.

2.3.3 New Zealand

There has been growth in the NZ PV market in recent years, with 110 kW of grid connected systems installed in 2008, to give a cumulative installed capacity of approximately 4.9 MW. The majority of PV installations in NZ are small stand-alone systems under 2 kW. Growth has mainly been driven by corporate clients looking to make a statement about their environmental credentials, and to gain credits as part of a green building rating scheme. Smaller private systems have been installed by individuals with a desire to make a personal contribution to address the challenges of climate change¹⁴. Currently, the biggest markets are in off-grid residential, farming, and island applications where electricity alternatives

are unavailable, or economically or logistically difficult to deliver. These markets are relatively small, although they will remain and are likely to grow as PV cost effectiveness improves with time¹⁴.

NZ has climate conditions favourable to the uptake of PV, with radiation levels significantly higher than in Germany and Japan, countries which currently have the highest level of PV deployment in the world. The NZ government has supported clean energy for several years; however, although the current National-led government supports renewable energy, it has a greater focus on security of energy supply. NZ has a RET of 90% by the year 2025, and currently around 60-70% of this target is already met by renewable power generation, which is primarily hydroelectric¹⁵. There are currently no government incentives or subsidies available in New Zealand to encourage the installation of PV systems, which are required if the NZ market is to grow significantly, given the current price of PV¹⁴.

2.3.4 Australia

Australia experienced huge growth in 2009, installing 66 MW of PV to reach around 170 MW of installed capacity, which is three times the previous years' installations. Much of the past growth was driven by an 8 AUD/W_p Federal Government rebate (capped at 8000 AUD), which when combined with Renewable Energy Certificates (RECs) meant that zero-cost 1 kW solar power systems were being offered by a number of companies. These 'free' systems are no longer available, however, growth is still forecast due to favourable FiTs. Prior to this, the growth rate of PV in Australia had previously been slower than in other leading markets, mainly due to the lack of development in the on-grid market, where most of the growth is concentrated. As Australia has unique problems in terms of geography, location of rural and aboriginal communities, isolated tourist facilities, etc., up until recently the market consisted of mainly off-grid industrial and agricultural installations¹¹. However, with the recent introduction of FITs the residential market dominated in 2009, holding 80% of the market⁹, and can be expected to dominate over the coming years. Australia is an excellent candidate for solar energy, as it has the highest average solar radiation of

any continent in the world¹⁶. Figure 7 shows the growth in cumulative installed PV capacity in Australia over the last decade^{10, 17}.

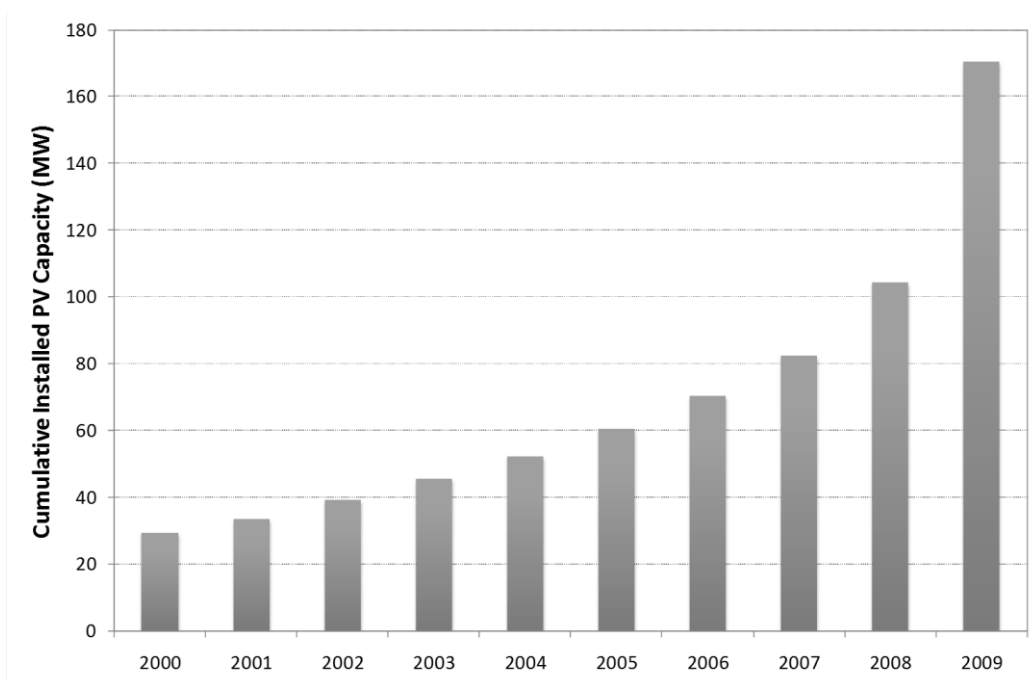


Figure 7 - Cumulative installed PV capacity in Australia over the last decade^{10, 17}

Australia is one of the largest contributors to global warming per capita, mainly due to emissions from the mining industry. In 2008, only 2.5% of electricity in Australia was generated from renewable sources¹⁸, with the bulk of electricity being produced at coal and gas fired power stations. The Federal Government mandatory RET will ensure renewable energy obtains a 20% share of electricity supply in Australia by 2020. Targets call for an increase in renewable energy generation from 9,500 GWh to 45,000 GWh by 2020¹⁵. The mandatory RET guarantees a market for additional renewable energy generation, using a mechanism of tradable Renewable Energy Certificates (RECs), backed by a legislative obligation. RECs are allocated to renewable energy producers, who can on-sell them to wholesale purchasers of electricity (such as electricity retailers or industrial operations) who are required to purchase a certain number of RECs. System owners can create and sell the RECs themselves; however, in practice, providers of solar PV systems usually take control of the RECs in exchange for a discount on the price of the PV system, or a cash payment. The price paid for RECs has been prone to significant fluctuation; because as the uptake of

renewable energy increases, the price of RECs is depressed. To address this, the RET scheme fixed the price at 40 AUD per REC for small scale-scale technologies on 1 January, 2011. Large scale technologies still continue to operate in a market driven manner. Solar credits is a mechanism within the RET scheme that boosts support to households, businesses and community groups that install small-scale solar PV by allowing a greater number of RECs to be created for eligible installations. Solar credits apply to the first 1.5 kW of installed capacity, with any additional power generation only receiving the standard 1:1 rate of REC creation¹⁹. Currently the solar credit multiplier is 5, however it is set to decrease over the coming years.

Australia currently has no nationalised FiT program, only state run schemes. An overview of the state run schemes is presented in Table 1. Rates are the same regardless of installation type, be it ground mounted, roof mounted, or building integrated. Attractive incentives are offered in ACT, with gross models offered up to 45.7 c/kWh.

Table 1 - Feed-in tariffs offered in Australian states²¹

State	Max Size (kW)	Current Rate Paid (AUD/kWh)	Program Duration	Model
VIC	5	0.60 ¹	15	Net
SA	10	0.44	20	Net
ACT	<30 <200	0.457 0.3427	20	Gross
TAS	tbc	0.20	tbc	Net
NT	tbc	0.45 (Alice springs) 0.1438 (Elsewhere)	tbc	Net
WA	5 (30) ¹	0.20	10	Net
QLD	10 (30) ¹	0.44	20	Net
NSW	10	0.20	7	Gross

1. Up to 30kW for 3 phase systems and depending on provider

ACT is a relatively small market, with a population estimated at just under 350,000 at the end of 2008. The ACT Government recently passed legislation to introduce a feed in tariff (FiT) for medium scale solar in the Territory; an Australian first. The gross FiT is now available at 34 c/kWh for installations 30kW to 200kW in size. As at August 2009, there were 10,476 PV systems installed within NSW, providing a total generation capacity of just over 13MW, of which 80% are grid-connected.²⁰. At the time this review was started, the highest incentive was offered in NSW at a gross rate of 60c/kWh, however this has since been reduced to 20c/kWh after a sudden boom in the market.

The national solar schools program provides a grant of up to \$50,000 to schools installing a PV system of over 2 kW, with up to \$30 000 available for smaller installations (GST exclusive). The program operates from July 2008 until 30 June 2015, although the program was suspended in October 2009 following a high demand for funding. However, the program will re-open to new claims on 1 July 2011. Additionally, Australia has shown its commitment to increasing renewable energy power generation by introducing a \$75 mil solar cities program. The cities are Adelaide, Alice Springs, Blacktown, Central Victoria, Moreland, Perth and Townsville. Each Solar City will integrate a unique combination of energy options such as energy efficiency measures for homes and businesses, the use of solar technologies, cost reflective pricing trials to reward people who use energy wisely, and community education about better energy usage in an increasingly energy-reliant world.

2.3.5 Europe

Europe holds by far the largest share of the PV market, of which Germany has the largest market share. The share of the European PV market in 2009 is shown in Figure 8. Italy, Spain, and France are among other major EU countries exhibiting a large market for PV. The Czech Republic shows an important growth in 2009 with 411 MW installed, however, due to overly generous support schemes, the market is expected to shrink in 2011 after another year of strong growth in 2010. The previously weak UK market is expected to expand in the coming years with the recent introduction of FiTs. Over the next five years Germany and Italy are expected to remain the largest European markets, followed by France & Spain¹⁰.

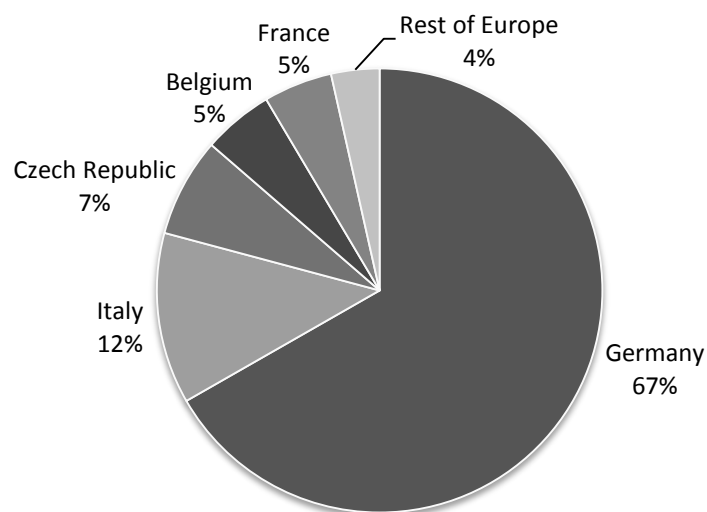


Figure 8 - Share of European PV market in 2009

The European BIPV market is a niche market with great potential but currently only takes up around 1% of the total PV market. There is considerable interest in BIPV due to its high annual growth, and supportive legislation for BIPV¹³. The BIPV market is estimated at 143 million euro in 2007, with 25.7 MW, the bulk of income coming from commercial and industrial sectors. In 2008 it is estimated at 214 million euro, with 37.2 MW installations²². Luxembourg has the highest market penetration levels for BIPV, although it is only a small market with a population of under 500,000, while Germany has largest BIPV market. The residential sector has had the highest growth and has become the largest market for BIPV, mainly due to large rise in the French market, and to a lesser degree the Italian market, driven by high tariffs for small scale BIPV systems. The commercial sector has started utilising BIPV more and will become more dominant after 2011, with high growth projected in the office and warehouse sectors¹³. In 2007, the residential sector held the majority of the market with 55%, followed by commercial installations with a 30% share¹³. A selection of FiTs offered at the time of this review across Europe are summarised below in Table 2.

Table 2 - FiTs offered in Europe (€)²¹

Country/Region	Roof-Top	Ground-Based	BIPV	Term
Belgium				
Flanders	0.24-0.31	0.24-0.31	0.24-0.31	20 years
Wellonia & Brussels	Varies	Varies	Varies	20 years
Czech Republic	<30kW - 0.4963 >30kW - 0.4925	<30kW - 0.4963 >30kW - 0.4925		20 years
France	0.42 100kW+ 0.12	0.314 - 0.377 100kW+ 0.12	Fully integrated: 0.58 Commercial/ industrial: 0.50 Simplified BIPV: 0.42	20 years
Germany	0.2111 to 0.2874	0.21.11 to 0.28.74		20 years
Greece	0.40 - 0.50	0.40 - 0.50		20 years
Italy	1-3 kW - 0.392 3-20 kW - 0.372 >20kW - 0.353	1-3 kW - 0.392 3-20 kW - 0.372 >20kW - 0.353	1-3 kW - 0.48 3-20 kW - 0.451 >20kW - 0.4312	20 years
Spain	0.32-0.34	0.32	0.32 - 0.34	25 years
Switzerland	<10kW 0.49 <30kW 0.43 <100kW 0.41 >100kW 0.39	<10kW 0.43 <30kW 0.35 <100kW 0.33 >100kW 0.32	<10kW 0.59 <30kW 0.48 <100kW 0.44 >100kW 0.41	25 years
Turkey	0.9	0.9		10 years
Ukraine	<100kW - 0.2369 >100kW - 0.2477	<100kW - 0.2369 >100kW - 0.2477		To 2030
United Kingdom	<4kW - 0.47 >4-10kW - 0.41 >10-100kW - 0.35 >100kW-5MW - 0.33	0.33	0.47	25 years

2.3.5.1 Germany

The German market is the leading PV market, currently having the highest installed capacity, as well as the highest added capacity in 2009. Germany installed around 3.8 GW in 2009 to reach over 9 GW of cumulative installed PV capacity, which represented over half of worldwide PV installations that year. Most of the solar resource in Germany is at the lower end of the 1000-1500

kWh/m² per year range¹¹. Figure 9 shows the growth in cumulative installed PV capacity in Germany over the last decade.

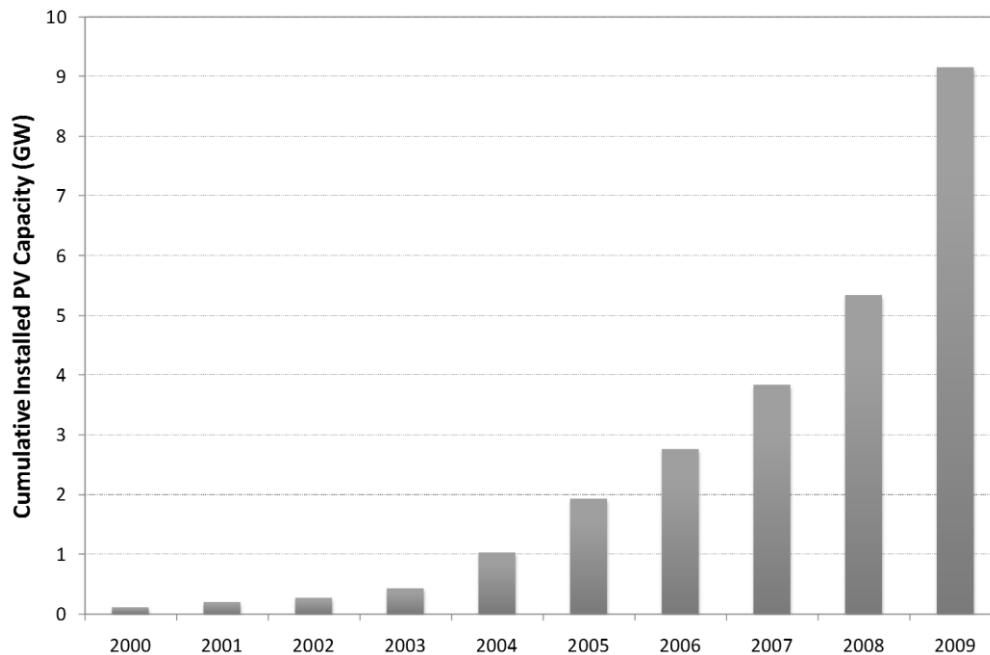


Figure 9 - Growth in cumulative installed PV capacity in Germany over the last decade

The German market has developed rapidly over the last decade as a result of strategic and long term support programs, initially focusing on low interest loans and grants, and now focusing on FiTs which have been in place since 2000. Germany has recently reduced FiTs to between €0.21.11 to 0.28.74 per kWh for small roof top installations, although there is no distinction between roof-mounted and BIPV systems. The market remains strong and Germany is expected to continue to dominate for the next few years¹⁴.

2.3.5.2 Spain

In 2010, Spain had a cumulative installed PV capacity of around 3.3 GW as a result of accelerated growth in 2007 and 2008. Spain added around 2.5 GW of new PV installations in 2008, passing Japan in cumulative installed capacity and becoming the second largest world market. This represented 45% of the global PV market, and came as a result of the introduction of favourable FiTs. This was Spain's second year of accelerated growth, with a cumulative increase of around 300% the previous year¹³. However, this high growth was unsustainable, and the Spanish market collapsed towards the end of 2008 due to changes in the FiT

scheme and PV program caps²³, with 2009 demand decreasing to just 4% of the previous year⁹. Figure 10 shows how the cumulative installed PV capacity has grown in Spain over the last decade.

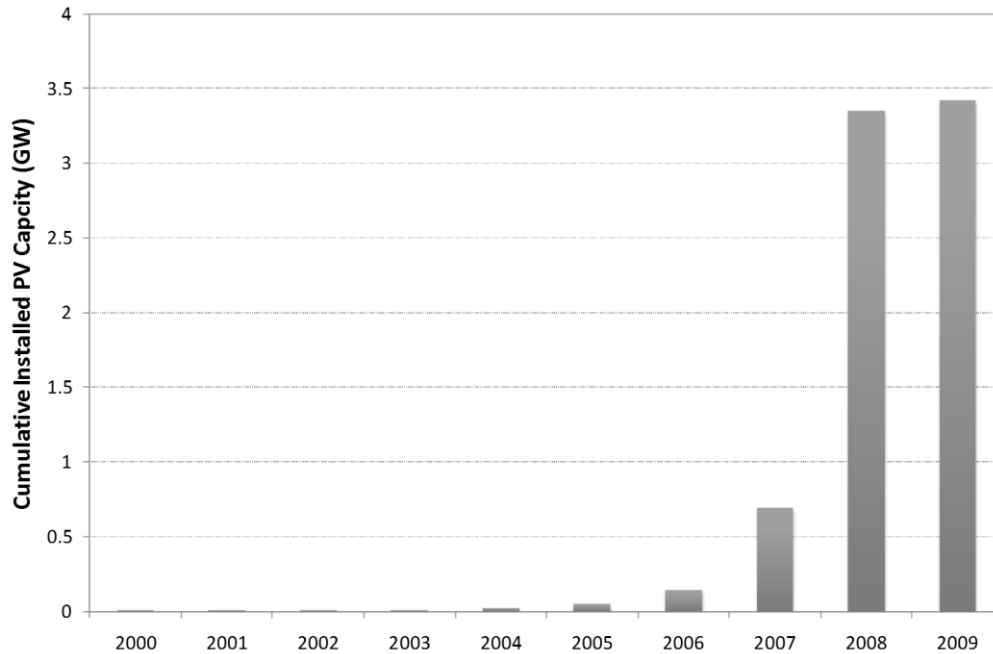


Figure 10 - Growth in cumulative installed PV capacity in Spain over the last decade

Spain have a RET of 20% on final consumption of energy by the year 2020, and as of 2007 9% of final consumption of energy was met by RES²⁴. Integration of smaller PV systems in buildings is being promoted through higher tariffs and quotas. Spain offers FiTs of between 0.32 and 0.34 euro per kWh which were set in 2009 for a 25 year period, with annual installations capped at around 400 MW²⁴. The Spanish solar resource is between 1300 and 2000 kWh/m² per year¹¹.

2.3.5.3 Italy

The Italian market emerged as one of the most promising markets in 2009, growing to almost 1.2 GW with over 700 MW of installations that year. This was a continuation of the strong growth the year before, where the cumulative installed capacity rose from 120 MW to 458 MW¹¹. The high growth in Italy can be attributed to the support provided by the recent introduction of high FiTs for BIPV, which are currently as high as 0.48 EURO per kWh (reducing 2% per annum). The market is expected to continue to grow rapidly in the coming years, despite administrative and bureaucratic hurdles which have been limiting

growth¹³. Figure 11 shows how the cumulative installed PV capacity has grown in Italy over the last decade.

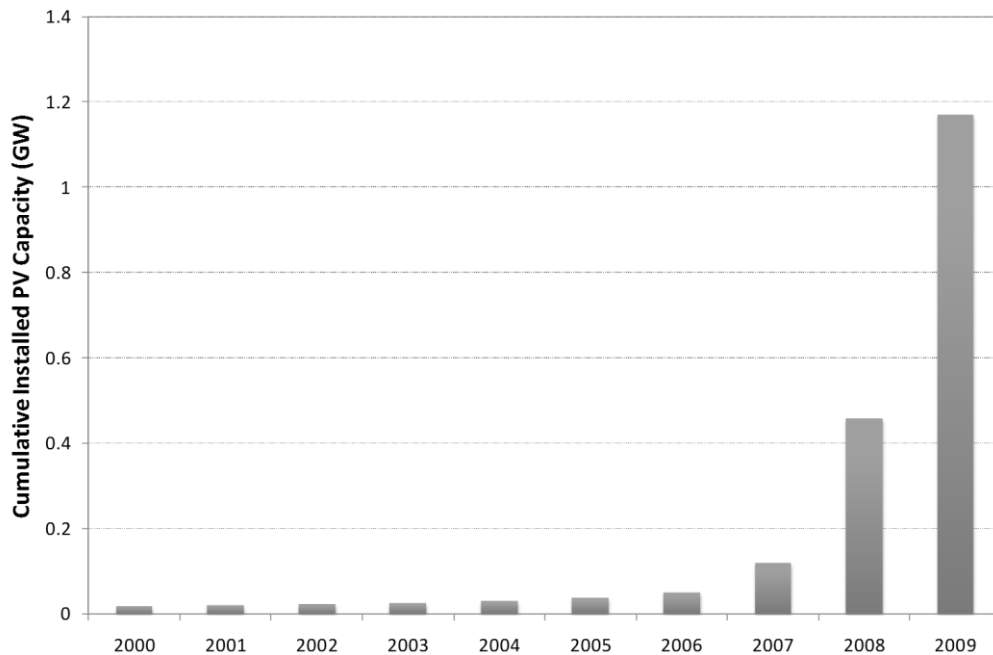


Figure 11 - Growth in cumulative installed PV capacity in Italy over the last decade

2.3.5.4 France

France installed about 285 MW in 2009 (which includes 100 MW installed but not connected to the grid yet.) to give a cumulative installed capacity of 460MW. The 100 MW not yet connected is indicative of the challenge faced by manufacturers over the recent high demand from the French market, as there is a lack of expertise in PV design and installation. France has recently had a focus on BIPV¹³, and offers higher FiTs for such systems over standard PV systems, which is the highest FiT in Europe at up to 0.58 EURO per kWh. From 2012 onwards, all FiTs will have a 10% reduction per year²⁵. The residential market accounts for 40% of installations, with the typical installation size being about 3 kW. The French FiT system distinguishes between fully integrated systems and simplified integration which require separate water-proofing measures to be applied. Figure 12 shows how the cumulative installed PV capacity has grown in France over the last decade.

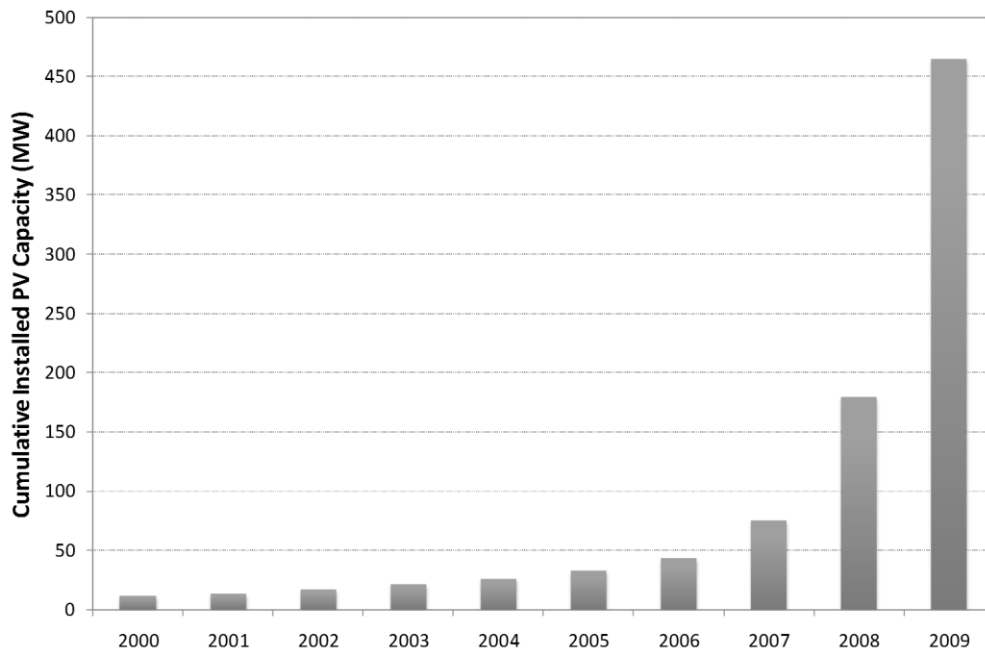


Figure 12 - Growth in cumulative installed PV capacity in France over the last decade

France have a RET of 23% on final consumption of energy by the year 2020; as of 2007 this share was 11%²⁴. Since 2007 the country has seen considerable growth in all areas of renewable energy, however, the share of renewable energy has not increased as energy demand has been growing at a steady rate²¹. The French PV market is dominated by Tenesol, Apex BP Solar and Photowatt.

2.3.6 Japan

Japan was the first country to actively support development, manufacture and use of PV, and has shown steady growth cumulative installed PV capacity over the last decade, as shown in Figure 13. Japan's cumulative installed capacity was around 2.5 GW in 2010, with over 0.4 GW installed in 2009. Japan was the largest market until it was surpassed by Germany in 2005, which coincided with the end of Japan's '70,000 roofs' program¹¹. Japan currently has a FiT of the equivalent of approximately 0.39 € per kWh.

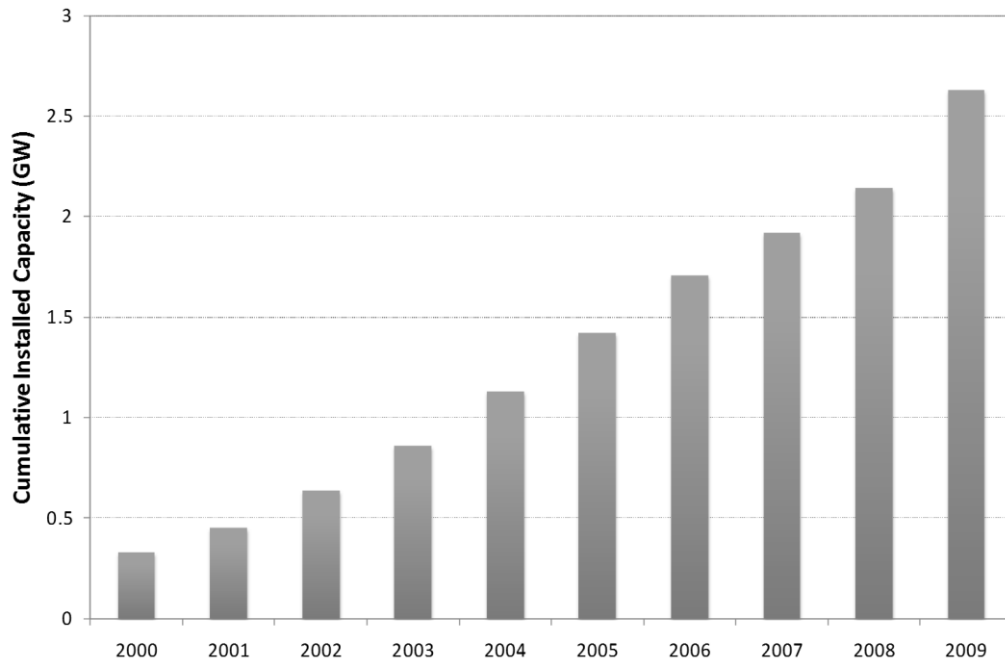


Figure 13 - Growth in cumulative installed PV capacity in Japan over the last decade

Japan is quite a mountainous country and its usable land area is limited, which means the price of land is extremely high, therefore BIPV installations are preferable. The major R&D project in Japan is called the ‘New Sunshine programme’, which includes the following fields: mass production technology of low cost PV cells, cost reduction of PV systems, BIPV modules and improvements in efficiency. There is a focus to increase PV uptake in public, commercial and industrial facilities, where the level of market penetration is significantly lower than the domestic sector⁵. Due to the recent incident at the Fukushima nuclear plant as a consequence of the earthquake and resulting tsunami, Japan will be looking to decrease its reliance on nuclear energy, with more of a focus on other energy sources²⁶.

2.3.7 United States

PV installation growth in the United States (US) has been accelerating in recent years, with over 1.6 GW of cumulative installed capacity in 2010. US installations amounted to around 477 MW in 2009, up from approximately 340 MW installed in 2008. The cumulative installed PV capacity in the US since the year 2000 is shown in Figure 14. Growth has been driven by the federal investment tax credit (ITC), state rebate programs and other incentives and financing mechanisms¹¹, at both the state and federal level.

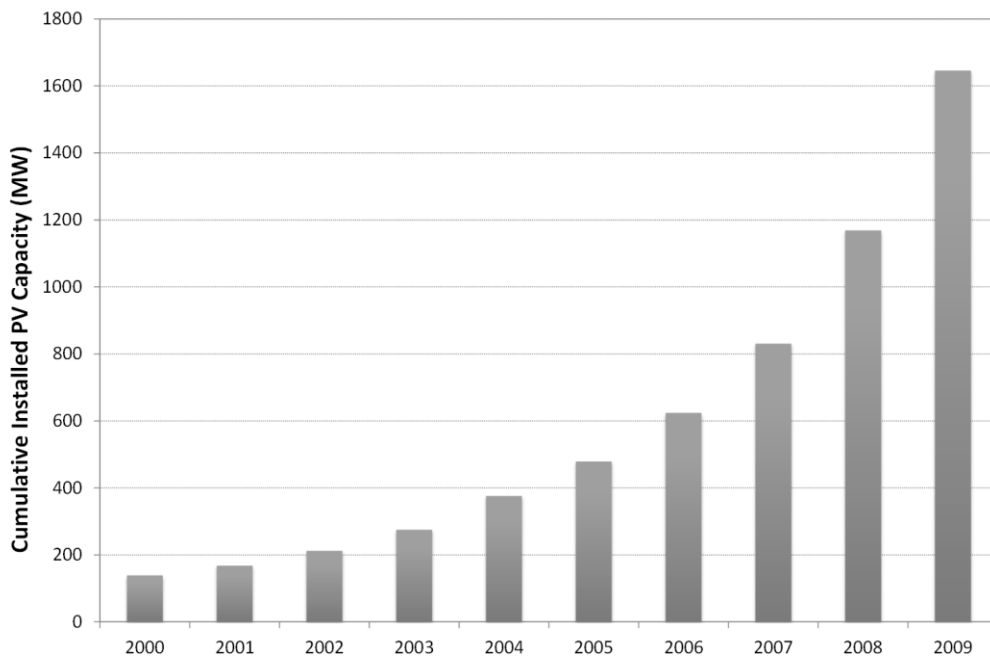


Figure 14 - Growth in cumulative installed PV capacity in the US over the last decade

A summary of the installed capacity and recent installation activity in major states is given in Table 3. California is by far the largest market in the US.

Table 3 - 2008 installed capacity and recent installation sizes in largest US markets

State	Installed Capacity (MW)	2007 installations (MW)	2008 installations (MW)
California	530	92	180
New Jersey	70	16	23
Colorado	36	11	22
Nevada	34	16	15
Arizona	25	2.8	6.4
New York	22	3.8	7

Off-grid cumulative installations were higher than grid connected in 2004, but grid connected has since dominated, and has a 71% share as of 2008. Rooftop installations accounted for an estimated 64% in 2008, with an additional 10% being roof integrated. In 2008 there were nearly 17,000 new residential installations, with only 2,000 being non-residential; however, due to the larger sizes of the commercial systems, 73% of the 0.29 GW of grid connected capacity added in 2008 consisted of commercial installations. There has been an increase in ground mounted systems in the past few years, and high growth is projected for

large PV systems, supported by the utilities need to meet renewable portfolio standards (RPS), and their recent ability to use the federal ITC. Solar resources across the US are mostly good to excellent, with solar radiation in the range of 1000 to 2500kWh/m² per year. Southwest US is at the top of this range, while Alaska and part of Washington are at the low end and mainland US typically receives 1350 - 2500 kWh/m² per year.

2.3.7.1 Incentives

The US has incentive schemes on both the federal and state level. On the federal level, a taxpayer may claim an investment tax credit (ITC) of 30% of eligible expenditures for a system that powers the taxpayer's residence. Expenditures include labour costs for onsite preparation, assembly or original system installation, and for piping or wiring to interconnect a system to the home. If the federal tax credit exceeds tax liability, the excess amount may be carried forward to the succeeding taxable year. The excess credit can be carried forward until 2016²⁷. On the state level large incentive programs offer rebates covering a significant proportion of up-front PV system cost. FiTs offered across the US are summarised below in Table 4 (note prices have been converted to EURO to make them comparable to other FiTs listed).

Table 4 - FiTs across the US

State	Roof-Top	Ground-Based	BIPV	Term
Hawaii	≤20kW 0.1604/kWh >20 kW, ≤500 kW 0.139181/kWh	≤20kW 0.160451/kWh >20 kW, ≤500 kW 0.139181/kWh		20 years
California	0.070	0.070		20 years
Florida Gainesville	<25kW - 0.2133	<25kW - 0.2133 >25kW - 0.1866		20 years
New Jersey	0.23	0.23		20 years
Rhode Island	<30kW 0.46	<30kW 0.46	<30kW 0.50	20 years
Washington	<30kW 0.46 30-100kW 0.44 100kW+ 0.43	0.35	<30kW 0.50 30-100kW 0.48 100kW+ 0.47	20 years

Further information on incentives for PV in the US can be found at the Database of State Incentives for Renewable Energy (DSIRE) website at <http://dsireusa.org>.

2.3.7.2 California

California has by far the largest PV market in the US. There are incentives for an upcoming solar boom in California - there is a need for energy expansion, over 340 days of sunshine per year, and political support needed to encourage PV usage²⁸. The California Solar Initiative (CSI) program was adopted in 2006 to provide more than \$3 billion in incentives for solar-energy projects with the objective of providing 3 GW of solar capacity by 2016. The program provides rebates for PV systems based either on either expected, or actual, performance. Expected performance based buydowns for systems less than 30 kW began in 2007 - 2.50 USD per W AC is paid up-front for residential and commercial installations, and 3.25 USD per W AC is paid for government and non-profit entities²⁷. Higher payments are available for low income residences. Performance-Based incentives for systems 30 kW and larger began in 2007 (smaller systems also have the option of opting for a performance-based incentive rather than the expected performance incentive), at a rate of 0.39 USD/kWh for the first five years for taxable entities, and \$0.50/kWh for the first five years for government entities and nonprofits. The incentive levels decline as the aggregate capacity of PV installations increases. The performance based incentive is paid monthly based on the actual amount of energy produced.

2.3.8 Rest of the World

The PV market is also growing in other areas around the world. China has rapidly become a world leader in PV manufacture, although its local markets remain relatively small, and in 2008 only 2% of PV produced was installed locally. South Korea is also of note, with a cumulative installed capacity of around 360 MW in 2008¹¹. There has also been interest in the PV market recently in South Africa, Brazil and Canada. Ontario, Canada offers particularly attractive rates for PV systems at up to 0.51 € / kWh and could therefore be a region of potential interest.

2.3.9 Trends

The European PV Industry Association (IEA) projects continued strong growth for the PV industry, with annual installations reaching around 30 GW by 2014, assuming a policy driven scenario, as shown in Figure 15. The scenario assumes the follow up and/or introduction of support mechanisms, accompanied by a strong political desire to consider PV as a major power source for coming years¹⁰. Europe is expected to remain the largest market, but the North American market is expected to grow the fastest¹¹.

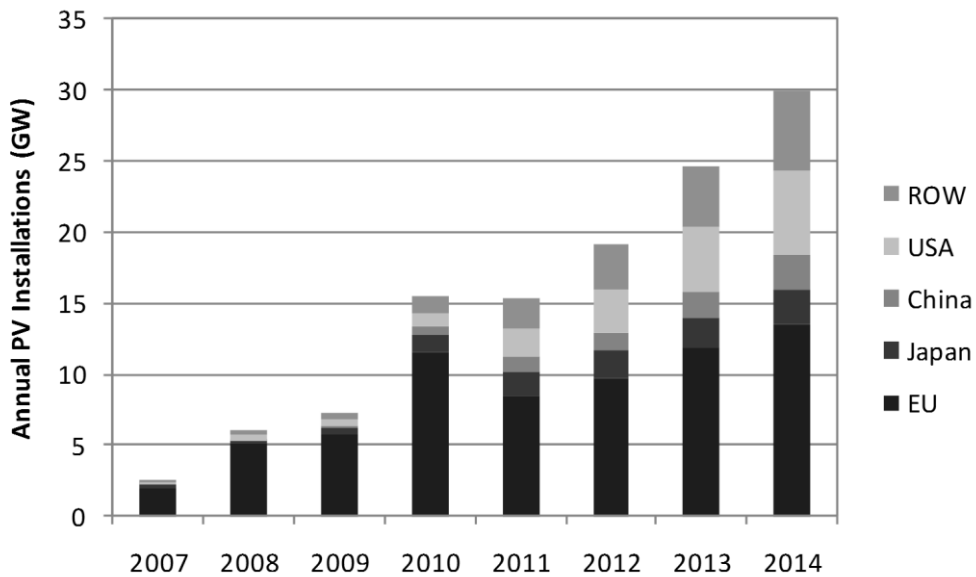


Figure 15 - Projected annual PV installations until 2014 under a policy-driven scenario ¹⁰

2.4 Australasian Metal Roofing Market

This section provides an introduction to the metal roofing market, with focus on Dimond Roofing in New Zealand and Stramit in Australia, both which are divisions of Fletcher Building. The New Zealand and Australian roofing market have a high proportion of metal roofs suitable for the integration of PV technology.

2.4.1 New Zealand and Dimond

NZ has a relatively high ratio of metal roofs which are particularly suitable for the application of low cost roof laminates¹⁴. Residential roofs typically span 5-6m, or up to 8 m on some houses (double if the house is monoslope, however this is not common), and typically have an inclination of 18-23 degrees²⁹.

Dimond Roofing Limited is the largest supplier of metal roofing to the New Zealand market. The main product of Dimond Roofing is long run metal roofing which can be applied residentially, commercially or industrially. Dimond's long run roofing range is made from COLORSTEEL, produced by NZ Steel. COLORSTEEL consists of a steel substrate with a ZINCALUME coating which is available in a variety of colours. ZINCALUME is an alloy composed of 43.5% zinc, 55% aluminium and 1.5% silicon. Both sides are primed with a corrosion inhibitive primer, and then a top coat is applied to the outer surface, and a backer to the reverse side, which is oven cured. Sheets are typically 0.40 mm or 0.55 mm thick, of which 0.55 mm is the most common thickness.

Dimond targets four profiles at the residential roofing market, the most popular of which is corrugate, which has a huge advantage over the second most popular profile, Styleline. Unfortunately, corrugate is not suited to the integration of PV cells due to the shape of the profile, however, with a pan width of 127 mm, Styleline may be an option for BIPV. There is a greater range of commercial profiles available than residential, which can be categorized into low rib, high rib, and concealed fasteners. The low rib profiles may be able to be applied to residential applications. The commercial profiles typically have wider pans than the residential profiles, and therefore may be better suited to the integration of PV cells. Brown Built 900 is the most popular commercial metal roofing profile, however, Dimond's innovative new DP955 profile is taking an increasing market share. Brown Built 900 is not well suited to the integration of cells as it only has 75 mm wide ribs, however DP955 has a large pan at around 239 mm and therefore could be suitable.

2.4.2 Australia and Stramit

Stramit supplies the Australian market with a range of building products including roofing, cladding, purlins and flooring. Stramit distributes approximately two million square metres of metal roofing annually. The split is roughly even between residential and commercial applications (around a million square metres each). Similarly to NZ, corrugate dominates the residential metal roofing market, accounting for approximately 90%. The most popular commercial profile is Speed Deck, which holds approximately 40% of the commercial market in

Australia, which equates to 400,000 m² of roofing per annum. Stramit has identified their Speed Deck Ultra profile as a promising candidate for PV integration, which is mostly targeted at commercial buildings; however, it can also be used domestically³⁰.

Speed Deck Ultra is a concealed fastener profile which is produced by six roll formers throughout Australia. Speed Deck has dimensions favourable to the integration of crystalline silicon solar cells, which are typically 156 mm square, or 125 mm pseudo square. Speed Deck has a trough width of approximately 182 mm - refer to Figure 16 for approximate dimensions. Speed Deck's unique rib design allows adjacent sheets to clip over each other without the need for fasteners. Specially designed Speed Deck clips are screwed to the purlins and the panels are clipped in over top of these.

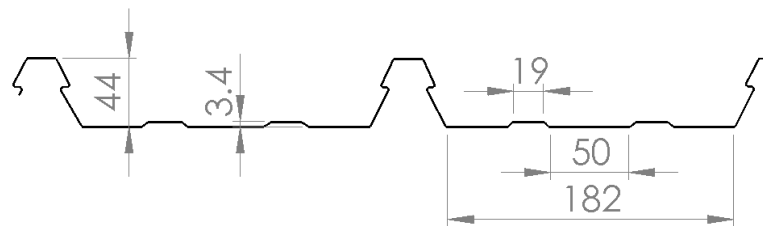


Figure 16 - Speed Deck Ultra Profile (third pan not shown)

Stramit has recently entered a roof lap joint product onto the market called Farlap, as pictured in Figure 17, which negates the need for steps where there are joins in the roofing sheet. It works on a clip in principle, designed specifically for Speed Deck Ultra. The system is installed by clipping the product onto the ribs of the bottom sheet at a purlin, before overlapping the top sheet, which too is clipped into place. The ends of the top sheet are turned down using a special tool. It can be used on roofs with pitches as low as 1°.

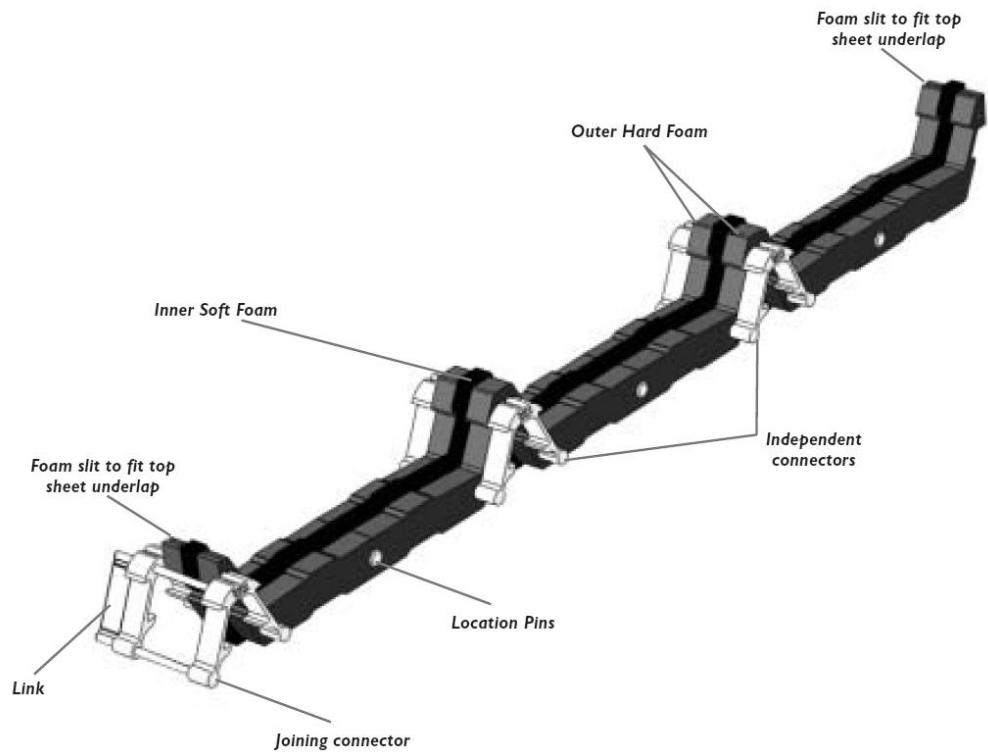


Figure 17 - Farlap roof lap joint system

Figure 18 shows the principle of the Farlap system and the required over and under hangs of the top and bottom Speed Deck sheets. As Farlap separates the top and bottom sheets, a small cavity approximately 20 mm high is formed at the joint.

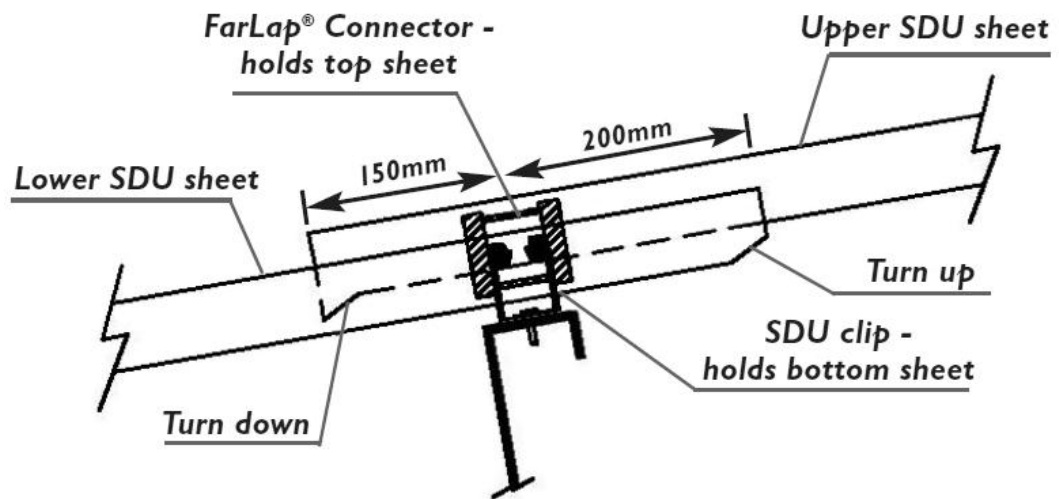


Figure 18 - Recommended over and under lap spans with Farlap

2.5 BIPV Products

This section reviews BIPV products already available on the market. The review is limited to products integrated into roofs, and does not include glass integrated products such as skylights and facades. It does not list every roof integrated PV product available, as there are so many similar products on the market.

2.5.1 Tiles/Slates

A number of companies have PV products on the market which are integrated into roofing tiles/slates, which provide a finish which sits flush with other tiles in the roofline. All such products are quite similar to each other, and as such only a subset of these products will be listed here.

Atlantis Energy Systems markets a product called Sunslate, based on monocrystalline cells to the US, Canada, Asia & Europe. As shown below in Figure 19, it integrates very well into the roof, as the transition to a standard tile is only barely noticeable at the edges of the roof.



Figure 19 - Atlantis Energy Systems Sunslate

Sunpower produces a high efficiency monocrystalline BIPV product called Suntile which integrates with both flat and S-shaped tiles. It is all-black in appearance. It produces 63 W and has 22 cells in series. Dimensions are 59" x 17". It integrates well with flat tiles, however the difference between BIPV and

normal roofing is very noticeable when it is integrated into S-Tiles, as pictured in Figure 20.



Figure 20 - Sunpower's Suntile

SolarCentury is a leading solar energy company who supply both roof mounted and building integrated PV to the European market, including the UK, Spain, France, Portugal and Ireland. Solarcentury have completed over 1000 large installations, and thousands of home installations, as well as 150 installations for schools through the Solar4Schools programme. The total installed capacity at the end of 2008 was about 6 MW. SolarCentury have won a host of awards for their building integrated C21e solar photovoltaic tiles, which uses monocrystalline silicon technology. One solar tile covers the width of four conventional tiles, and they are designed to be installed by the roofing contractor, without the requirement of specialist skills. Adjacent tiles are connected together electrically using push-fit connections. Less than eight square metres is required per kW_p. An example of a C21e installation is shown in Figure 21. The minimum roof pitch is 17.5 degrees when installed with 100mm of head lap.



Figure 21 - Solar Century's C21e roofing slate

2.5.2 Complete roof

Cell manufacturer Suntech offers a PV roof integrated product called Just Roof, designed to form a complete roof which has been installed in over 5000 homes. It uses monocrystalline silicon technology and replaces tiles and other roofing material. Interlocking PV modules are mounted on vertical aluminium rails, which are connected together using plug and play connectors. Just Roof is suitable for roofs with a pitch as low as 5 degrees. Just roof has been used for small and large installations, and has completed a 4.5 MW project in France comprising of five large agricultural warehouse roofs. Figure 22 shows a typical Just Roof installation.



Figure 22 - Suntech's Just Roof

2.5.3 Membrane

There are various products which are ‘integrated’ with membrane roofing, the most noteworthy of which is Lumeta Powerply. Lumeta Powerply utilizes a fiberglass back sheet, EVA encapsulant, and fluoropolymer front sheet. It has a peak power output of approximately 400 W per panel, and has panel dimensions of around 2360 x 1230 x 10 mm. It incorporates 160 x 125 mm monocrystalline silicon cells. An array of Lumeta Powerply modules are pictured in Figure 23.

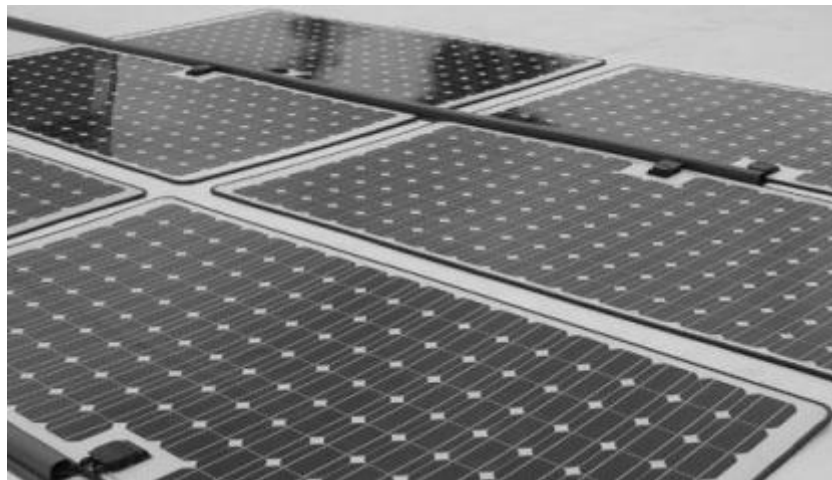


Figure 23 - Lumeta Powerply for flat roofing

2.5.4 Metal Roofing Products

There are numerous companies which provide integrated solutions for standing seam metal roofing, which are based on UNI-SOLAR triple-junction thin-film silicon technology. All of these products are very similar, so can all be categorized together. The cells have been manufactured into a roll, with an adhesive on the underside. The PV cells are attached to the roofing profile using a ‘peel and stick’ action. There are no external frameworks, structures or roof warranty worries due to the solar installation. Due to the width of the laminates, they are only used in standing seam profiles with pan widths of over 400 mm. Listed below are two products using UNI-SOLAR technology.

2.5.4.1 *Calder Stewart*

Calder Stewart Industries Limited is one of New Zealand’s most successful construction companies, with a significant presence in both the commercial and residential sectors. Calder Stewart has recently developed a metal roofing profile

called Solar Rib, which is designed specifically for electricity generation using UNI-SOLAR laminates. Solar Rib has three 52mm high ribs with two wide pans and gives a 1 metre wide cover. It is capable of working down to a 3 degree roof pitch, and can be draped curved to produce architectural roof shapes. Wires are hidden by a specially designed ridge. Solar Rib can generate up to 50 W_p per metre. Fixing the roofing sheets is as per standard using load spreading washers on standard roof purlins. Solar panels can be added straight away during the installation of the roof or in the future.

Installations appear limited, although Calder Stewart has been in recent collaboration with DOC. The product was trialed on a small section of Mintaro Hut, before being installed on Dumpling Hut on the Milford Track, completed in March 2010. Figure 24 shows a photograph of a section of solar rib roofing installed on Dumpling Hut. The company sees DOC as a "huge customer in years to come"³¹.



Figure 24 - Solar rib installation completed in March 2010 on Dumpling Hut on the Milford Track

2.5.4.2 EnergyPeak

EnergyPeak is a distributor of BIPV to the standing seam metal roofing and metal building industries, formed in 2007 by CENTRIA Services Group, in partnership with UNI-SOLAR. EnergyPeak integrates UNI-SOLAR PV laminates with standing seam metal roofs, which are applied in the metal roofing factory. EnergyPeak systems are distributed through roofing manufacturers throughout the US, also having a presence in Canada. EnergyPeak systems come in seven system sizes, and can be fitted to projects ranging from residential to industrial.

Figure 25 shows an example of EnergyPeaks roofing using UNI-SOLAR PV laminates.



Figure 25–EnergyPeak’s metal roofing using UNI-SOLAR PV cells

Other companies using UNI-SOLAR laminates include Thyssenkrupp, American Energy Technologies Inc., and Sun Edison LLC, & Rock Systems and Technologies, just to name a few.

2.6 Conclusions resulting from Market Review

The strongest forces driving the photovoltaic market are government incentives, most importantly FiTs. Currently there are no such incentive programs available in New Zealand, and due to the state of the market, NZ may be better suited as a test market, before the product is introduced internationally. The Australian market would be a good entry point for the product, specifically the commercial market in the A.C.T., and it may be able to take advantage of the national schools program. Further market expansion would see the product being sold in larger markets including the US, and parts of Europe, most notably Germany, Italy and France. The French market is particularly attractive due to the high FiTs for building integrated products.

Since the product is likely to be marketed in Australia, it makes sense to base it on a profile which is already marketed there by Stramit, a division of Fletcher Building, as it would be much more difficult to introduce a new roofing profile into the market. Stramit's Speed Deck Ultra has been identified as a good candidate for the integration of PV.

There are a multitude of companies offering PV products integrated into metal roofing, however these are mostly all based on the same 'peel and stick' technology provided by UNI-SOLAR. These have a questionable level of integration into the roof, however will be the main competitors for the BIPV product.

Chapter 3: Review of Solar Technologies

3.1 Introduction

The previous chapter outlined the potential for the BIPV product to be accepted into the current market. This chapter reviews current photovoltaic technologies and materials in order to provide an insight into the underlying technical knowledge which is essential to design such a product.

PV modules typically consist of a front sheet, an encapsulant which surrounds and protects the cells, and bonds the module together, and a back sheet. Most have frames and an edge sealant; however some frameless modules are available. Firstly, different solar cell technologies are reviewed, categorised by generation. The following section then outlines the range of different materials used in module construction. An overview of module encapsulation and failure mechanisms is provided before conclusions are presented.

3.2 Solar Cells

Solar cells generate electric current when exposed to light and form the basis of photovoltaic modules. Solar cells can be categorized by generation:

- First generation: crystalline silicon cells
- Second generation: thin film solar cells (CIGS, CdTe, Si)
- Third generation: Dye sensitised cells, nano-technology, polymer cells

Crystalline silicon technology is by far the most dominant, with a market share of around 90% in 2007. The remainder of the market is held by thin film solar cells (TFSCs), with a negligible contribution by third generation technologies. Refer to Figure 26 for how the technology share was distributed in 2007. TFSC has since risen to 18% of production in 2009⁹.

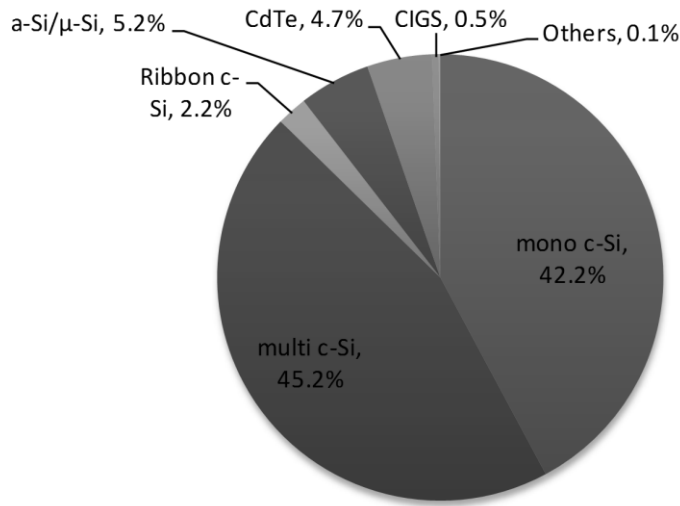


Figure 26 - Market share of solar cell technologies, 2007¹⁰

3.2.1 Principle of Semiconductor Solar Cell Operation

In 1839 Becquerel observed that certain materials, when exposed to light, produced an electric current. This is known as the photovoltaic effect, and is the basis of the operation of photovoltaic cells. Most solar cells are manufactured from semiconductor materials; and by far the most common material used is silicon. In semiconductors electrons are confined to specific bands of energy, and forbidden from occupying other regions in between. The valence band (VB) is the highest range of electron energies where electrons are normally present. The conduction band (CB) is the range of electron energies higher than the VB, in which electrons are free to move about the crystal lattice. The energy difference between the valence and conduction bands is termed the band gap, and represents the energy required to free an electron from the atom. It is possible to ‘promote’ an electron from the VB to the CB, which can then produce a current. When photons of higher energy than the bandgap strike the semiconductor, electrons are promoted to the conduction band. Refer to Figure 27 for a schematic of the principle.

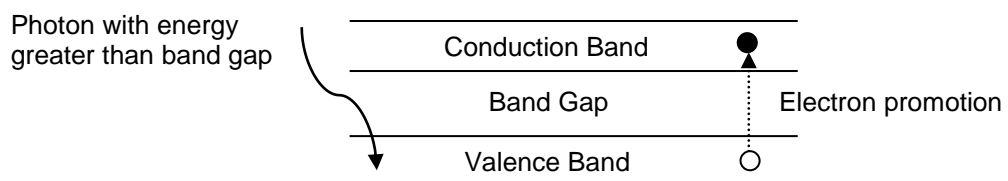


Figure 27 - Principle of photon absorption and electron promotion in semiconductors

When an electron is promoted to the conduction band, it leaves a hole behind. The hole can be filled by bonded electrons of neighbouring atoms, and the hole can propagate through the lattice. The electrons in the conduction band can flow through an external load, creating electricity, although it is much more energetically favourable for the electrons to recombine with a hole within the material. To overcome this, semiconductors are doped with impurities in small quantities, which create an excess of electrons in one side (n-type) and an excess of holes in the other (p-type). Where these two meet, a p-n junction with an electric field is formed, which causes current to flow readily in one direction only. An external circuit can then be connected through which the electrons flow from the n-type material, which recombine with holes in the p-type layer after flowing through the load.

3.2.2 First Generation

The first generation of solar cells is based on crystalline silicon (c-Si) wafers, and is by far the most widely used solar cell technology. The dominance of crystalline silicon in the PV market is mainly due to the already established scientific and technological silicon based infrastructure of the electronics industry, which the PV industry has been able to utilise. Cells of around 200 μm thickness are sawn from either a single crystal ingot or a polycrystalline casting in a wasteful process where about 50% of the material is lost. This contributes to a high wafer cost, which makes up more than 50% of the module cost³². Silicon is typically doped with boron to create the p-type layer, and phosphorous to create the n-type layer.

Crystalline silicon solar cells are the most reliable and efficient in use today, although they exhibit a drop in efficiency with rising temperature (approximately -0.5% per K) and cloud cover. Bare silicon by itself reflects around 40% of incoming light³³, therefore to minimise losses due to reflection, anti-reflection coatings, and surface texturing are commonly applied.

3.2.2.1 Mono-crystalline Silicon

Mono-crystalline silicon cells (mc-Si) have an ordered crystal structure, and achieve higher commercial cell efficiencies than alternative technologies, in the range of 16-22%¹². Commercial mc-Si cells are cut from single crystals grown

using the Czochralski (Cz) method. Feedstock material, polycrystalline silicon pieces or residues from single crystals, are melted in a crucible in a vacuum chamber, and a seed crystal is dipped into the melt. The seed is slowly withdrawn vertically to the melt surface where the liquid crystallizes at the seed to form a single crystal ingot. The Cz process is commonly used for commercial cells, although it has several disadvantages for high efficiency laboratory or niche market solar cells, for which Float Zone (FZ) wafers are used instead. FZ crystals do not contain the same impurities as Cz grown crystals, as the process moves a liquid zone through the material, in which the impurities stay, and do not join into the solid crystal. The FZ growth process however, requires an expensive form of silicon feedstock material that brings the price of a FZ wafer far above the acceptable range for the PV industry.

3.2.2.2 Polycrystalline

Polycrystalline Silicon (pc-Si) cells typically achieve lower efficiencies than mc-Si cells, with commercial efficiencies in the range of 14-16%. The lower efficiency is attributed to the introduction of extra recombination sites at the grain boundaries, dislocations and impurity atoms. Wafer cost is reduced compared to mc-Si cells due to the lower manufacturing cost, higher feedstock tolerance, and faster crystal growth³². Bridgman is the most popular casting process, followed by block casting. Bridgman uses one crucible for melting and crystallization, while block casting uses a second crucible for crystallization. Bridgman achieves temperature reduction by descending the crucible containing the liquid silicon out of the hot area of the crystallisation furnace. Temperature control in block casting is controlled by adjustment of the heaters, the crucible itself does not move during solidification.

3.2.2.3 Ribbon Technology

Ribbon growth techniques which avoid the material loss associated with the sawing step and costly wafer process have been developed in an attempt to produce cheaper solar cells. Thin sheets of silicon are pulled from the crystalline melt, or silicon powder is melted into a substrate, which produces a cell of similar quality and efficiency as a pc-Si product. These are similar in efficiency to

polycrystalline silicon cells, and typically have efficiencies around 14%. They have a small share of the market, holding only 2.2% in 2007.

3.2.3 Second Generation

Second generation PV cells are based on thin film technologies, and are receiving increased interest which is projected to continue in the coming years. Thin film solutions are being developed to address the issues associated with the costly crystalline silicon wafer process, and are typically 1-3 μm in thickness, which is around 100 times thinner than c-Si technology. Lower efficiencies are achieved with thin film solar cells and the technology has a much less developed knowledge and technology base when compared to c-Si. Despite achieving lower efficiencies than c-Si, they perform better than crystalline silicon under low irradiation, and show around half of the thermal deterioration in performance¹². Thin-film technology drastically reduces the material and energy used in manufacturing and this will allow PV solar energy to become economically viable in a few years. Particular care must be taken with edge sealing of thin film modules since all thin films are badly affected by the ingress of moisture. In the manufacturing process, a clear gap must be left around the edge of the cell for proper sealing of the module³⁴. The three leading thin-film PV solutions are:

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Diselenide (CIGS)

3.2.3.1 Silicon Based

Several silicon-based thin film technologies exist, the most popular of these is by far amorphous silicon. Other technologies based on small grained c-Si are also available, however these are nowhere near as widely used.

3.2.3.1.1 Amorphous Silicon

Unlike crystalline materials, amorphous silicon (a-Si) has no long range order in the atomic structure. The development of amorphous silicon TFSCs spawned from the realisation that, in principle, high efficiencies could be obtained from silicon films of only a micron or so thickness³⁵. a-Si cells have been used in

consumer products such as calculators and wristwatches since the early 1980s³⁶. Amorphous silicon has a bandgap of approximately 1.7 eV.

Hydrogenated amorphous silicon deposited by plasma enhanced chemical vapour deposition (PECVD) is the baseline of a-Si technology. The anatomy of a typical a-Si cell is pictured in Figure 28. The manufacturing process can be summarised as follows³⁷:

1. Deposition of front transparent conducting oxide (TCO) layer onto a substrate (typically glass)
2. Initial set of parallel scribes to define individual solar cells
3. Deposition of three semiconductor layers
4. Second set of parallel scribes which expose the buried TCO layer.
5. Blanket deposition of the rear electrode (rear TCO plus metal)
6. A third set of parallel scribes cuts through the rear electrode and the semiconductor layers, removing the shunting path for the current flow and leading to the series connection of all solar cells on the glass.

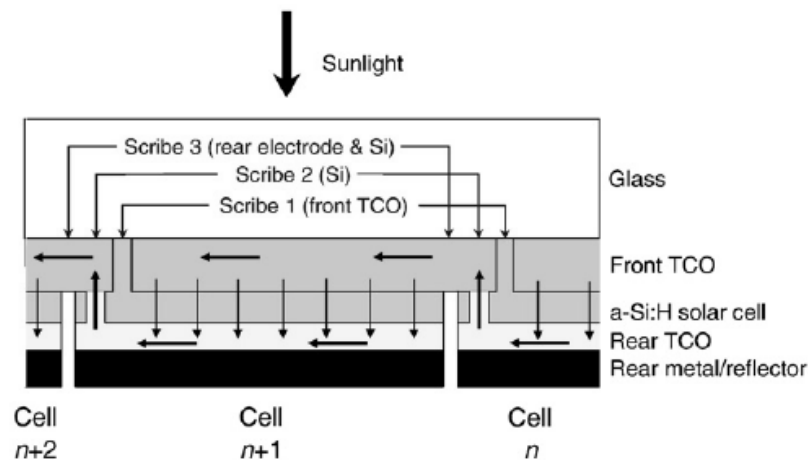


Figure 28 - Anatomy of a-Si cell³⁷

a-Si possesses several properties favourable for low-cost PV, including a high optical absorption coefficient (enabling very thin absorber thicknesses of 300 nm or less), large-area silicon diode deposition at low temperature (~200 °C) onto rigid or flexible substrates, and monolithic series interconnection of the individual cells. a-Si technology is able to utilise large scale, high-volume PECVD silicon deposition systems which have been developed for liquid crystal displays³⁷. The main reason why the technology is not dominant is that they have a lower

efficiency than crystalline silicon cells, in the range of 6-8%¹². a-Si cells initially undergo light induced degradation of the module efficiency over time until a stable module efficiency, known as the Staebler-Wronski effect. Growth of technology is also restrained due to manufacturing issues associated with processing large substrates, including spatial non-uniformities in the Si film and the TCO layer³⁷.

3.2.3.1.2 Microcrystalline

When silicon is deposited into a thin film using very high frequency (VHF) PECVD, a PV cell consisting of both amorphous and microcrystalline regions can be produced. Its optical bandgap energy is around 1.0 eV³⁷. By the end of the 1990s stable efficiencies of up to 8.5% had been reached, however, single junction PV cells do not seem to be commercially viable at present. This is due to the low deposition rate of the silicon film and technical difficulties with the development of industrial-scale VHF PECVD systems.

The importance of μ c-Si PV cells is increased if they are coupled with a-Si cells to form a two layer cell, in which the a-Si cell faces the sun. The tandem cell utilises the solar spectrum more effectively, as the two layers of the cell have a large difference in bandgap energy. Stable efficiencies of about 10% are expected for large-area mass-produced modules using low temperature processing equipment from the LCD industry. The two main issues with these tandem cells is the requirement of a textured TCO layer between the a-Si and μ c-Si layers, and the high capital cost of deposition tooling for the μ c-Si layer³⁷.

3.2.3.1.3 Polycrystalline

Development of polycrystalline thin films, also known as crystalline silicon on glass (CSG), began in the late 1980s to address fundamental difficulties associated with the traditional thin-films, including issues with stability, complexity, resource availability, and toxicity³⁸. Silicon nitride and three layers of differently doped amorphous silicon are deposited onto a textured glass substrate, followed by a capping layer of silicon oxide³⁹. The silicon is then crystallised at around 600C in a batch oven, sliced into a series of strips using a pulsed laser, and coated with a reflective resin³⁷. Aluminium is deposited over the entire rear device

surface and is patterned joining the n+ to the p+ of the adjacent cell³⁹. Figure 29 shows the construction of a CSG module (texturing omitted for clarity).

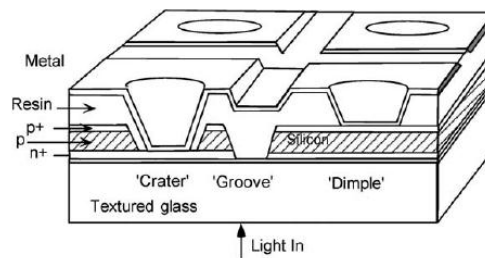


Figure 29 - Key features of CSG technology³⁹

Unlike other thin-films, the silicon layer is of high enough quality to allow lateral current conduction. This means that no TCO layer is required, which is associated with cost and durability issues. The textured glass surface and rear reflector provide a high absorption of light, which allows the use of a silicon layer which is thinner than the active layer in all traditional TFSCs³⁹. In mid-2007 the module efficiencies were in the 6–7% range and were improving steadily³⁷. CSG manufacture has benefited from equipment development within the microelectronics industry, particularly true for the silicon deposition step³⁹. CSG delivers a high level of durability by avoiding common failure modes in traditional modules such as wafer breakage, fatigue of the metal interconnect strips joining the cells, discolouring or delaminating of encapsulants, or degradation of the solder joints between interconnects.

3.2.3.2 Copper-indium-gallium-diselenide (CIGS)

CIGS modules are fabricated in the substrate configuration, i.e. from back to front. In this case there is no need for a transparent supporting material, giving flexibility with respect to the choice of the substrate. While flexible substrates are available, the standard substrate is soda-lime glass due to its availability, cost effectiveness, and the enhancement of the doping concentration in the CIGS absorber layer by sodium atoms that diffuse from the substrate into the CIGS layer during the module fabrication process. The process starts with the deposition of a thin molybdenum (Mo) film onto a glass substrate which is then scribed. A polycrystalline CIGS absorber film is then deposited. A slight natural non-stoichiometry automatically produces the desired p-type and n-type doping of

the CdS layer. A heterojunction is formed by adding a layer of n-type CdS, and the semiconductor layers are then scribed. A TCO layer is deposited, which is then too scribed. Figure 30 shows the layers of a CIGS cell (scribing not shown).

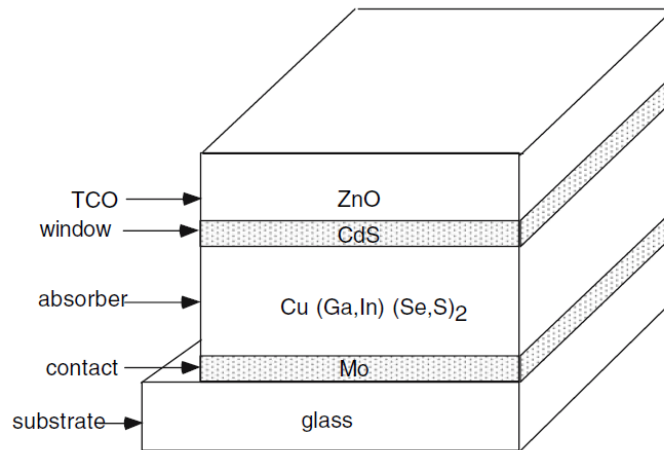


Figure 30 - Anatomy of a typical CIGS solar cell³⁶

CIGS cells are the most efficient of the commercially available thin film cells, with efficiencies typically in the range of 7-11%. CIGS cells demonstrate excellent long term stability in outdoor testing³², and high radiation resistance compared to crystalline solar cells. Being a direct bandgap material, CIGS has very strong light absorption and only 1-2 micrometers of CIGS is enough to absorb most of the sunlight. There are issues associated with CIGS cells, including the complexity of the CIGS layer, and also the scarcity of indium; estimates of reserves suggest there is only enough material for the production of a few GW of CIGS PV modules³⁷.

3.2.3.3 Cadmium Telluride

Cadmium telluride (CdTe) PV modules are fabricated in the superstrate configuration. CdTe modules are manufactured as follows:

1. A TCO layer is deposited onto a planar soda lime glass sheet and scribed.
2. A CdS window layer is deposited
3. A CdTe absorber layer is deposited
4. A second set of scribes then patterns the CdS/CdTe layers followed by the formation of the back contact and the third set of scribes. A slight natural non-stoichiometry automatically produces the desired p-type doping of the

CdTe layer and the n-type doping of the CdS layer. The anatomy of a typical CdTe cell is pictured in Figure 31.

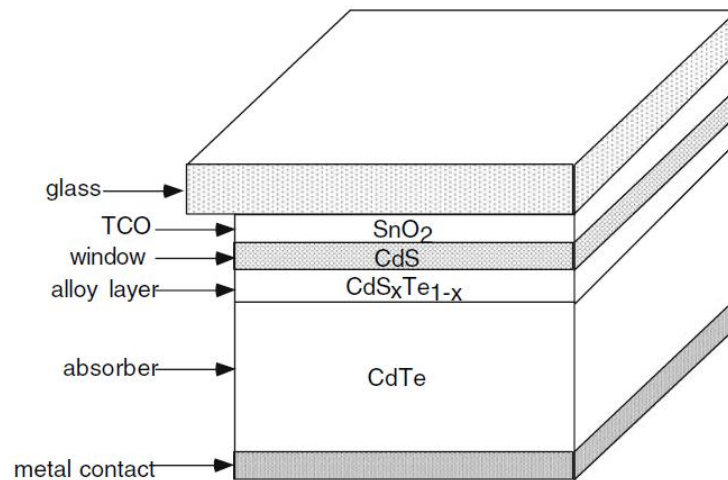


Figure 31 - Anatomy of a typical CdTe solar cell³⁶

CdTe has a bandgap very near the optimum for solar energy conversion efficiency, making it ideal for single junction solar cells. It typically has commercial efficiencies in the range of 8-10%¹². The main technical issue of the CdTe technology is related to the back contact. The relatively light p-type doping of the CdTe layer complicates the realisation of a low-resistance, long-term-stable back contact. However, the main issue with CdTe cells is related to toxicity of Cd - it is questionable whether Cd based modules are sufficiently benign environmentally to justify their use over less toxic PV alternatives. Despite their toxicity, they are currently the most 'eco-friendly' devices, as they require the least amount of energy to manufacture. Also, tellurium is a very scarce element, and it is estimated that PV module production is limited to a few GW per year³⁷.

3.2.4 Third Generation

Several novel concepts belonging to the third generation of PV are under investigation, which operate on different principles to traditional semiconductor PV cells. Third generation cells currently only possess a very small proportion of the market, with a share of only 0.1% in 2007, however, they are expected to account for a significant part of the market in the long term. 3G technologies

include dye-sensitised solar cells, which are already finding use in BIPV applications, organic cells and nano-technology.

3.2.4.1 Dye-Sensitised Solar Cell

Dye-sensitised solar cells (DSSC) operate on a principle comparable to photosynthesis. A dye is excited when exposed to light, which causes an electron to be injected into the conduction band of a mesoporous oxide semiconductor (typically TiO₂). The dye is restored to its original state by accepting an electron from the electrolyte, which itself is regenerated at the counter electrode by electrons which have passed through the load. Figure 32 shows a diagram of the principle of operation of a DSSC by Grätzel, 2003.

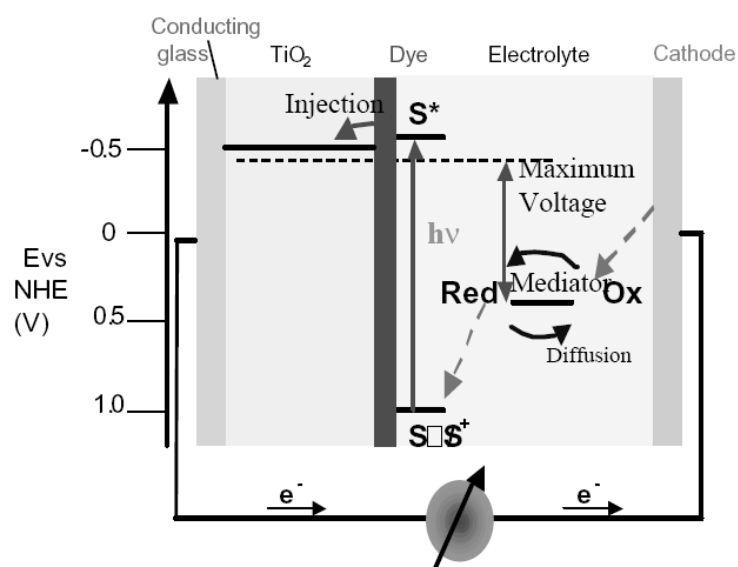


Figure 32 - Principle of operation of DSSC by Grätzel, 2003

DSSCs can be made to be transparent, colourful, and flexible, which makes them promising for building integrated applications⁴⁰. The cost of DSSCs is around 1/3 to 1/5 the cost of silicon solar cells, as high temperature treatment, advanced equipment, high vacuum, and materials of high purity are not required⁴⁰. Commercial DSSCs achieve efficiencies of about 5%, although lab efficiencies of 11% have been achieved. DSSCs work well under low light conditions, although they degrade when exposed to UV radiation. There are issues associated with the manufacture of such cells - the current electrolyte used achieves high efficiency but reacts with sealing materials, is toxic, and can lead to desorption of the dye.

As such DSSCs still require a great deal of research before they will be able to gain a considerable market share.

3.2.4.2 Polymer

Polymer PVs, also known as plastic solar cells, are based on a pair of electron donor and acceptor materials, rather than semiconductor p-n junctions. They typically consist of fullerene molecules embedded into a conjugated polymer conductor. The photoactive polymer is excited by photons and the electron is transferred to the fullerene due to its higher electron affinity. After exciton dissociation, the electron and hole must be collected at contacts. The disadvantages of polymer solar cells are that they offer low efficiencies, not yet high enough for commercial applications (approaching 5%), and they are relatively unstable toward photochemical degradation⁴¹.

3.2.4.3 Quantum Dots

A novel solar cell technology based on nano-crystals, known as quantum dots (QDs), is currently under development, which shows promise of providing a low cost, high efficiency alternative to traditional technologies. QDs have demonstrated the potential to achieve higher efficiencies than the accepted maximum efficiency of about 31% for the conversion of unconcentrated solar irradiance into electrical free energy. The limiting efficiency is mainly due to:

1. the absorption of photons of higher energy than the band gap results in loss of energy, as the excess is converted into heat, and;
2. photons of less energy than the bandgap are not absorbed.

It has been observed in various materials (PbSe, PbS, PbTe, and CdSe) that the formation of two or more electron-hole pairs per absorbed photon becomes very efficient in QDs. This means that the excess energy held by highly energetic photons is no longer wasted as heat, but can contribute to producing a higher current. It has also been proposed that QDs could allow the absorption of sub-bandgap photons through the introduction of an intermediate band (IB) within the bandgap. The IB could enable a 2-stage promotion of electrons to the CB - low energy photons first excite electrons from the VB to the IB, and after absorbing another sub bandgap photon, the IB electrons are further excited to the CB⁴².

Up to 3 excitons per photon have been observed in PbSe QDs at photon energies greater than four times the bandgap, and 7 excitons per photon have been reported for excitation at eight times the bandgap. Partial effects of the IB principle have been demonstrated (production of photocurrent for sub-bandgap photons and existence of a quasi-Fermi level split), however, improved photocurrents have been created without associated voltage degradation.

3.2.5 Prices

TFSCs have recently become the cheaper alternative to traditional crystalline products in terms of price per peak Watt, although the higher availability of c-Si has resulted in much faster adoption rates of c-Si for BIPV applications¹². Table 5 shows that first generation technologies were in the 2-4 USD per Wp range in 2007, while second generation are around 1-2.50 USD per Wp, with CdTe being the cheapest technology available.

Table 5 - Estimated manufacturing & module costs in 2008⁴⁴

Cell Type	Manufacturing Cost (US \$/Wp)	Module Cost
Mono crystalline	2.24	3.83
Multi crystalline	2.12	3.43
a-si	1.80	3
CdTe	1.25	2.51
CIGS	1.26	2.81
3 rd Gen	-	-

In 2009, crystalline silicon prices dropped dramatically, by approximately 38%⁹. As of July 2010, there are now 518 solar module prices below 4.00 USD per watt or 36.4% of the total survey, performed by Solarbuzz. The lowest retail price for a multicrystalline silicon solar module is \$1.74/Wp from a US retailer, and the lowest retail price for a monocrystalline silicon module is \$1.94/W, from a German retailer. The lowest thin film module price is at \$1.07 per Watt from a US-based retailer⁹. Figure 33 shows how the price of crystalline silicon modules has changed since 1989.



Figure 33 - c-Si module cost since 1989⁴³

3.2.6 Trends

Figure 34 shows how the technology share of the PV market is expected to change until the year 2030. Thin-film modules are expected to increase in market share rapidly in the next few years¹², however, 1G technologies have long dominated the PV market, and will continue to do so for years to come. There is unlikely to be a technology ‘winner’, the market will continue to support multiple technologies. By the year 2030 it is expected that all three generations of technologies will have a similar market share.

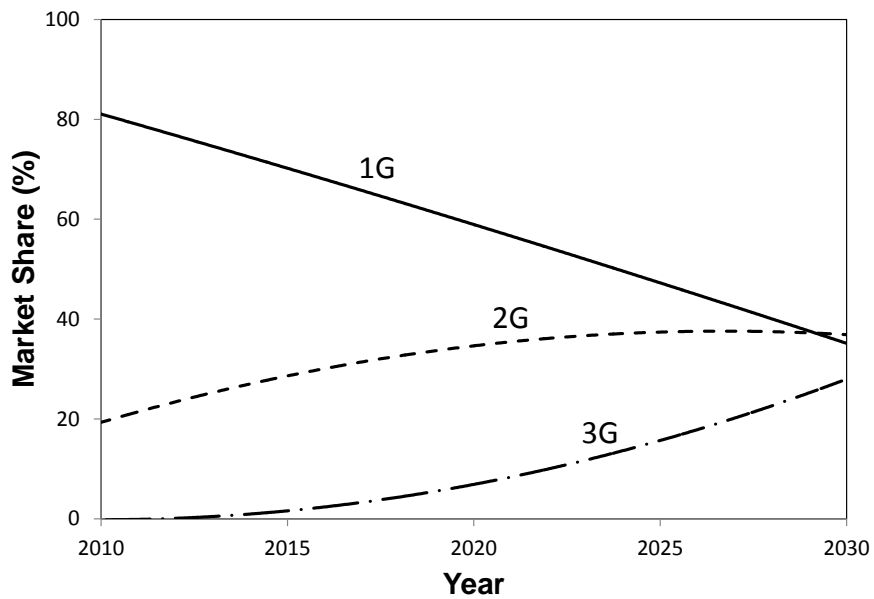


Figure 34 - Projected technology market shares until 2030

Figure 35 shows how the efficiencies and cost of the three generations of solar cells are expected to vary between now and the long term. Currently, first generation technologies are the most efficient; however, Si thin-films are expected to approach these efficiencies in the long term. Thin film technologies are expected to maintain their lower cost over 1G into the long term. 3G technologies (excluding QDs) are low efficiency, but will be expected to be far cheaper than alternatives in the future.

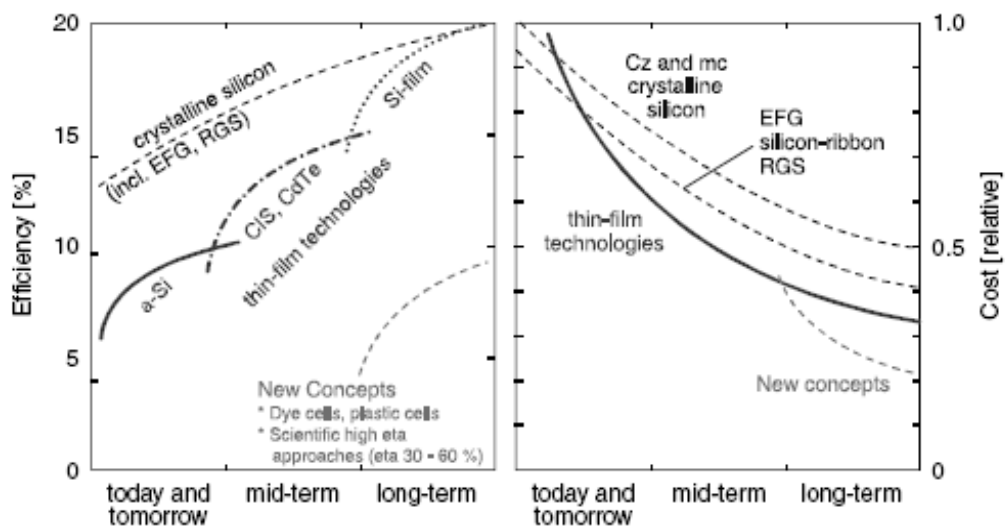


Figure 35 - Technology road map

3.2.7 Selection of PV Cell

A summary of the associated advantages and disadvantages of the different types of photovoltaic cells is presented in Table 6, so that a selection of the most appropriate technology can be made. 3G technologies are still in an early stage of development, and will therefore not be suitable for the BIPV application, although are likely to become the most viable option in the long term. DSSCs are already in use, mainly in BIPV applications, and in the long term are expected to take a significant share of the market due to their low cost nature, and comparatively simple manufacturing processes.

Table 6 - Summary of PV cell technologies

Cell Type	Cell Efficiency (%)	Pros	Cons
Mono crystalline	16-22	Highest Efficiency Best researched technology	Lengthy production process Wafer sawing necessary Expensive
Multi crystalline	14-16	Good Efficiency	Cheaper than mono Wafer sawing necessary Most important production procedure for next ten years
TFSC	6-11	Higher performance under diffuse conditions Continuous processing is possible	
a-si	6-8		Degradation in performance over time Low efficiency Shorter lifespan
CdTe	8-10	Currently lowest cost	Toxicity of Cd Scarcity of Te
CIGS	7-11	Highest efficiency of thin films More stable efficiency	More complex than other TFSCs Scarcity of Indium
3 rd Gen	~3-5	High cost reduction potential	Not well established Low efficiencies for polymer and DSSCs

When choosing between 1G and 2G technologies, it must be taken into account that the apparent large gap in the efficiencies of crystalline and TFSC is misleading. This is because the efficiencies are measured under conditions of 1000 W/m² and 25 °C, whereas average radiation on earth is around 170 W/m², and the temperature of the cells typically largely exceeds 25 °C. The performance of crystalline silicon cells decrease with rising temperature and a cloudy sky, where TFSCs generally perform better under low irradiation, and show less than half of the thermal deterioration in performance. On projects with less than optimal positioning, specifically near flat roofs as commonly found with long run metal roofing, thin film solutions become more attractive. However, c-Si products can be expected to last longer which is desirable for metal roofs which typically have lifetimes of around 40 years or longer.

c-Si cells are generally perceived of being of higher quality, which is desirable for the specialised BIPV product. c-Si is more of a commodity, with little differentiation between manufacturers when compared to TFSC solutions, and is therefore more widely available. c-Si would provide product differentiation in the market compared to other metal roofing BIPV products, as other metal roofing BIPV products all appear to use TFSCs, specifically UNI-SOLAR a-Si cells. Additionally, crystalline silicon becomes favourable when compared to TFSCs in terms of efficiency, as for the same peak powers, it is typical to expect a doubling in area for TFSCs when compared to c-Si. A smaller area required by c-Si cells reduces the size of the system, and therefore minimises the installation cost. It is recommended that mc-Si cells be integrated into the BIPV product, however pc-Si will also be suitable.

3.3 Module Materials

There are several layers of materials which go into constructing a PV module, each serving their own purpose.

- **Back sheet:** provides mechanical support and moisture barrier
- **Encapsulant:** protects and cushions cells and electrical components and allows light to reach cell
- **Front sheet:** provides a high protective top layer to stop accumulation of dirt and grime and to protect from the environment, allows a high proportion of light to reach cell

In addition to these laminate layers, other main components typically included in PV module design include edge seals for stopping moisture intrusion through the encapsulant, and junction boxes and bypass diodes for ensuring safe electrical operation.

3.3.1 Front Sheet

The front sheet must be able to transmit a high proportion of light, have a low permeability to water, and be UV resistant. By far the most common material for the front sheet of both crystalline silicon and thin film PV modules is glass.

Polymer alternatives are growing in popularity in applications where lightweight or flexible modules are required.

Glass is impermeable, which is a desirable attribute, as moisture intrusion is the main method of module failure. The light transmittance of low iron solar glass is typically around 92%⁴⁵. As PV cells are the most expensive component, glass used in the front sheet of PV modules must have a low-iron content, to provide maximum light transmission, and hence maximum power generation. Crystalline modules typically use 3 mm thick low-iron glass (most thin film uses 3 mm glass on the front AND back of the module). Glass used in PV modules must be tempered, since the central areas of the module become hotter than areas near the frame. There are several disadvantages with integrating glass into the BIPV product, some of which are:

- Glass is not easily worked
- It is heavy
- Glass is easily chipped
- It bows during tempering (around 2 mm per metre), and is difficult to produce flat sheets, especially if they are long and thin.

Fluoropolymer films are gaining popularity as the material for front sheets in PV modules as a substitute for glass. They are rugged, clear thermoplastics that can be made very thin, and are typically produced in the range of 13 to 127 μm ⁴⁶. Due to the thin nature of the film, these dissipate heat faster than glass. Fluoropolymer films transmit more light than low iron glass, at around 95%⁴⁶

- Very lightweight
- Non-fragile
- Flexible
- Higher transmittance than glass -> higher output
- Very little degradation over time
- Safe to handle (No sharp edges)

Fluoropolymer films exhibit slightly different properties depending on the chemical composition of the film. The most commonly used polymer is ETFE,

however others are available, including FEP. Various manufacturers produce fluoropolymer films for use as photovoltaic front sheets, the major players being DuPont and Saint Gobain. There are significant weight savings to be achieved by choosing Fluoropolymer films over glass - a Teflon film front sheet on a typical 1600 mm x 800 mm module weighs less than 150 grams, while the same glass front sheet would weigh around 10 kg. DuPont markets ETFE front sheet materials under the brand name Teflon (also sold under the Tefzel trademark), which cost in the region of 10 USD per square metre⁴⁷. Dupont has been producing a front sheet based on FEP which outperforms ETFE in several areas, including an increased light transmittance, resulting in an increase of approximately 5% more power output by the PV module. However, this product is set to be discontinued in the near future⁴⁸. ETFE has an excellent adhesion to EVA, with testing by DuPont showing cohesive failure in the EVA, rather than adhesive failure between films.

Polycarbonate (PC) has been proven to be a viable option for the front sheet of photovoltaic modules. However, lamination using PC requires low temperature cure EVA, and there are difficulties associated with the buckling of the PC sheet⁴⁹. Such front sheets can provide a decent level of impact resistance.

3.3.2 Back Sheet

The back sheet must meet the following requirements:

- vapour barrier
- physical protection of wiring and other components
- electrical insulation
- reduction of cell temperature
- UV resistant

By far the most commonly used material for PV back sheets in c-Si modules is TPT, which is a tri-laminate of Tedlar/PET/Tedlar. A typical Tedlar backsheet consists of a 1.5 mil Tedlar PVF film laminated to each side of a 3 mil sheet of PET film. Tedlar is made from PVF, and has high toughness and durability, with

over a 25 year lifetime under outdoor exposure. A roll of Tedlar film is shown below in Figure 36.



Figure 36 - Tedlar film by Dupont

Tedlar has a high UV resistance, and is a good barrier to moisture. It is UL recognized, and is inert toward a wide variety of chemicals, solvents, and staining agents. Numerous other formulations for back sheets exist, based on Tedlar, including:

- TPE: Tedlar/PET/EVA
- TAPE: Includes aluminium
- TAT: Tedlar/aluminium foil/Tedlar
- TPAT: Tedlar/PET/aluminium foil/Tedlar
- TPOT: Tedlar/PET/oxide/Tedlar

PET is attractive for PV module packaging applications because of its good mechanical properties and low cost. However, uncoated PET exhibits high permeability. Aclar film (PCTFE) has excellent moisture barrier and chemical stability. It is transparent, chemical-resistant, nonflammable, and does not need plasticizers or stabilizers. PCTFE has desirable moisture-barrier properties, but is very costly⁵¹.

Metal is another option for the substrate. The most common metal used as PV back sheets is aluminium. Aluminium has a high thermal conductivity, meaning the module will be able to dissipate heat quickly. It is easily formable into

different shapes and it is easily extruded into a variety of shapes. Stainless steel has been successfully used to create a prototype at the University of Waikato, in conjunction with a polymer top sheet, however it has exhibited a degree of lamination at the corners. It is not a favourable material, as it can be quite expensive, and has a much lower thermal conductivity than aluminium. COLORSTEEL has been proposed as a new back sheet for this application, and could possibly even serve as the roof surface for an integrated solution. The thermal conductivity of COLORSTEEL is not as high as aluminium, however it would be beneficial to utilize this cheap product which is the basis of Dimond's metal roofing range. Using the same material as the roof means there are not issues with the differences in thermal expansion between materials, and corrosion will not occur as may be encountered with different metals.

Some products use fibreglass as the backsheet, which can even come as fibreglass-EVA prelaminate from some suppliers, including Etimex. There are limitations using plastics, as they have to be able to withstand lamination temperatures of 150-160 degrees. However, there are certain plastics which show these properties, although higher temperature plastics are more expensive.

Ethylene propylene diene monomer (EPDM) based polymers formulated for specific use as a combined back sheet and rear encapsulant have recently been investigated⁵². They have been shown to outperform standard materials while coming at a lower cost. EPDM formulations are advantageous because they can use the same lamination/cure cycle as EVA, they do not need a second back-sheet protective material (e.g. PET/Tedlar), they have a lower glass transition temperature, no melting transition, more constant mechanical moduli as a function of temperature, they are less polar than EVA (provides better corrosion protection), and they have excellent damp heat resistance against delamination. Module designs typically use EVA on the back side of cells despite the fact that transparency is not advantageous. Because a single low-cost material layer is used, it will provide a significant materials cost savings of about \$6 to \$8/m² as compared to traditional back sheets⁵².

3.3.3 Encapsulant

The encapsulant protects the cells and bonds components of the module together. To ensure module durability and long-term power generation, the cell encapsulation material must meet the following criteria:

- Mechanical protection of the cell (impact resistance, barrier to oxygen and water, etc)
- Electrical insulation (dielectric strength and volume resistivity)
- Prevention of cell corrosion
- Adhesion to other module components - front sheet, back sheet, cell and contacts
- High transparency and high UV protection

The most commonly used encapsulant is by far Ethylene-Vinyl-Acetate (EVA), followed by Polyvinyl-Butyral (PVB). Silicones, thermoplastic polyurethanes (TPU) and ionomers are among other less widely used encapsulants. The reasons for the low market shares of other plastics are lack of experience with the products of the solar industry, in some cases their inadequate technical properties and their excessively high cost

EVA is by far the most widely used encapsulant, which is sold in rolls of extruded film around 0.5 mm thick, and typically available in 0.3 to 1 mm thickness. EVA is the market leader and standard encapsulation material for solar cells. EVA, like most polymers, is known to undergo photothermal degradation - UV radiation breaks molecular chains. EVA incorporates UV absorbers in its formulation to stop yellow/browning of EVA which reduces its optical transmission. Diffusion of chemical species is also relatively easy through it; moisture and corroding agents can enter while absorbers and stabilizers can out diffuse. This means that modules using EVA as the encapsulant must have some form of edge sealant. EVA encapsulants typically use about 67wt% ethylene and 33wt% vinyl acetate and are typically processed to temperatures of up to 160 °C. PVB has been long used in module fabrication, and is processed in a similar way to EVA, requires low temp storing. PVB is generally used in modules with glass-glass

construction, and has gained acceptance among manufacturers of thin film modules.

Silicone encapsulants are expensive but very stable³². Essentially transparent to UV light, UV stable, therefore no additives to protect against UV degradation such as used in other encapsulants. Use of silicone encapsulants give a more efficient module, as UV light is converted into electricity, rather than being absorbed by the UV stabilizers. Light transmittance with silicones is very high, at around 98%. 2 part formulations are available which can be cured at room temperature.

Ionomers are polymers which consist of electrically neutral repeating units, with a smaller amount of ionized units (typically around 15%). Some manufacturers have recently started offering encapsulants based on ionomers, such as DuPont which provides their PV5300 film. DuPont's PV5300 is around 100 times stiffer than PVB, five times stronger, and more resistant to moisture intrusion. The diffusion coefficient of DuPont PV5300 is approximately 4 times slower than that of EVA, meaning the migration of water into the module can be significantly decreased. They have high impact resistance, and high adhesion to glass. As they are much stiffer than EVA, they are much easier to handle in the manufacturing stage. They have a light transmittance of approximately 94.3 %. As this encapsulant has such a low diffusivity for water vapour, there is no need for an additional edge seal. Several producers of PV modules have successfully utilized this has utilized this encapsulant, and produced modules without edge seals. Unfortunately, PV5300 does not adhere well to polymers, and is there not suited for use with TPT⁵³, fluoropolymers or other plastics⁵⁴. It is targeted at glass-glass module construction, however, it can also adhere well to ceramics and metals.⁵³ Therefore it would only be an option for the BIPV product if glass was to be used as the front sheet.

3.3.4 Edge Seals

Edge seals are generally necessary to prevent moisture diffusing through the encapsulant into the module, in cases where the encapsulant has a relatively high diffusivity for water vapour. Edge sealant may be applied either on the exterior

edge of the module (typically coupled with aluminium framing), or wedged inside the laminate on the edge, between the front and back sheets. Polyethylene and polyurethane tapes have been popular in the solar market for more than 20 years⁵⁵. Now, these tapes are joined by acrylic foam tapes as possible solutions for solar application challenges⁵⁵. Butyl tapes are also available, which are usually targeted at thin film applications. In addition to tapes, manufacturers are also looking at silicone adhesives, as well as epoxies⁵⁵.

3.3.5 Junction Boxes & Bypass Diodes

Junction boxes provide a means for connecting adjacent panels safely and easily. A typical junction box is shown below in Figure 37.



Figure 37 - Typical PV junction box

It is normal practice to put a bypass diode every 15-18 cells to prevent hotspot formation due to shaded or mismatched cells. These are wired in parallel across the string of cells. Bypass diodes are usually incorporated into the junction box making these a trivial matter. However, if it is to be incorporated into the laminate itself, there are additional factors to consider - the diode must be able to resist lamination conditions (temperatures and pressures), and it must be low profile. Certain high-temperature and low profile bypass diodes are available which can be incorporated into the laminate and withstand processing conditions. One such diode is produced by Diodes Incorporated, which is rated to 200 °C, and has a slim profile, at only 1.1 mm.

3.3.6 Compatibility of Laminate Materials

Not all laminate materials are compatible with each other. Several combinations for materials have been identified as possibilities. Table 7 lists compatibilities of

the main encapsulants with front and back sheet materials, by category. Almost every c-Si module has glass as a front sheet, EVA as the encapsulant, and TPT as the backsheet, an Al frame with edge sealant.

Table 7 - Compatibility of laminate materials

	Glass	Polymers	Metal	Ceramic
EVA	✓	✓	✓	✓
PVB	✓	✗	✗	✗
Ionomer	✓	✗	✓	✓
Silicone	✓	✓	✓	✓

3.4 Photovoltaic Encapsulation

Encapsulation bonds the layers of the laminate together and protects the solar cells from the environment. The vast majority of photovoltaic modules are encapsulated using flat-bed laminators. The next most popular method is autoclaving. Other methods are available based on alternative encapsulants (eg room temperature silicones) which do not require the application of such heat and pressure, however these are far less widely used, and tend to be more expensive.

3.4.1.1 Flat Bed Lamination

The three basic steps of a lamination process are:

1. applying a vacuum to remove the air and other volatiles to prevent bubbles
2. heating the laminate lay-up to about 120-160 °C to cross-link EVA
3. application of pressure to ensure good surface contact and adhesion between the laminate layers

This is the industry standard, and by far the most common method. These basic principles are valid for various crystalline silicon and thin film modules using various encapsulants, e.g. PVB, silicones, ionomers and polyolefins. Laminates formed using conventional methods should be flat, as encapsulant readily flows, also to ensure flexible membrane applies even pressure. A vacuum is important to

extract air - to prevent voids and bubbles from forming - and moisture and other gases.

A flatbed laminator consists of a processing chamber that is divided by a flexible (silicone) membrane into an upper and lower chamber. Both chambers can be individually evacuated. The laminate is first placed into the lower chamber, vacuum applied and then heated. After crossing the EVA softening point at about 60–80 °C, the PV module is directly pressed on the heating plate and the actual EVA cross-linking process is performed⁵⁶. The pressure application on the PV module is established by venting the upper chamber, and as a result of the pressure differential, the flexible membrane is pressed on the PV module. A subsequent controlled cooling step leads to a stop of the cross linking process and completes the lamination cycle⁵⁶.

The time of applying a vacuum as well as the evacuation rate has to be varied to optimise the process. Reducing the pressure too early can result in significant outgassing of the additives in the EVA, and hence in a decreased quality of the PV modules. Applying vacuum too late will lead to air inclusion and unwanted bubble formation. Care has to be taken when applying the pressure, to what extent and at what rate. Applying the pressure too early increases the chance of unwanted cell breakage whereas applying the pressure too late will most often result in a shift of the cell strings⁵⁶.

Several manufacturers produce laminators which can process laminates up to 4500 mm long, and 2000-2400 mm wide (e.g. Spire, Meier Solar Solutions, Trident Electronics Technology). The standard lamination process limits the length of the BIPV product, meaning it will need to be modular in design, with discrete lengths at a maximum of 4-5 m. Conventional flat-bed laminators are incapable of processing the size and shape of a standard roofing profile. Laminators typically allow 15 mm thickness, which can be increased to 35 mm or so for certain applications, by increasing the depth of the bottom chamber. As there are no PV laminators in New Zealand, the module lamination will have to be outsourced overseas. The trend is towards outsourcing to China, as recently demonstrated by BP Solar⁵⁷.

3.4.1.2 Autoclaving

Autoclaves can encapsulate PV modules by applying heat and pressure to the laminate. Autoclaves are usually not economically competitive with conventional multi-opening flat bed presses. One serious autoclave disadvantage is longer cycle time because heat transfer occurs only through convection. Energy cost is also higher because a large volume of gas must be compressed, heated, cooled and then dumped to the atmosphere.

3.4.1.3 2 Part Cure

Certain encapsulants, e.g. silicones, allow for greater flexibility in the encapsulation step. It is possible to encapsulate without the need for special equipment. Silicones are dispensed as a liquid and certain formulations can be cured at room temperature. A huge amount of pressure does not usually need to be applied, however it is advantageous to aid bonding and evacuation of air. Vacuum and heat are not necessary, however it is desirable to produce a higher quality laminate with a shorter lamination cycle time.

3.5 Conclusions

c-Si is the most sensible choice for solar cell for the BIPV product. It is important that the module is encapsulated adequately to ensure a long product lifetime, as this is the main method of protecting the cells. Moisture ingress is the main mechanism cause PV module degradation and failure. Flat bed lamination is the industry standard for producing solar modules. This process has strict limitations relating to the dimensions of the PV laminate. Roofing profiles cannot be used in the laminator unless modifications are made to the equipment.

Chapter 4: Design of BIPV Product

4.1 Introduction

Chapter 3 reviewed current PV technologies, which provided the underlying technical knowledge necessary to be able to begin the design process. This chapter follows the design process undertaken in the development of the BIPV product, from analysis of the design problem to detailing of the chosen concept.

It is important to apply a logical methodology when undertaking design work to ensure a clear project direction, where all aspects are thoroughly investigated, and time is not wasted exploring irrelevant or unfeasible avenues. The basic structure of a standard design model is followed which can be found in most good engineering design textbooks.

The stages in the design process can be summarised as follows:

- 1 Analysis of the design problem
- 2 Construction of PDS
- 3 Concept generation
- 4 Concept Selection
- 5 Detailing of selected concept

4.2 Fundamental Considerations

The main issues associated with the design of PV modules have already been discussed. This section identifies the standards which must be adhered to in order to produce a PV product capable of passing certification. Additionally, it raises considerations associated with the design of a product to be integrated into metal roofing. This will then aid in writing a meaningful PDS.

4.2.1 Standards

Numerous standards apply to the design and safety of photovoltaic modules. The most widely recognised international standards are provided by the International Electrotechnical Commission (IEC). IEC 61215 and IEC 61730 are the most widely applied standards to the design and testing of crystalline silicon PV modules. In the case of thin film modules, IEC 61215 is replaced with IEC 61646

as there are a different set of requirements for testing of thin film modules. UL 1703 and the CE mark are other commonly applied standards.

As of 1st June 2009, it became a requirement under the Australian Standard AS/NZS5033, Photovoltaic Installations, that modules must be compliant with IEC 61730 and either IEC/EN61215 (crystalline silicon modules) or IEC 61646 (thin film modules). Australia requires solar panel testing and certifying to IEC Standards⁶⁰. In addition to IEC standards, the design will need to meet the appropriate AS/NZS roofing standards.

4.2.1.1 IEC 61215

The following is taken from the abstract of IEC 61215:

IEC 61215: *Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval*

- Lays down requirements for the design qualification and type approval of terrestrial photovoltaic modules suitable for long-term operation in general open-air climates.
- Determines the electrical and thermal characteristics of the module and shows, as far as possible, that the module is capable of withstanding prolonged exposure in certain climates.

Various combinations of test procedures summarised in Table 8 are applied to a sample of 8 modules. The modules qualify if no major failures are found, the visual inspection reveals no damage, the electrical power does not degrade more than 8% of specs, and isolation is maintained, and specific requirements for individual tests are met. If 2 modules are to fail, the design does not pass certification. If 1 fails, a sample of another 2 modules is taken. If both of these pass, the design is said to have passed, otherwise it has failed certification.

Table 8 – Summary of IEC 61215 test levels

Test	Title	Test Conditions
10.1	Visual inspection	Examine for cracked or broken cells, torn surfaces, faulty connections, etc.
10.2	Maximum power determination	In accordance with IEC 60904-1
10.3	Insulation test	Dielectric withstand at 1 000 V d.c. + twice the maximum systems voltage for 1 min. For modules with an area of less than 0,1 m ² the insulation resistance shall be not less than 400 MΩ. For modules with an area larger than 0,1 m ² , the measured insulation resistance times the area of the module shall be not less than 40 MΩ·m ² measured at 500 V or maximum systems voltage, whichever is greater
10.4	Measurement of temperature coefficients	See IEC 60904-10 for guidance.
10.5	Measurement of NOCT	Total solar irradiance: 800 W·m ⁻² Ambient temperature: 20 °C Wind speed: 1 m·s ⁻¹
10.6	Performance at STC and NOCT	Cell temperature: 25 °C and NOCT Irradiance: 1000 and 800 W·m ⁻² with IEC 60904-3 reference solar spectral irradiance distribution
10.7	Performance at low irradiance	Cell temperature: 25 °C Irradiance: 200 W·m ⁻² with IEC 60904-3 reference solar spectral irradiance distribution
10.8	Outdoor exposure test	60 kWh/m ²
10.9	Hot-spot endurance test	Five-hour exposure to 1000 W/m ² irradiance in worst case hot spot condition
10.10	UV preconditioning	15 kWh/m ² total UV irradiation in the wavelength range from 280 nm to 385 nm with 5 kWh/m ² UV irradiation in the wavelength range from 280 to 320 nm
10.11	Thermal cycling test	-40deg to 85 deg, 50 and 200 cycles (STC peak power current during 200 cycles)
10.12	Humidity freeze test	10 cycles from 85 deg C 85% RH to -40 deg C
10.13	Damp heat test	1000 h at 85C and 85% RH)
10.14	Robustness of termination test	As in IEC 60068-2-21
10.15	Wet leakage current test	For modules with an area of less than 0,1 m ² the insulation resistance shall be not less than 400 MΩ. For modules with an area larger than 0,1 m ² the measured insulation resistance times the area of the module shall be not less than 40 MΩ·m ² to be measured at 500 V or maximum systems voltage, whichever is greater
10.16	Mechanical load test	2400 Pa, spread uniformly, for three cycles, front and back, applied for 1 hr
10.17	Hail test	25 mm diameter ice balls at 23 m/s, directed at 11 impact locations
10.18	Bypass diode thermal test	One hour at <i>I</i> _{sc} and 75 °C One hour at 1,25 times <i>I</i> _{sc} and 75 °C

Two tests have been identified in IEC 61215 which are likely to require a greater deal of consideration than others during the design process. Of course the product needs to be designed to withstand all tests, however, many of these are trivial if standard practices are followed. The main test worth noting is the damp heat test, which demands 1000 hours of testing at 85% RH and 85 °C, after which the power output must not degrade by more than 5%. This imposes strict sealing requirements on the product. Additionally, the impact test may require some consideration if a non-glass front sheet is selected, however the product review uncovered Lumeta PowerPly, which has passed certification simply using a thin polymer cover and by increasing the thickness of the top layer of EVA. It must be able to withstand impact in various locations (around 11 different locations on the module) from a 25 mm diameter hailstone of 7.53 grams fired at a speed of 23 m/s.

4.2.1.2 IEC 61730

IEC 61730 is divided into two sections. The following is taken from the abstracts of these standards:

IEC 61730-1: Photovoltaic (PV) module safety qualification Part 1: Requirements for construction

- Describes the fundamental construction requirements for photovoltaic modules in order to provide safe electrical and mechanical operation during their expected lifetime.
- Addresses the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses.

IEC 61730-2: Photovoltaic (PV) module safety qualification Part 2: Requirements for testing

- Describes the testing requirements for PV modules in order to provide safe electrical and mechanical operation during their expected lifetime.
- Addresses the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses.

Upon inspection of the requirements laid out in IEC 61730, there appear to be no tests that will be of concern if proven solar module materials are to be used in the design of the product. However, it is worth noting that the PV modules are likely to require an earth, especially since they will be so close to metal roofing, and may possibly have metal framing or substrates.

4.2.2 Mechanisms of PV Failure

There are many different mechanisms by which PV modules can fail. PV modules are subject to far longer warranty terms than are expected in almost any other product. As such it is important to understand what mechanisms cause their degradation and failure to ensure a long lasting product.

Thermal: Thermal expansion between unlike materials can cause stresses to be induced in the product. All module interfaces are also subject to thermal cyclic stress, which may eventually lead to delamination. Connections between cells are usually looped, to minimise cyclic stress. Hot spots can also be formed due to cell shading which can cause the module to fail.

Embrittlement of encapsulant: The life of a solar module is predominantly influenced by the durability of the encapsulation. Crystalline silicon modules often fail at the cell interconnections or because of cracked cells, and thin-film devices often fail at the scribe lines or experience degradation of the cell itself. Because of this, crystalline silicon cells can be sensitive to the embrittlement of the encapsulant over time, and thin films are sensitive to moisture that can corrode the module. Both of these degradation processes are accelerated by exposure to hot and humid environmental conditions.

Moisture ingress: Water molecules enter in the polymer structure and cause different processes such as swelling, dissolution, plasticizing or hydrolysis. This can lead to discoloration, embrittlement, loss of mechanical and electrical properties and lower resistance to weathering. Because of the relatively high diffusion rate of water in EVA, even a module with a glass/glass construction will have significant moisture ingress over the lifetime of the module. The only way to prevent moisture ingress is with a true hermetic seal or by using a low-diffusivity

edge seal containing a large amount of desiccant⁵⁹. Hydrolysis of EVA leads to the formation of acetic acid, which accelerates the corrosion reactions of metallic parts of the circuit⁵⁸. Various other defects, such as delamination, bubble formation and edge cloud, are all known to be influenced by the presence of moisture. Breathable module layers allow moisture to enter the module with ease, however, moisture is also able to exit the module on hot, sunny days. If low permeable layers are used, water ingress is minimised, but once inside it is unable to escape easily, which can accelerate corrosion rates. As such, it is not clear which is the better choice for front and back sheets⁵⁸.

4.2.3 Roofing considerations

There are certain considerations to take into account when designing a product to be integrated into metal roofing. If the product is not designed correctly, the roof may not function as intended, and it is therefore necessary to understand the fundamentals issues which may affect its function.

One of the most important considerations is maintaining the integrity of the roofing structure, and not introducing any sites for water ingress in between roofing sheets. Additionally, water runoff is very important, therefore the design should not incorporate any areas where water could potentially pool, and the roof surface should be as smooth as possible. Dirt and debris collection can also significantly decrease the life of the roof, and reduce the power output, and lifetime of the PV module. The added weight due to integrating PV into the roof needs to be accounted for when designing the roof. A well designed product should add minimal weight and not require extra purlins or strengthening of the roof structure unless absolutely necessary. If the added weight turns out to be significant, the problem could be solved by reducing the purlin spacing.

Due to the large spans of many commercial roofs, the length of the module should ideally be maximized, in order to minimize the number of parts, and simplify integration into the roof. Commercial roof spans can exceed 60 m in Australia. Speed Deck Ultra has recommended maximum span of 20 to 35 m depending on the situation to account for thermal expansion. However, if the product is to be applied residentially as well, where roof spans are typically 5-6 m, the product

should be a maximum of 5 m. The length is limited by difficulties associated with handling and transporting long, narrow modules. It is common to construct modules with cells in a multiple of 18, with 36 and 72 cell modules being common. A module with 18 cells would be of a manageable length of just under 3 m, and fit comfortably into most laminators, using 156 mm cells.

It is important to keep in mind whether the product is for new roof installations, or whether it will also be used in retrofits. Retrofitting opens up a much wider market, however, depending on the design this may pose difficulties. Ideally, the PV should be a permanent fixture on the roof. No bolting should be required, as this takes away from the integrated 'feel'. However, removable panels have their advantages, specifically, modules can be easily removed and replaced if they are damaged.

It is desirable that the roofing panels are able to be walked on, however, there are physical limitations associated with using crystalline silicon cells. Cells are very brittle and are prone to breakage if the product is not designed correctly. Crystalline silicon cells are traditionally thought of as being very brittle, with no degree of flexibility, however, it has been proven by Duke/Anderson that if laminated correctly, the cells are able to have a limited degree of flexibility. This has been shown with a laminate using stainless steel as the substrate, EVA as the encapsulant, and a flexible fluoropolymer front sheet, in this case Tedlar.

The ribs in the profile may present issues due to partial shading of cells, early in the morning, and late in the afternoon, as depicted below, in Figure 38. With the cells only sitting just above the swages, partial shadowing will become an issue. However, cell mismatch will not be an issue as each cell will be shaded by the same amount (assuming the entire BIPV is facing in the same direction)

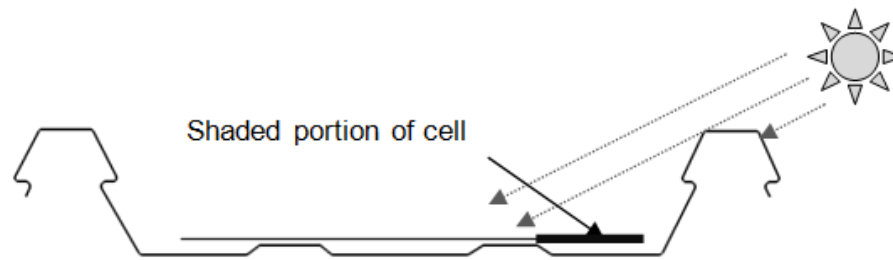


Figure 38 - Shading effect on cells due to ribs

The capital cost of tooling a new roll former to produce a new profile specifically for BIPV is too high to currently make this an attractive option for an entry level product, as it is approximately 600,000 to 1,000,000 NZD²⁹. However, certain minor adjustments may be possible if necessary, such as raising the swage rollers to create a flat bottomed pan.

4.3 Product Design Specification

This section presents a PDS which has been constructed based on the findings of background research performed in Chapters 2 and 3, along with the design considerations which were raised in the preceding section.

Design brief: A PV product is to be designed to integrate with long run metal roofing which will be an addition to Dimond Roofing’s existing product range. The design should be innovative and differentiated from other BIPV products on the market, without compromising the aesthetics or function of the roof.

4.3.1 Aesthetics

- The product is to be integrated into the Speed Deck Ultra profile, produced by Stramit.
- The product should resemble the original roofing profile as much as possible.
- The product is to have as little architectural impact as possible, and should blend into the rest of the roofing structure without being intrusive.
- The product should look professional to improve perception within the market.

4.3.2 Performance

- Power output per square meter should be comparable to existing (BI)PV products on the market.
- The product must not yellow, or delaminate during its lifetime.
- It should be durable enough to allow light foot traffic without damage.
- The product must not collect dirt or debris which will impair the output.
- Shadowing of cells due to the ribs should be minimized.
- The product must withstand reasonable handling practices without damage to electrical components
- Each module should produce the same power output to within 5%
- The roof surface should be as smooth as possible to prevent water pool and dirt accumulation.
- The integrity of the roof needs to be maintained to prevent water ingress between roofing panels.

4.3.3 Market

- Initially a low volume of test installations are to be made in New Zealand.
- The first target market will be Australia market, with a focus on the A.C.T.
- The product will initially be targeted at the commercial roofing market.
- The product should also be able to be applied residentially.
- The product will be mainly used in Australian weather conditions.
- The main competitor to the product will be UNI-SOLAR laminates.

4.3.4 Size and weight restrictions

- Each panel will incorporate 156 x156 mm crystalline silicon cells.
- The product should be of a manageable length to ensure ease of handling and installation.
- Weight should be minimized so that reinforcing to the standard roofing structure is not required.
- The length of an individual module should not exceed 5 m.

4.3.5 Manufacture

- If industry standard flat-bed lamination is to be used, lamination of modules will be outsourced.
- Start up costs should not be extravagant.
- Proven PV materials are to be used where possible.
- New roll forming tooling should not be required, however slight modifications to existing equipment may be permissible.
- The product is to be manufactured to a high and consistent standard

4.3.6 Installation

- The product should be easily installed without the requirement of specialised labour.
- Terminals should be easily accessible, and should be 'plug and play' type connectors.
- System voltage must be no more than 1000 V.

4.3.7 Maintenance

- To be maintenance free except for an annual inspection and wash-down of the PV modules, however, the product shall be designed under the assumption that they may not be inspected for periods of years.
- Modules should be able to be replaced in case of failure

4.3.8 Safety

- Earths must be incorporated to ensure the roof does not become live if the module should fail.
- Risk of electrical shock to installers must be minimized.
- The product should be able to withstand fire without causing an unsafe condition.

4.3.9 Lifetime

- The power output of the product should not degrade to less than 80% after 25 years in service.

- The product should continue to produce power for the lifetime of the roof, which is expected to be upwards of 40 years.

4.3.10 Shipping

- Transport within New Zealand is by truck which can typically transport 6 m lengths
- Shipping abroad will be by sea

4.3.11 Cost

- Where ever possible, material usage and costs are to be minimized.
- The integrated product should be cost less than purchasing a roof and PV modules separately.

4.3.12 Standards

- The product must adhere to IEC standards 61215 & 61730, and be designed to pass certification.
- Relevant AS/NZS roofing standards must be followed.

4.3.13 Disposal

- Recyclable and environmentally friendly materials are to be used wherever possible.

4.3.14 Documentation

Documentation is to contain:

- Installation instructions describing the methods of electrical and mechanical installation
- Electrical ratings of the module
- Application class under which the module was qualified and any specific limitations

4.3.15 Marking

Each module shall be marked with the following clear and indelible markings:

- Name, monogram or symbol of manufacturer

- Model number
- Serial number
- Polarity of terminals or leads (colour coding is permissible)
- Maximum system voltage for which the module is suitable
- The date and place of manufacture

4.4 Concepts for BIPV Product

The previous section raised issues associated with the design of the BIPV product, and formulated a set of constraints in the form of a PDS. This section builds a range of holistic concepts addressing the PDS.

A number of design considerations were raised in Section 4.2, each which can be resolved in numerous ways, with different solutions possible based on which category they fall into. Constructing a list of concepts created from all possible combinations of these solutions would be far from practical as the list would be immense. The approach followed in this study is to construct a morphological chart as outlined in most good engineering design books. From this, overall feasible concepts were then generated from compatible combinations of the different ideas.

A number of products are possible with varying degrees of integration. Broadly speaking, the BIPV product concepts can be grouped into two main categories based on the level of integration:

1. Indirect integration - A separate PV module is produced which is then fixed into the pan of the Speed Deck profile by an appropriate means, e.g. adhesives or clips.
2. Fully integrated - PV cells are bonded directly to a substrate which also acts as the roofing surface.

Concepts have been categorized by the level of integration. Firstly, indirectly integrated concepts are generated, followed by fully integrated concepts. The various concepts are then evaluated based on criteria formulated from the PDS, and the most appropriate concept is chosen.

4.4.1 Indirectly Integrated Concepts

This section presents concepts based on PV modules which are designed to be an addition to a standard Speed Deck roofing panel, without heavily infringing on the aesthetics and continuity of the roof. In order to achieve this, the product must retain the basic rib and pan structure, which essentially limits the design to low profile PV modules secured in the pans of the roofing panel. As the product is to be targeted at a commercial market, the product needs to be able to span long lengths. This means that modules need electrical connections at either end, so that they can be strung together to increase the span of the BIPV. At the ridge end, positive and negative power terminals can be fed into the roof under the ridge cap, as is common in similar applications (eg Uni-Solar). This method is the obvious choice, as the junction box will be out of view, shielded from the elements, and no roof penetrations are necessary.

Ideally, the same module should be used for the top, middle, and bottom modules, to simplify the manufacturing process. However, the ridge end module will differ slightly from the remaining central modules - ideally all modules should be made identical. This is because the top module requires a junction box with sturdy terminals, where the wires are fed into the roof. Since wiring should be hidden, it was decided that all indirectly integrated concepts (Concepts 1 to 6) all have the same wiring configuration. Connection of adjacent modules is performed in the swage cavity. There may be some technical issues in connecting adjacent modules as room is limited in the swages, as they are only approximately 3.5 mm high.

Table 9 shows the morphological chart used to construct concepts for an indirectly integrated product. The main factors which shape the design pertain to:

- The support method - what provides support to the back of the module and transmits forces to the roof, avoiding excessive bending. Swages are incorporated into the roof, so it is important that some support is provided at these points.
- The method of isolating cells from moisture
- Seal to rib, to prevent moisture leeching down the sides of the module.

- Mechanical connection of BIPV modules
- Method of attaching module to roof

Table 9 - Morphological chart for indirectly integrated concepts

Support Mechanism	Isolation of cell from moisture	Attachment method	Impact resistance	Mechanical connection
Backing bar	Rubber Extrusion	Adhesive	Impact resistant front sheet	Lapped join
Shaped back sheet	Tape	Fastener	Impact resistant encapsulant	Butt join
No traffic	Sealant bead	Welding	Thick encapsulant	Interlocked join
Stiff front sheet	Moisture resistant encapsulant	Clip in	Thick front sheet	
Stiff back sheet		Magnetic		
Remove swages				

4.4.1.1 Concept 1: Extruded aluminium frame

Laminate materials: COLORSTEEL, EVA, ETFE

A PV laminate is produced with a COLORSTEEL substrate, and a fluoropolymer front sheet. The laminate is then framed with edge sealant tape and an extruded aluminium frame. The frame is multipurpose as it provides edge support, sealing of the module, with mounting points for clips to fix the module into the pan. Additionally, a groove is incorporated into the edge of the frame for attachment of a rubber cord to provide a seal against the rib. Alternatively the groove could be removed and tape or foam could be applied. The profile of the frame is pictured in Figure 39. The frame design leaves a cavity at the edges of the pan to allow water to drain in case the rib seal should fail. Also, it raises the laminate slightly out of the pan, increasing the size of the swage cavity, and making it easier to wire adjacent modules.

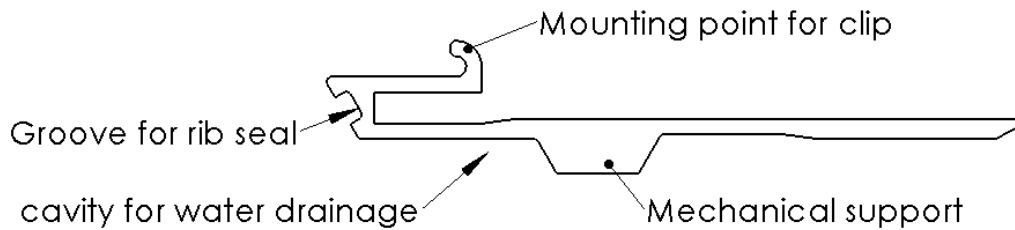


Figure 39: Extruded aluminium frame

Figure 40 shows how the module is attached into the Speed Deck pan using wire clips.

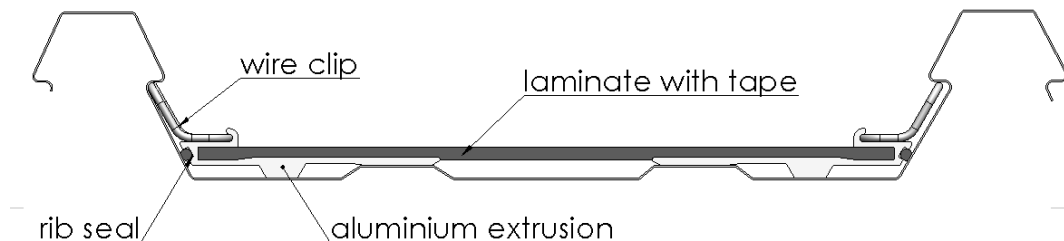


Figure 40: Extruded aluminium frame

Adjacent modules are mechanically connected using an extruded aluminium joiner. Tape is applied to the module ends to provide moisture protection, and the profile is fitted to the end of the upper module. The lower module is laid first, before the upper module with attached joiner is laid over the top, as depicted in Figure 41. The joiner can also be used at the end of the PV run as an end cap.

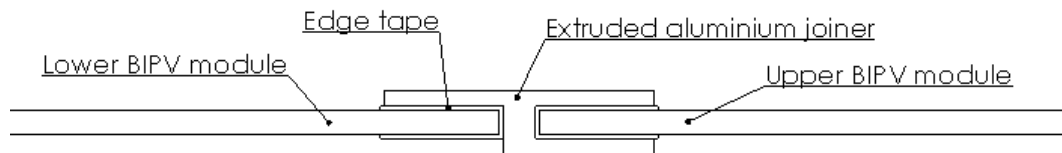


Figure 41 - Join between adjacent modules

A rendering of the concept fitted to a single Speed Deck pan is shown in Figure 42. The advantages and disadvantages of the concept are listed below.

Advantages:

- Frame provides mechanical support at edges
- Provides longitudinal stiffness
- Most accepted and proven method of edge sealing
- Frame resists delamination
- Simple installation
- Swage cavity slightly enlarged to provide room for connection of wires
- PV is easily removed and replaced if need be
- Very easy to install

Disadvantages:

- Ideally should not require frame as it is supposed to be building integrated
- Requires tooling for two custom extrusions
- Clip design could potentially collect dirt, leaves and debris

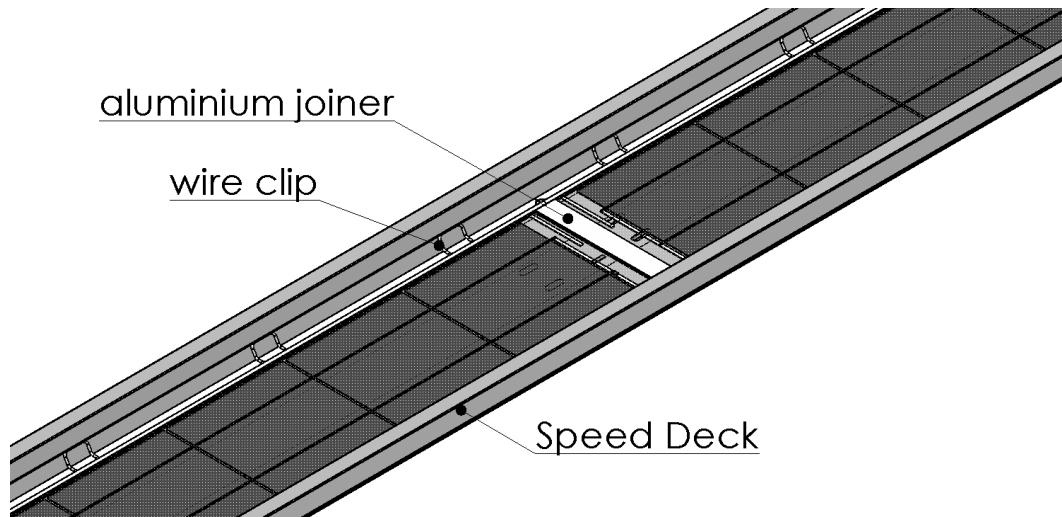


Figure 42 - Rendering of Concept 1 fitted to Speed Deck

4.4.1.2 Concept 2: Interlocking

Laminate materials: COLORSTEEL, EVA, ETFE

Flat laminates are produced which are able to be formed into interlocking profiles, as pictured in Figure 43.

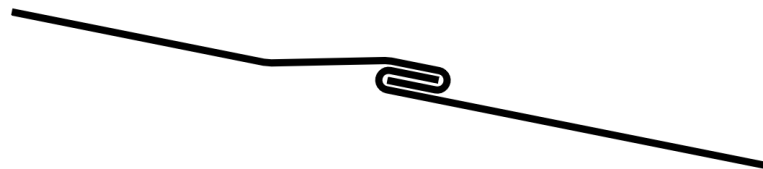


Figure 43 - Interlocking ends of modules

Module edges are hemmed, as shown in Figure 44. This is sealed with butyl tape on the underside, which also acts as the seal against the rib (not pictured). The tape provides a dual purpose, acting as a seal between the module and the roof as well as an edge seal for the laminate, as shown in. The edge sealing is not visible.

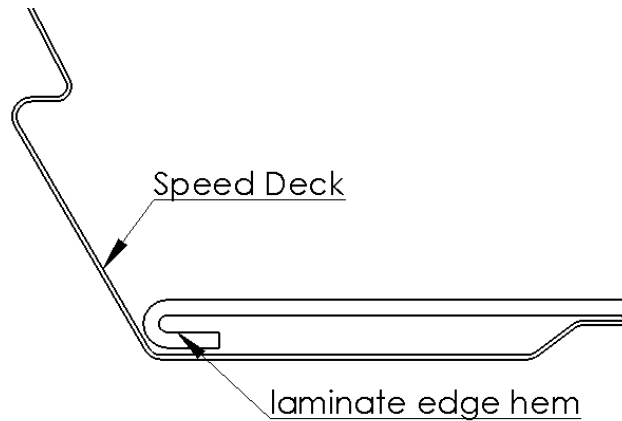


Figure 44 - Edge hem on laminate

Advantages:

- No seal required between panels, as interlocking profile doesn't allow water to penetrate
- Edge seal not visible
- Dual purpose edge seal
- Stiffness added by hem
- Hem can provide edge support
- Lightweight

Disadvantages:

- Extra manufacturing step
- May provide additional path for water ingress in through side
- Tight bending required

4.4.1.3 Concept 3: Extruded rubber frame

Laminate materials: COLORSTEEL, EVA, ETFE

This concept is based on a rubber extrusion which provides a double seal, which seals the module and against the rib, as depicted below in Figure 45. The extrusion will flex when it comes in contact to the rib, which will provide a decent contact force. The contact patch will be slightly concave to aid the sealing process. The bottom of the extrusion is cut away, to leave a cavity which can act as passage for any water should the seal fail. The top flange is tapered to assist installation. The bottom flange is a lot larger to provide mechanical support for the edges of the module. The PV module is attached to the pan using adhesives. The rubber extrusion may be required to be lined with a sealant to prevent moisture ingress into the module. Adjacent modules are joined using an H-seal, and the ends of the modules are sealed with a rubber C-seal.

Advantages:

- Simple
- Attractive
- Easy to clip seals onto edges of modules
- Edge support from rubber extrusion
- Few parts
- Provides both the edge seal for the module, and a seal between the rib and the module

Disadvantages:

- Cost of tooling
- Requires multiple extrusions
- May have difficulty slotting adjacent panels together

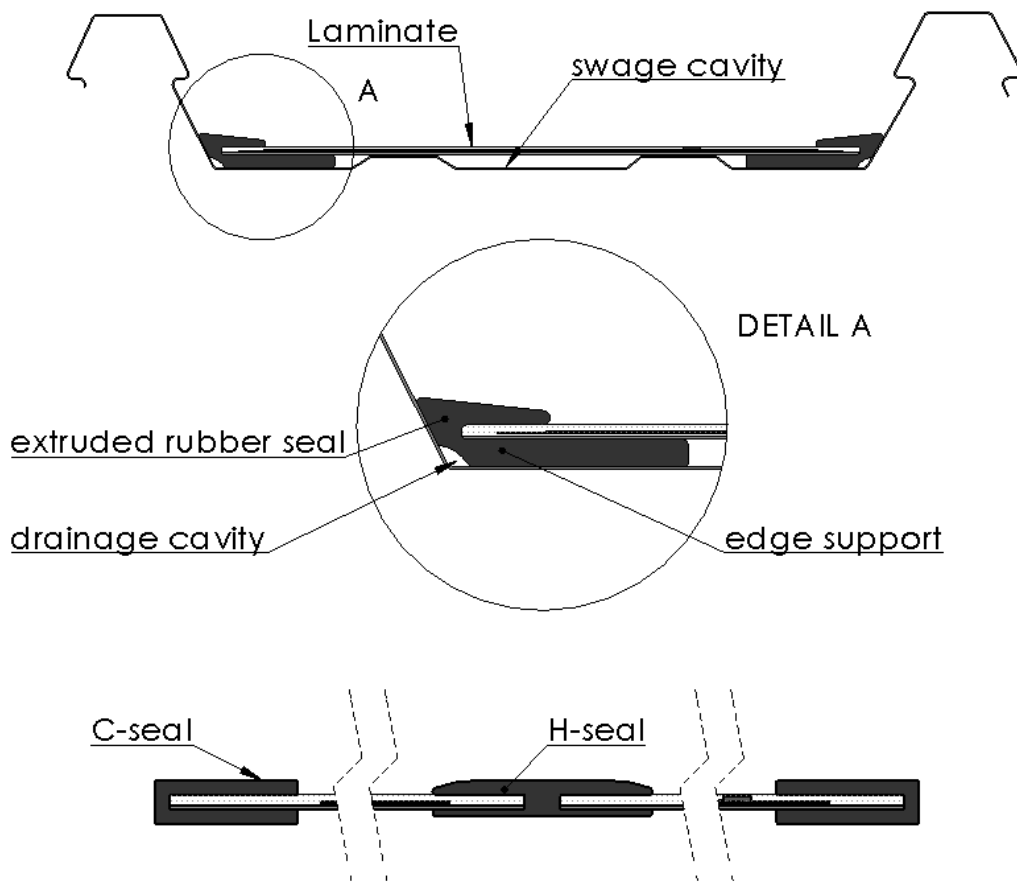


Figure 45 - Rendering of Concept 3

4.4.1.4 Concept 4: Aluminium Extruded Substrate

Laminate materials: Aluminium extrusion, ionomer, glass

This concept is based on an extruded aluminium substrate which is shaped to fit into the pan. No edge seals are required due to the moisture resistant ionomer encapsulant. A glass front sheet provides impact resistance. A silicone sealant bead is run down the edges, between the module and the rib. A rubber T-seal is used to provide a seal between adjacent modules. The concept is pictured in Figure 46.

Advantages:

- No edge seal
- Provides good support
- Stiff - will provide good support for foot traffic & handling
- Room for integration of thermal at later date
- Thermally conductive back sheet

Disadvantages:

- Uses glass which is undesirable
- Custom tooling required for extrusion

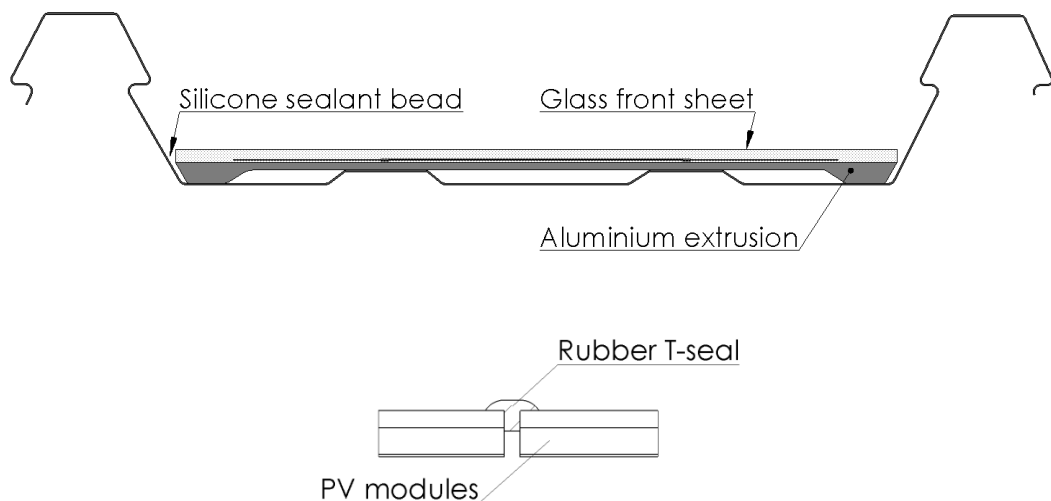


Figure 46 - Rendering of Concept 4

4.4.1.5 Concept 5: Pultruded fiberglass substrate

Laminate materials: Fibreglass pultrusion-EVA-ETFE

This concept is very similar to the previous concept, except a fiberglass pultrusion is used as the substrate instead of aluminium. Since the ionomer encapsulant can not be used with a fiberglass substrate, it is replaced with EVA and an ETFE front sheet is used. Laminate edge sealing is achieved with an in-laminate butyl seal.

Advantages:

- Provides good support
- Stiff - will provide good support for foot traffic & handling
- Insulating back sheet

Disadvantages:

- Custom tooling required for extrusion
- Edge seal visible
- Tooling more expensive than for aluminium

4.4.1.6 Concept 6: Overlapping modules with edge flanges

Laminate materials: COLORSTEEL, EVA, ETFE

Modules are bent up and down on the ends to allow overlapping with the adjacent module, with edge sealing by in-laminate butyl seals. Edge support is provided by a backing strip (e.g. EPDM), with a double sided adhesive which fixes the module to the roof. A butyl tape seal is placed between the modules at the overlap. The edges of the module are folded up to the same angle as the rib, and then taped to provide a seal to the rib. This locates the module in the pan, and also means that moisture has a more difficult path to get into the module. Renderings of the concept are shown in Figure 47.

Advantages:

- No tooling
- Backing strip dual purpose
- Overlap utilizes advantages of formability of sheet metal
- Locates panel easily

Disadvantages:

- Extra manufacturing steps
- Requires bending of module
- Seals are visible
- Not very attractive

- Folded edge provides stiffness
- Folded edge makes water ingress down the sides more difficult

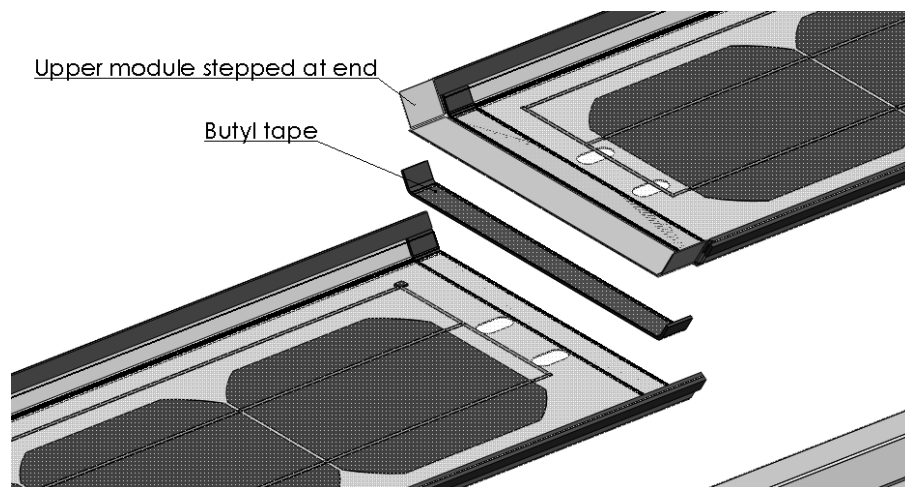
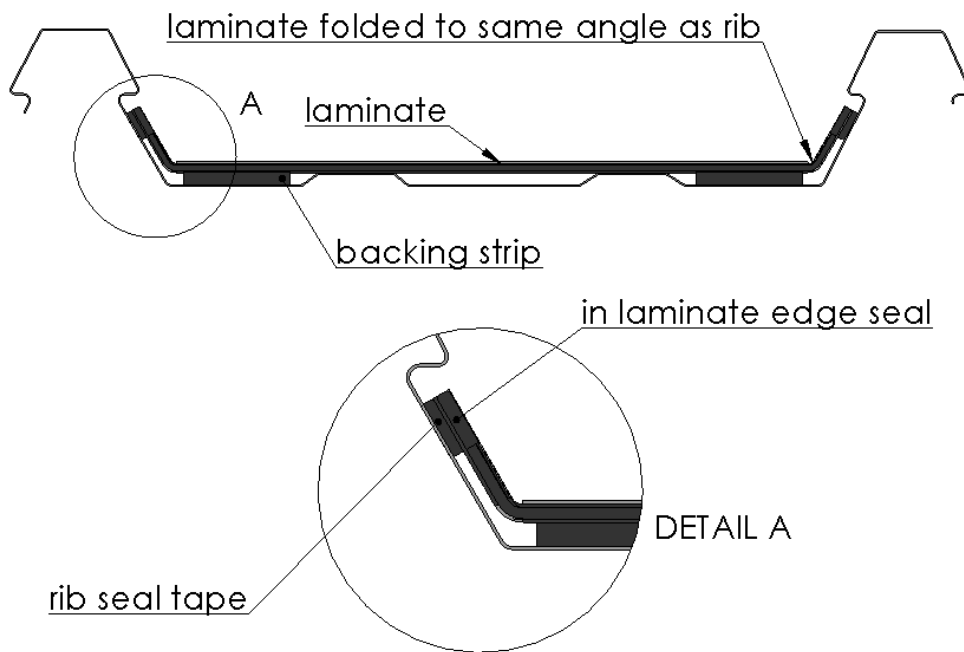


Figure 47 - Rendering of Concept 6

4.4.2 Fully integrated concepts

The concepts presented in this section can be considered truly integrated solutions, as the PV module also acts as the roof surface, and is not just an addition to the roof. BIPV panels can either be modular, or one run, as standard roofing is, however it is most likely it will be modular. A one run product would require custom sized panels to be fabricated for each job, which isn't very practical, and may not even be possible due to technical limitations associated with the lamination process. Therefore, the BIPV will be manufactured at a fixed length, with joins in the roof if necessary to extend the length of the run.

Advantages:

- Standardized product
- Fully integrated solution
- Lower material usage - cost of PV is offset as it is dual purpose and also acts as the roof surface.

Disadvantages:

- Breaks up the roofline and requires extra laps/joins in the roof
- Destroys the long run capabilities of the roof.
- Joins potentially introduce sites for leakage

All of these concepts could be used in conjunction with a Farlap type roof lapping system. Alternatively, butyl tape could be used to seal the overlap between panels. Either way, the only feasible way to produce reliable joins in the roof is to overlap the panels. It would be beneficial to utilize the Farlap lap sealing system if possible. Farlap has a major advantage desirable for the BIPV product - it raises the top panel approximately 20 mm off the bottom panel, creating a hidden cavity where junction boxes and wiring can be hidden. Junction boxes are available which have profiles as low as 13 mm, and perhaps smaller. The topside junction boxes provide easy installation. BIPV panels are connected side-to-side with adjacent panels using standard plug and play type connectors found on the junction boxes. At the end panels the leads will be fed into the roof cavity where they can be connected in series or parallel to the other rows of panels. The junction box will have bypass diodes incorporated into it, to prevent hot spot formation and subsequent module failure.

Each length of BIPV is likely to a few metres in length, and will therefore have a supporting purlin in the centre of the module, in addition to the purlins at either end at the lapping point. The BIPV panel should have a small degree of flexibility, so that it is able to bend slightly in order to sit flush on the centre purlin, as a result of the bottom end of the module being approximately 20 mm higher than the centre purlin. Stiff modules, for example those with glass front sheets, may require a spacer on the centre purlin to account for this, as pictured in Figure 48.

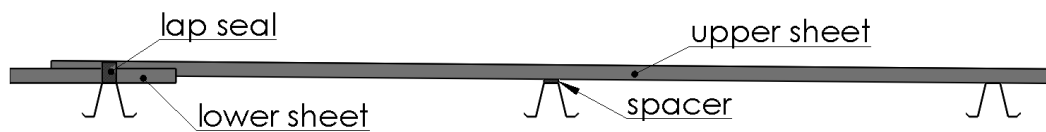


Figure 48– Spacer on centre purlin to account for stiffness of module

As these designs will rely on lapping of panels to achieve a long span, it would be desirable to produce the BIPV modules in lengths as long as possible to reduce the number of overlaps. In practice, however, this will probably not be feasible due to limitations already mentioned pertaining to the lamination process. On the flip side, shorter panel lengths have a number of advantages. These include a reduction in thermal expansion at end of each sheet and also reductions in handling, transportation and installation costs. Table 10 shows a morphological chart for the generation of fully integrated concepts. In comparison to Table 9, the fully integrated concept simplifies the design problem significantly.

Table 10 - Morphological chart for fully integrated concepts

Moisture resistance	Impact resistance	Lap sealing	Attachment of cells
Rubber Extrusion	Impact resistant front sheet	Farlap	Autoclave
Tape	Impact resistant encapsulant	Butyl tape	2 part cure
Liquid	Thick encapsulant		Flat-bed lamination
Moisture resistant encapsulant	Thick front sheet		

4.4.2.1 Concept 7: Silicone Encapsulant

Laminate materials: COLORSTEEL, EVA, Glass

A room temperature cure silicone encapsulant is used to bond the cells directly to the roof surface. A glass cover provides impact resistance. This would require holes to be drilled in the glass prior to tempering to allow the ribbons to be fed through for termination in the junction box. The design is not limited by the lamination process anymore. Silicone encapsulants are two part, and certain formulations can be cured at room temperature, however this can be a lengthy process, so heat will most likely be applied. It would be beneficial to remove the swages for this concept, or else extra expensive silicone will need to be used, and also the cells are in danger of being subjected to a bending stress under foot traffic.

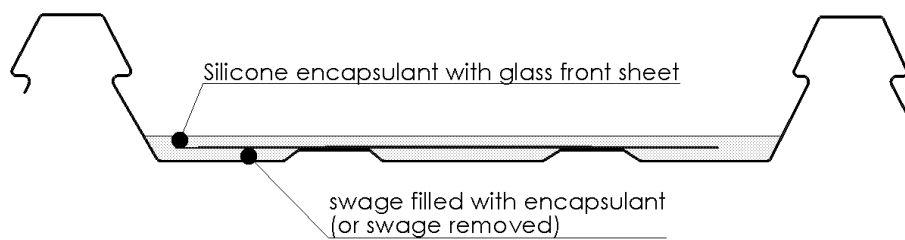


Figure 49– Concept 7: Silicone Encapsulant

Advantages:

- Minimal tooling required
- Maintains clip in capabilities of Speed Deck
- Attractive
- Easy installation
- Lightweight
- Product is one-piece - helps transmit forces to ribs, retain strength etc

Disadvantages:

- Glass is heavy and not easily workable
- Silicones are expensive
- Laminate quality may be lower due to no vacuum

4.4.2.2 Concept 8: Autoclaving

Cells are autoclaved directly to the surface of the Speed Deck panel. Cells/encapsulant would only be in the pans. Panel lengths are limited by the size of autoclaves. An extruded EPDM formulation is used as the back sheet which is shaped to fit around the swages.

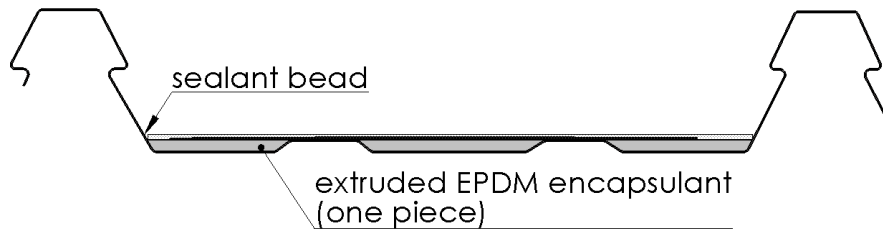


Figure 50 - Integrated concept by autoclaving

Advantages:

- Minimal tooling required
- Maintains clip in capabilities of Speed Deck
- Attractive
- Lightweight
- One piece
- Edge sealing may not be necessary

Disadvantages:

- Energy intensive lamination process
- Tooling for EPDM extrusion
-

4.4.2.3 Concept 9: 3-piece Aluminium Extrusion

Laminate materials: Aluminium extrusion, PV5300, glass

This concept is based on a 3 piece design where aluminium extrusions slot together to form the roofing profile. An extruded frame is produced with a profile which clips into the Speed Deck ribs. This frame then mates with a specially designed extruded backsheet to produce a 3 piece product. A silicone sealant bead is run down the length of the module in between the glass and extrusion to stop the collection of dirt and moisture ingress into roof. No edge sealing of the module is required due to the moisture resistant encapsulant. The principle of the concept is pictured in Figure 51.

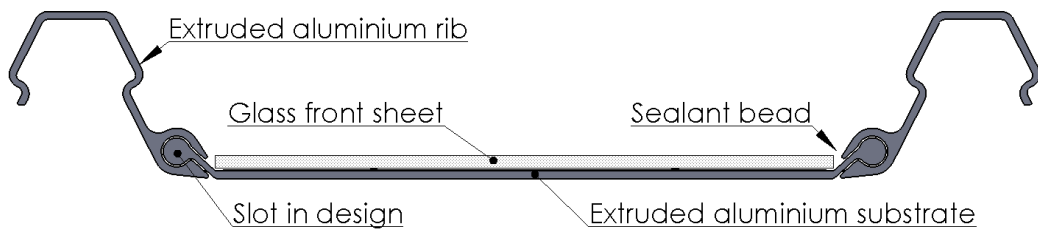


Figure 51 - Principle of 3 piece BIPV

The module is able to be laminated in a standard commercial laminator in the superstrate configuration (glass facing downwards) with the use of spacers to provide support for the module. The principle of lamination is pictured in Figure 52.

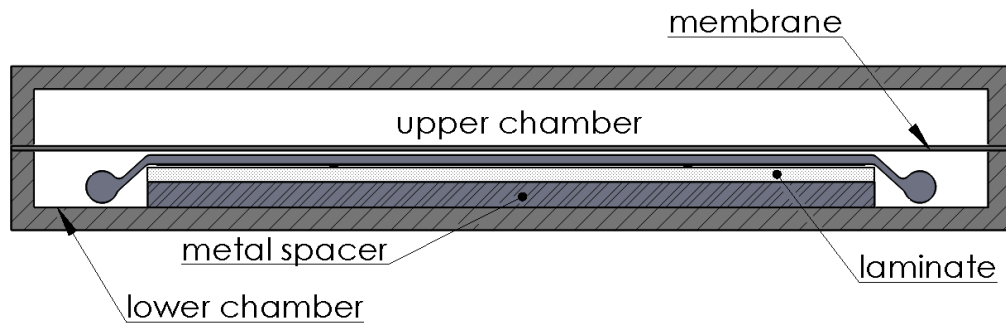


Figure 52 - Principle of lamination

Advantages:

- Retain clip in functionality
- Easy to adapt to BIPVT
- No module edge seal required
- Impact resistant

Disadvantages:

- Tooling for two extrusions needed
- Glass is not desirable
- May be difficult to slot extrusions together
- Heavy
- Stiff - spacer may be required on purlin

4.4.2.4 Concept 10: COLORSTEEL substrate folded post lamination

Laminate materials: COLORSTEEL, EVA, ETFE

A wide flat module is laminated with COLORSTEEL as the backsheet, ETFE as the front sheet, and an in-laminate butyl edge seal around the perimeter. Strings of PV cells are placed in three strips on the laminate, as pictured in Figure 53.

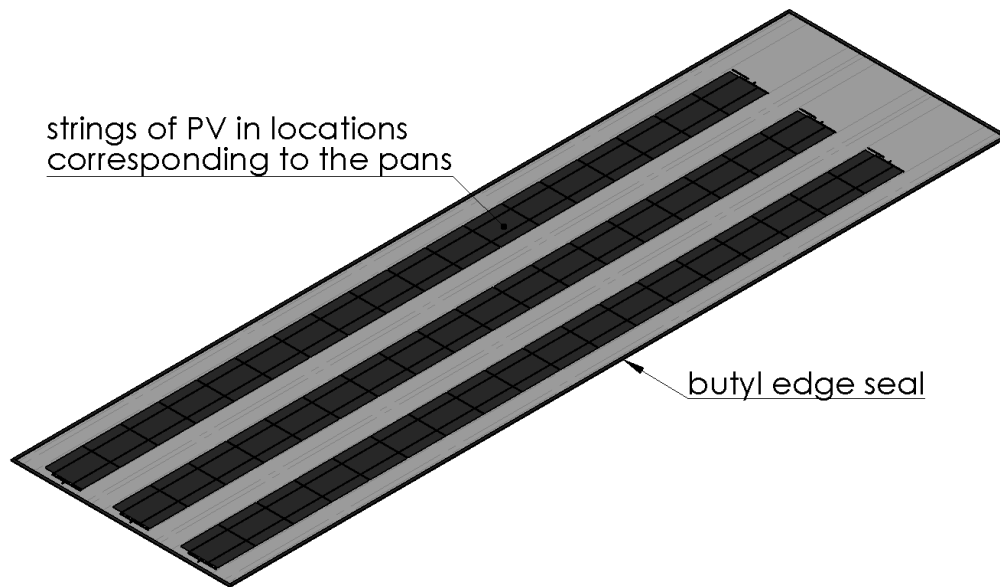


Figure 53 - Flat PV laminate

The laminate is then CNC folded to a trapezoidal profile capable of mating with the Speed Deck profile, neglecting the swages, as pictured in Figure 54. Clip in functionality is lost, meaning the panel needs to be screwed into place. FarLap will not be well suited for BIPV-BIPV joins, as the swages and clip in functionality have both been removed, therefore an adaptation of Farlap is required specifically for this application for lapping panels. The BIPV lapping system does not require clips, and could just be foam shaped to the profile of the BIPV panel.

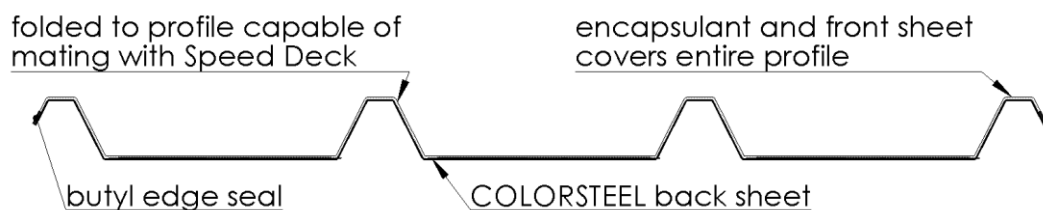


Figure 54 - Profile of folded BIPV laminate

Advantages:

- Few parts
- Retooling is not required to integrate into other profiles e.g. Styleline - just change laminate size and re-program folder
- Roof life may be increased due to extra protection layer of FEP/EVA on surface.
- Don't have to be concerned with varying pan sizes due to manufacturing tolerances
- Lightweight
- May be valuable in terms of IP
- Far less parts than other 'BIPV' systems
- Product is one-piece - helps transmit forces to ribs, retain strength etc
- There is only one seal around the perimeter of the panel, rather than three

Disadvantages:

- Larger laminates are required (fewer laminates can be done simultaneously)
- Loses clip in functionality

4.5 Selection of Concept

It is critical to make the most appropriate selection when choosing a concept to develop. It is at this stage that the cost of the project starts to escalate. Indirectly integrated products are in danger of simply becoming building-*added* PV products, as such the fully integrated concepts are more desirable. Such designs are considered more elegant, and could be classed as 'smart' building products - dual purpose by producing both renewable energy and acting as a building material. A direct consequence of true integration is a lower material usage and fewer parts than the alternative.

A range of selection criteria was formulated based on the PDS and other desirable design attributes. A weighted selection matrix comparing the concepts is provided in Table 11. The fully integrated folded laminate (Concept 10) easily received the highest score. The integrated solution is desirable in terms of integration, simplicity, aesthetics, materials usage, weight etc.

The folded laminate concept has therefore been chosen for further investigation.

Table 11 – weighted selection matrix

CONCEPT		1		2		3		4		5		6		7		8		9		10	
Attribute	W	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS	S	WS
Aesthetics	0.08	7	0.56	5	0.40	7	0.56	6	0.48	6	0.48	5	0.40	10	0.80	10	0.80	10	0.80	9	0.72
Innovation	0.08	4	0.32	6	0.48	5	0.40	5	0.40	5	0.40	6	0.48	6	0.48	6	0.48	8	0.64	10	0.80
Tooling	0.04	6	0.24	10	0.40	6	0.24	7	0.28	5	0.20	10	0.40	5	0.20	1	0.04	5	0.20	10	0.40
Labour	0.05	9	0.45	6	0.30	8	0.40	8	0.40	8	0.40	6	0.30	5	0.25	9	0.45	8	0.40	8	0.40
Weight	0.05	6	0.30	9	0.45	7	0.35	3	0.15	6	0.30	9	0.45	6	0.30	10	0.50	10	0.50	10	0.50
Continuity of roof	0.03	10	0.30	10	0.30	10	0.30	10	0.30	10	0.30	10	0.30	5	0.15	5	0.15	5	0.15	5	0.15
Ease of integration into other profiles	0.02	7	0.14	9	0.18	9	0.18	7	0.14	9	0.18	9	0.18	9	0.18	8	0.16	7	0.14	10	0.20
Retrofitting	0.02	9	0.18	9	0.18	9	0.18	8	0.16	8	0.16	8	0.16	4	0.08	4	0.08	4	0.08	4	0.08
Materials																					
Proven Materials	0.02	7	0.14	6	0.12	5	0.10	8	0.16	5	0.10	6	0.12	7	0.14	6	0.12	6	0.12	7	0.14
Thermal match	0.01	7	0.07	8	0.08	6	0.06	6	0.06	4	0.04	7	0.07	10	0.10	10	0.10	7	0.07	10	0.10
Availability of materials	0.04	10	0.40	10	0.40	10	0.40	10	0.40	8	0.32	10	0.40	10	0.40	10	0.40	10	0.40	10	0.40
Recyclable	0.01	8	0.08	8	0.08	7	0.07	10	0.10	5	0.05	8	0.08	7	0.07	7	0.07	10	0.10	7	0.07

CONCEPT		1		2		3		4		5		6		7		8		9		10		
Performance																						
Impact resistance	0.03	6	0.18	6	0.18	6	0.18	10	0.30	6	0.18	6	0.18	10	0.30	6	0.18	10	0.30	6	0.18	
Efficiency	0.03	8	0.24	8	0.24	8	0.24	7	0.21	8	0.24	8	0.24	8	0.24	9	0.27	8	0.24	8	0.24	
Water run off	0.08	7	0.56	7	0.56	7	0.56	7	0.56	7	0.56	7	0.56	8	0.64	10	0.80	8	0.64	10	0.80	
Moisture resistance	0.08	9	0.72	6	0.48	5	0.40	8	0.64	8	0.64	7	0.56	9	0.72	6	0.48	8	0.64	9	0.72	
Heat dissipation	0.01	7	0.07	6	0.06	5	0.05	7	0.07	4	0.04	5	0.05	8	0.08	8	0.08	9	0.09	8	0.08	
Ability to walk on	0.05	6	0.30	6	0.30	5	0.25	10	0.50	6	0.30	6	0.30	8	0.40	6	0.30	8	0.40	8	0.40	
Safety																						
Fire	0.02	8	0.16	8	0.16	8	0.16	8	0.16	7	0.14	7	0.14	8	0.16	8	0.16	8	0.16	8	0.16	
Electrical	0.02	5	0.10	5	0.10	7	0.14	6	0.12	8	0.16	6	0.12	5	0.10	5	0.10	5	0.10	5	0.10	
Manufacture & Installation																						
Number of processes	0.05	7	0.35	7	0.35	7	0.35	8	0.40	8	0.40	5	0.25	9	0.45	9	0.45	9	0.45	8	0.40	
Number of Parts	0.05	6	0.30	9	0.45	8	0.40	8	0.40	8	0.40	6	0.30	10	0.50	10	0.50	7	0.35	10	0.50	
Complexity	0.04	8	0.32	6	0.24	8	0.32	7	0.28	8	0.32	7	0.28	10	0.40	9	0.36	8	0.32	10	0.40	
Handling	0.03	8	0.24	5	0.15	5	0.15	8	0.24	8	0.24	6	0.18	8	0.24	9	0.27	8	0.24	9	0.27	
Ease of installation	0.06	8	0.48	6	0.36	6	0.36	6	0.36	8	0.48	6	0.36	10	0.60	10	0.60	10	0.60	10	0.60	
TOTAL			7.20		7.00		6.80		7.27		7.03		6.86		7.98		7.90		8.13		8.81	

4.6 Detailing

The previous section selected the most desirable concept for further detailing. In this section the chosen concept will be detailed, including mechanical, electrical, manufacturing and installation details.

4.6.1 Mechanical

The mechanical details to be specified include the materials, dimensions, and lapping detail. The BIPV laminate will have an estimated thickness of less than 3 mm, based on the materials listed below. Figure 55 shows an exploded view of the layers of the laminate and identifies the materials used.

- Butyl seal : 10 mm wide, thickness dependent on top EVA
- Bottom EVA : 0.5 mm
- Top EVA - dependent on testing, however estimated at around 1-1.5 mm
- Top ETFE - 0.125 mm
- COLORSTEEL - 0.55 mm
- 156 x 156 mm monocrystalline silicon cells - approximately 0.2 mm

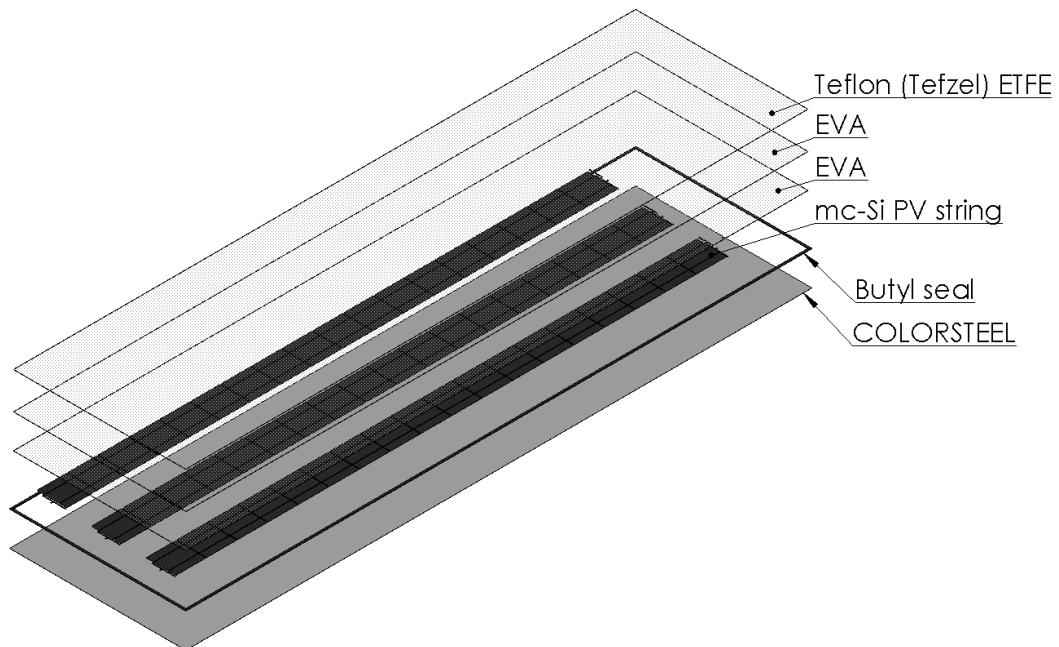


Figure 55 - Layers of BIPV laminate

The BIPV profile differs from the Speed Deck profile in two fundamental ways - the clip in profile has been replaced and is now trapezoidal, and the swages have

been removed. Besides these differences, the BIPV profile will be manufactured to the same dimensions as the Speed Deck profile. The rib height, width, angle and roof cover will all remain the same. Drawings of the Speed Deck profile acquired from Stramit show variations in the profile from pan to pan, which is a consequence of the high tolerance roll forming process. The angle and width of the ribs for the BIPV product was taken as the average of those in the drawing of the Speed Deck profile acquired from Stramit. The height of the ribs is 43 mm, and the profile has a 700 mm wide cover. This leaves a flat pan of approximately 169 mm for the cells to be laminated to, however, due to the thickness of the laminate and folding radii, it is likely to be a few mm narrower than this. This leaves approximately 6.5 mm free on either side of the cells, which should provide adequate space to allow for folding. Additionally, this gap will provide a margin of error to ensure that the cells are not damaged due to inaccurate placement, or cell migration during lamination. When flat, the PV laminate is 915 mm wide and 3250 mm long. CNC folding is dimensionally very precise, so each panel will be near identical to the last. The folded BIPV profile is pictured below in Figure 56.

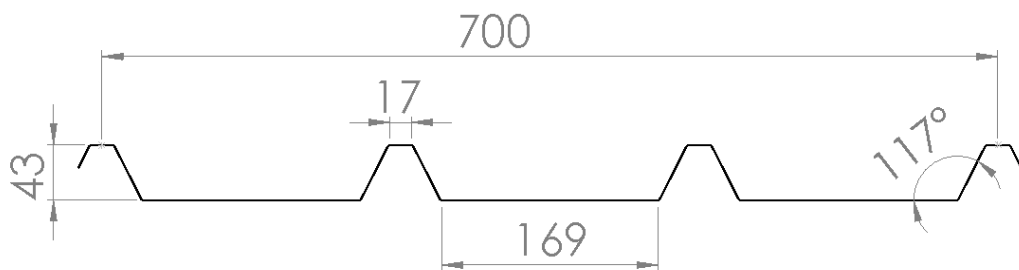


Figure 56 - BIPV profile

When used with translucent sheeting (which is the same profile as BIPV deck), Farlap requires the use of a silicone sealant to compensate for the difference in profiles between the translucent sheet and the Speed Deck sheet. This could be overcome by producing a modified version of Farlap where the upper face of the foam is cut to match the profile of the BIPV deck, which has no swages. This would be a straight forward task. Such a product would not be produced until sales were high enough, until this time the silicone method would be used.

However, to lay more than one row of BIPV panels, an additional lap sealing product would be demanded between BIPV-BIPV for reasons which are clear; the clips are no longer needed and the profile of the foam does not match on either side. The BIPV-BIPV would obviously require no clips, and could just be a total foam solution. It would be beneficial to apply a pressure sensitive adhesive to the underside of the foam. These could be fixed to the panel in factory, however it is more likely that this will be performed during installation. This will reduce waste, as they would be pointless on ridge end BIPV panels.

Farlap utilizes a combination of two different foams - one hard and one soft. The soft inner foam is able to easily conform to the panels to provide a seal - it is able to account for slight variations in the profile due to high tolerances in the roll forming process. The BIPV lap uses the same types of closed cell foams, and the same thicknesses and heights, however the top and bottom faces are shaped to the BIPV profile. Similarly to Farlap, holes are cut through the front face of all three foams in the centre of the pan, and a locating pin is used to tie them all together. The BIPV lapping system is pictured below in Figure 57.

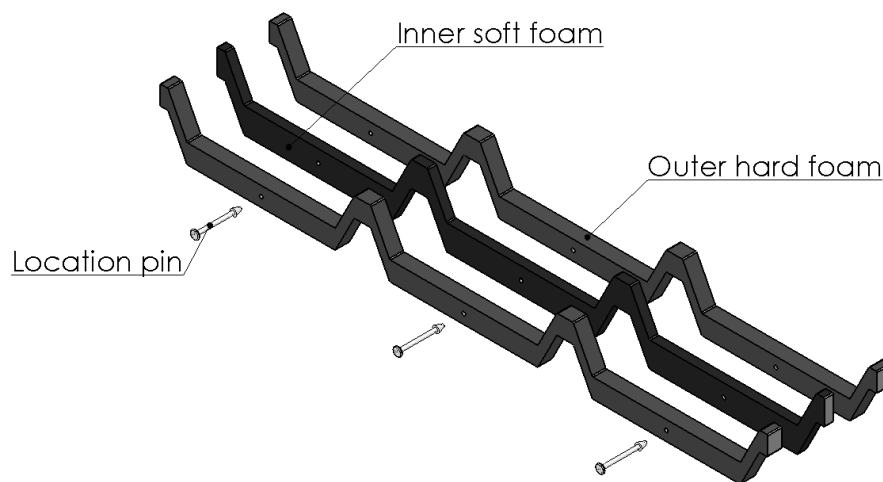


Figure 57 - BIPV lap sealing system

A basic assembly drawing of the product is shown in Figure 58.

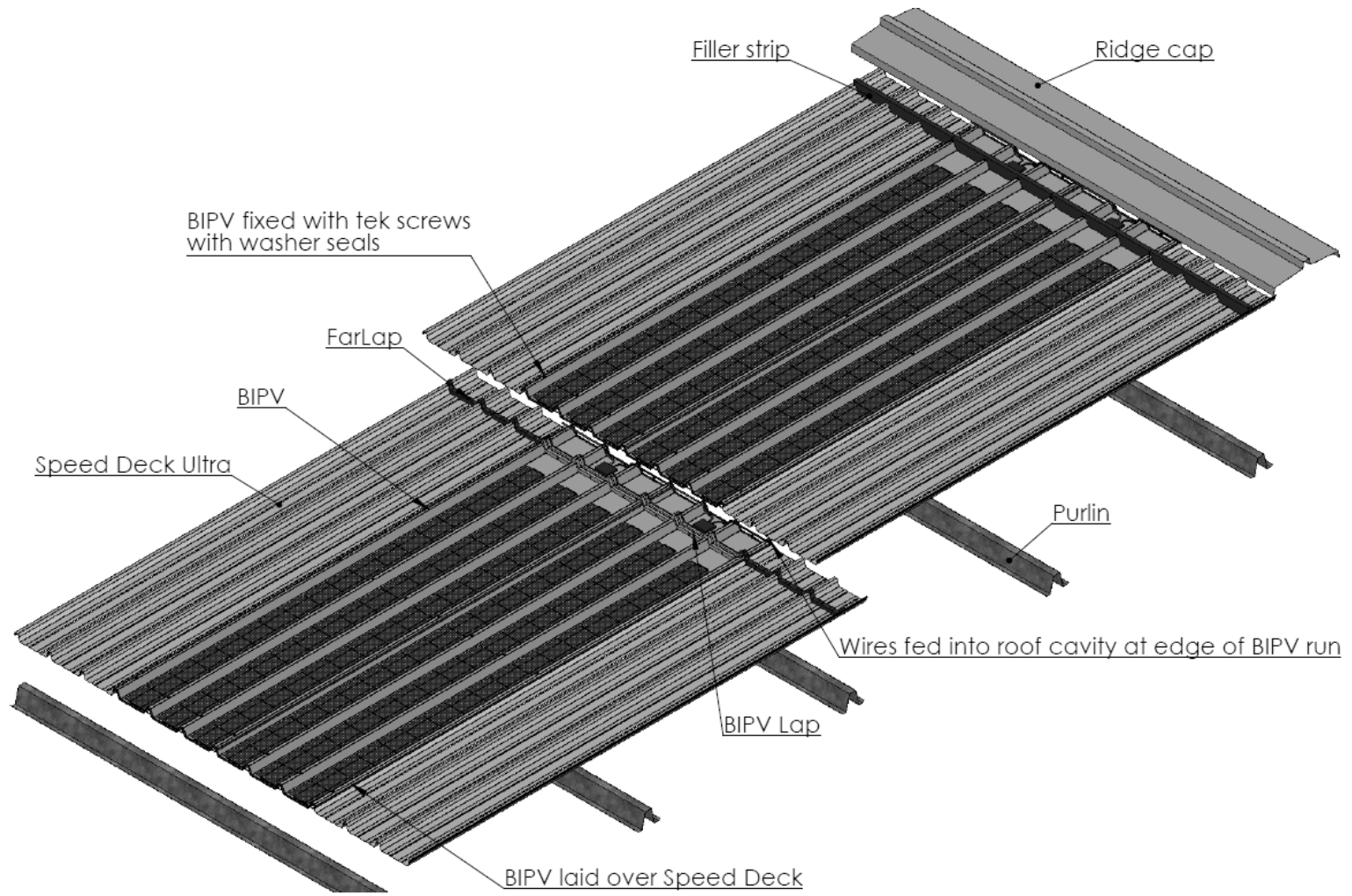


Figure 58 - Rendering of BIPV roof assembly

4.6.2 Electrical

There are several areas of consideration when specifying the electrical details.

These include:

- The power rating of each module
- Junction boxes and bypass diodes
- Ribbon wiring pattern
- Earths

Each pan holds 18 (mono)crystalline silicon cells wired in series. Cell spacing has been specified at 3 mm. These are then stringed together in series by ribbon which ends up feeding over the ribs when folded. A total of four ribbons are fed back to the 4 rail junction box (i.e. SOLARLOK Compact Medium Junction Box : 4 Rail or similar), where there is a bypass diode for each set of 18 cells. Drawings specifying the location and layout of the PV strings can be found in Figure 59.

Based on a product using the same solar cells, front sheet and encapsulant (Lumeta Powerply), it is estimated that each panel will output a peak power at STC of around 210 W. Stringing these in series, with an approximate voltage of 0.51V per cell, gives around 27.7 V per panel at a current of 7.6 A. The maximum system voltage specified by IEC standards is 1000 V. This means a maximum of 36 panels can be wired in series. This sized system would produce a power of roughly 7.5 kWp. This equates to approximately 100 Wp per square metre of roofing, or an area of 10 m² per peak kW.

As the substrate is a conductor (even though it has a non-conductive coating), it is necessary to incorporate earth wires into the product. It is sensible to attach these near the junction boxes. As the top surface has layers of EVA and ETFE, it will be wise to attach the earth to the underside of the panel. A small portion of the coating on the COLORSTEEL at the very edge in the vicinity of the butyl seal will be stripped back with the appropriate tooling, most likely using a drill with an abrasive attachment. A hole will be punched through the COLORSTEEL and protective layers. A corrosion resistant screw with a transverse hole will be fed through the hole, and a nut attached to the top. Earth wire will be fed through the

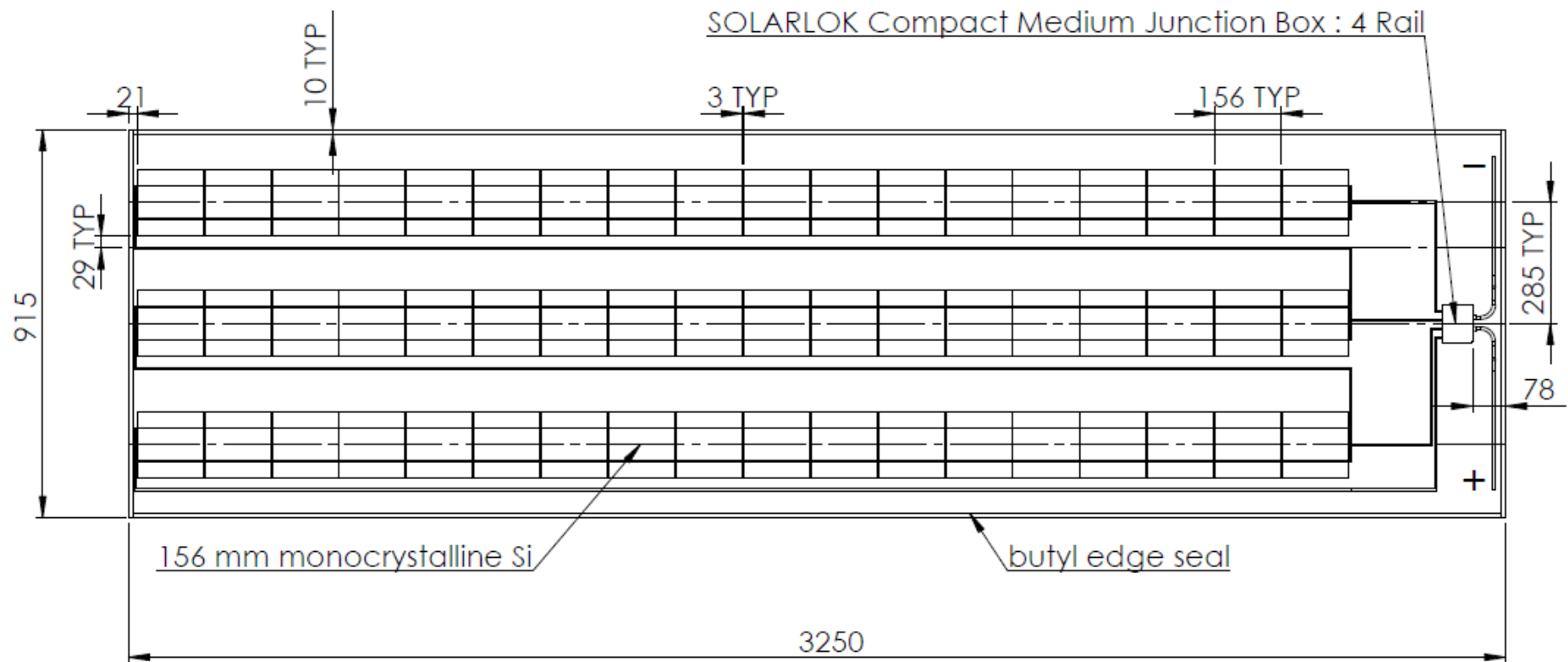


Figure 59 - Drawing of location of PV string

hole in the screw, and a second nut is screwed on over the first. The other end of the earth wire is then attached to the earth point on the adjacent panel. Similarly to the power leads, the earth will be fed into the roof cavity at the end of the BIPV run. Unlike the power leads, only one earth needs to be fed into the roof for each row of BIPV. The earths for each row will be fed to a termination block, which will have a more heavy duty earth running back to the switchboard, or other earth point. The exposed metal on the underside will need to be coated with a corrosion resistant primer.

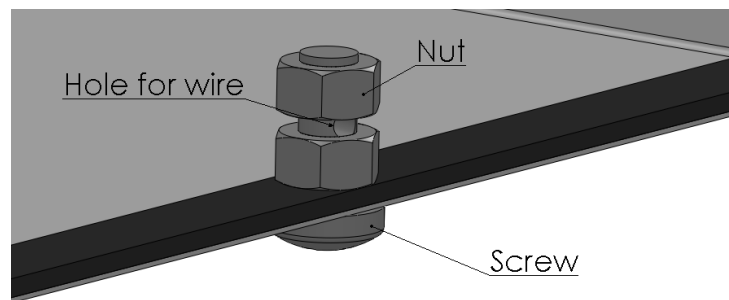


Figure 60 - Earth connection

4.6.3 Manufacturing Steps

This section will provide an outline and guidelines for manufacturing the BIPV product. The manufacturing steps can be summarised as below:

1. Flame treat COLORSTEEL
2. Cut laminate layers to size
3. String cells
4. Layer laminate and apply edge seal:
5. Laminate - likely to be outsourced
6. Pack and ship to Dimond/Stramit
7. Unpack and transfer to CNC folder
8. Fold
9. Pot Junction boxes and attach using adhesive tape
10. Turn up and down ends using Farlap tool
11. Attach earth
12. Testing
13. Sticker/plaque on bottom

Care needs to be taken when handling the photovoltaic panels at all times. This is especially true from the lamination step up to folding of the laminates. After folding, the module will have a level of stiffness and handling procedures will not have to be as strict. The greatest hurdle may well be transferring the laminate lay-up to and from the laminator. The laminate will have to be well supported along its length.

When laminates arrive from the laminators, they should be packaged in such a way to allow easy transfer to the folder. It would be beneficial to have the laminates loaded on top of a table, built to the same height as the folder. The table would be mounted on rollers, so that the laminates could just be rolled up to folder, and loaded in with no difficulty, simply from the table to the folder by two workers. Depending on the height of the stack of laminates, it may be beneficial to have the table adjustable in height.

4.6.4 System Design

4.6.4.1 Roof design

It is important to design the BIPV in the correct manner in order to maximize the power output, and therefore return on the system. For an initial idea of the maximum sized system in kW_p possible for a particular application, the following equation can be used:

$$P_{max} = 0.21 * \frac{W - 1.4}{0.7} * \left(\frac{H}{2.95}\right)$$

Where W is the width of the roof and H is the height. At the optimal roof positioning, it is estimated that the system will produce 4.3 kWh per kW_p a day. This equates to an annual income of 717 AUD per kW_p based on the FiT rate for small PV systems in the A.C.T. of 45.7 c/kWh. For systems between 30 and 200 kW_p, the rate is 34 c/kWh, which equates to an annual income of \$537 per kW_p. Over the *guaranteed* lifetime of the product, the optimistic scenario equates to 17,931 and 13,446 AUD respectively, assuming no degradation in power output over 25 years. Over the lifetime of the roof (which can be over 40 years) the returns will be much greater than this. A.C.T. is at a latitude of 35.3 ° S, where the optimal elevation to take advantage of the maximum solar radiation is

approximately 55 degrees, oriented north. Commercial roofs are typically not this steep and will therefore have a reduced output, with returns not as high as those calculated.

Correct roof design is crucial; guidelines similar to the design of translucent roofing used with speed deck should be followed. The most important aspect of this design is that due to the trapezoidal profile of the BIPV deck, BIPV deck MUST be laid OVER speed deck, and speed deck must never be laid over the BIPV deck. This becomes clear when the two profiles are laid side by side, the BIPV deck profile is slightly larger, and therefore can only be installed over speed deck. It is desirable to have the BIPV run the width of the roof, to minimise the number of laps required for a given installation, rather than have a narrow section of BIPV which runs all the way from the ridge to the gutter, which requires multiple laps. BIPV should not be installed at the very edges of the roof, as the pans at the very edges need to have flashing covering them.

All purlins are installed in the same plane. Where standard speed deck is to be used, follow the guidelines for purlin spacing. Where there is to be BIPV deck, purlins should be spaced at 1450 mm. If the BIPV is to be used on a roof with a slope as low as 1 degree, purlin spacing should be adjusted slightly, to 1700 mm from the lower join, and 1300 mm to the upper join, or alternatively a spacer should be used on the middle purlin, to allow for water drainage. The lapping spans at each joint shall be regarded as end spans for the purpose of determining wind and foot traffic capacity.

4.6.5 Installation

All relevant OSH standards and other safety regulations must be followed during installation of the BIPV system.

1. Panels are installed from the bottom of the roof, working upwards. The lower run is installed, making sure any BIPV panels are laid over the Speed Deck panels. BIPV panels are fixed using tek screws as they cannot clip in to the Speed Deck clips.

2. The upper end in every Speed Deck pan is turned up, while the lower end is turned down as with standard Farlap applications, using the Farlap up-down tool. BIPV panels will not have this requirement as these will have the ends pre-formed in-factory.
3. Plug junction box connectors together, and feed the last terminals through the roof at the ends of the BIPV run. Ensure that no more than 36 modules are connected in series in this manner, to ensure the system voltage does not exceed 1000 V.
4. Earths shall be connected to adjacent panels via the provided mounting method, and fed into the roof cavity at the end of the run.
5. Follow the guidelines for installing Farlap where there is to be a Speed Deck to Speed Deck overlap. BIPV-Speed Deck overlaps require a bead of silicone sealant to be deposited across the top and bottom of the Farlap connectors. BIPV-BIPV laps will use the custom foam sealing system, positioned in the same place as the Farlap system. Speed Deck laps should be made before BIPV laps as BIPV needs to be laid over Speed Deck.
6. BIPV panels are then fixed down using tek screws, allowing for a 150 mm overhang past the lap sealing system.
7. Once again, connect junction boxes and earths together and feed wires into the roof cavity.
8. The remainder of the electrical installation is then performed as normal by a qualified installer.

It is recommended that caution be taken when walking on the roof, especially when walking on BIPV panels. Always wear flat rubber soled shoes and place feet only in the pans except at supports, taking care to avoid the last pan or two near edges of the metal roof area.

Chapter 5: Experimental Verification of Concept

5.1 Introduction

There were several unknowns identified with the feasibility of the preferred concept selected in Chapter 4. This section will address the issues, and answer the question of whether the design will work in practice. The main unknowns pertain to:

1. the ability to fold laminates - the most important issue - whether laminates are able to be folded without damage to the cells, electrical components or polymer front sheet
2. Whether ribbons can be fed over the ribs and bent without damage
3. the adhesion of EVA to COLORSTEEL back sheets - will EVA adhere sufficiently to COLORSTEEL, and if so, are any surface treatments necessary?

This will require determining a suitable method of lamination for small scale testing purposes.

5.2 Adhesion of EVA to Steel substrates

5.2.1 Background

Sufficient adhesion strength between the layers in photovoltaic modules is vital to avoid delamination and moisture intrusion under prolonged service exposure. Previous prototypes constructed by the UoW based on stainless steel substrates have exhibited delamination at the corners, despite not having being exposed to the elements. No literature is available on the subject as COLORSTEEL is not traditionally used as a substrate in PV modules.

Surface treatment of COLORSTEEL may be necessary to ensure that it adheres adequately to the EVA. Several options are available, including flame, corona and chemical treatments, and priming⁶¹. Such treatments increase the surface energy of the material, resulting in greater adhesion between the treated layers. This study used flame treatment to increase the surface energy of the COLORSTEEL substrate, as corona treatment was not easily obtainable.

Peel strengths for commercial photovoltaic modules are commonly available, and are typically in the range of 20 N/cm (EVA_{sky} by Bridgestone), up to over 100 N/cm, with most lying somewhere in between these extremes, at a value around 60 N/cm (Ameyo, Stig-tech EVA, etc.). Therefore 20 N/cm will be taken as the baseline for the minimum acceptable peel strength between layers.

5.2.2 Lamination method

As there are no PV laminators in New Zealand, it was decided to first attempt to replicate the lamination process at the UoW. Several possibilities were identified for producing small scale PV laminates at the university - using combinations of the vacuum oven and hot plate press, vacuum bagging under heat, or more ideally the fabrication of equipment which more accurately simulates the commercial lamination process.

The vacuum oven and hot plate press were used to produce small PV test laminates in a two step process. These are small scale - the vacuum oven is approximately 380 mm wide by 300 mm deep, and the hot plate is approximately 350 x 350 mm. It has been proposed that the laminates can be first heated under vacuum to above the melting point of EVA, and subsequently transferred to the hot plate press to perform curing and cross-linking under pressure. The main difference between this and the conventional method is that vacuum is usually applied throughout the entire process. Alternatively, where application of pressure is not necessary the vacuum oven can be used by itself, without transferring the laminate to the hot plate press. This will obviously simplify the process, as only one piece of equipment needs to be used. Since the application of pressure helps to increase the strength of the bond between layers, strength between layers may be reduced using this method. Consequently, this method may be not as well suited to laminates which will undergo adhesion testing, and therefore this method was not selected.

PV lamination using this method and materials is not documented, therefore some experimentation was necessary when determining hold times. Documentation is available for EVA_{safe} for laminating Glass-EVA-Glass constructions using a vacuum kiln or autoclave, which outline hold times and temperatures. Heating

times for samples do not need to be as long as those shown for conventional modules, due to the small size of the laminates. Additionally, gradual heating is usually performed to compensate for warping of the module due to temperature gradients across the glass - COLORSTEEL will not pose the same difficulties as glass and will be able to heat up more evenly with less distortion. The lamination temperature and pressure profile as shown in Figure 61 was to be used for lamination of the PV samples to be used for the adhesion tests.

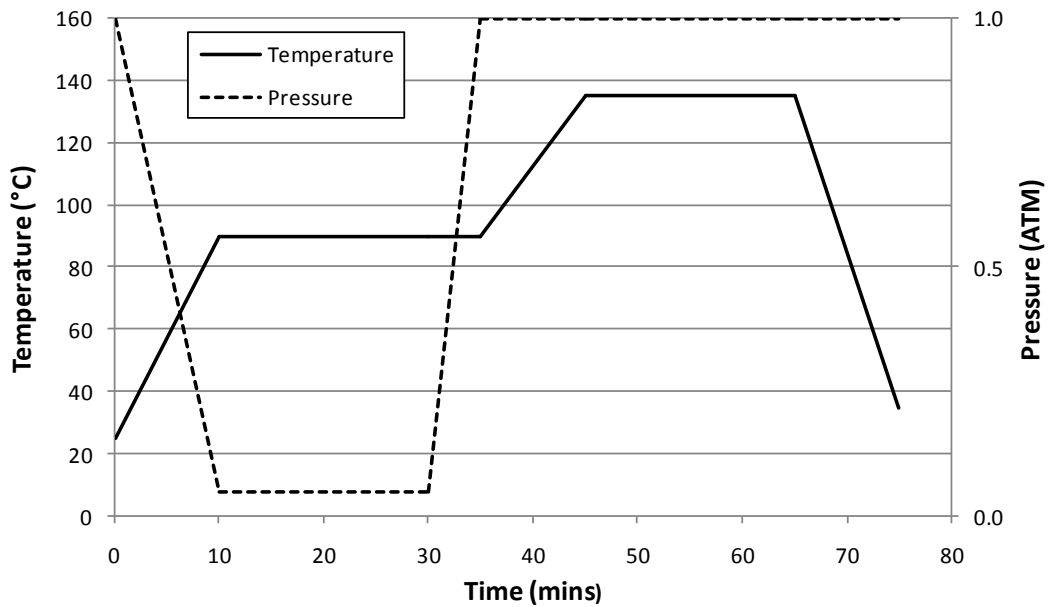


Figure 61 - Lamination temperature and pressure profile used for adhesion testing

5.2.3 Experimental Method

Laminate layers were cut to size - two 305x300 mm of COLORSTEEL and two 229x300 of EVA. This provided 229 mm of bonded region, with 76 mm unbonded, in accordance with ASTM D1876. Layers were stacked COLORSTEEL-EVA-COLORSTEEL as shown in Figure 62.

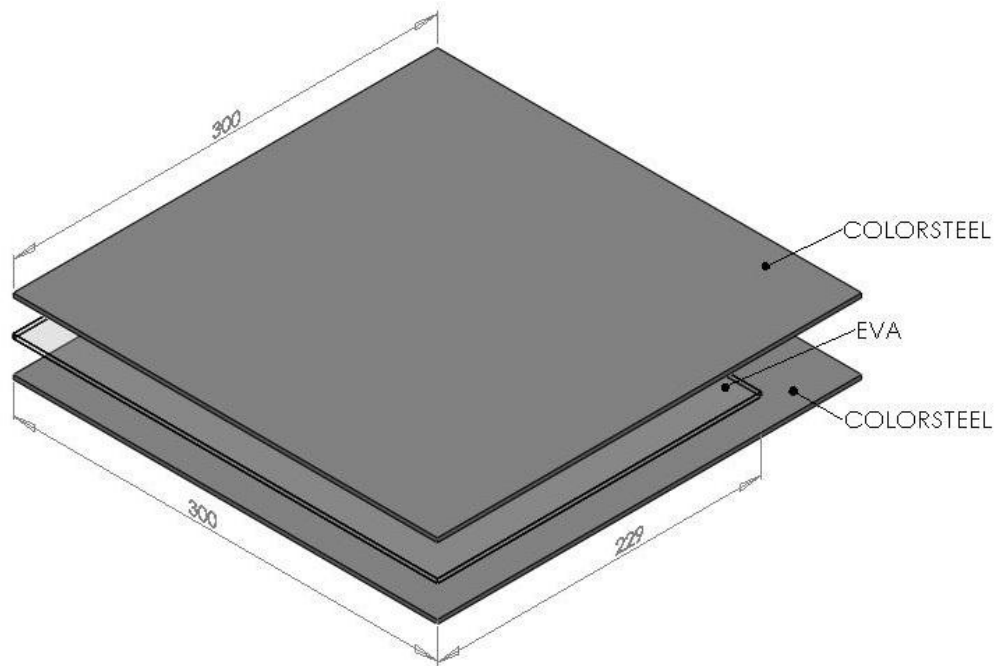


Figure 62 - Laminate layers

The laminate was then placed in the vacuum oven on a Teflon sheet to ensure easy removal of the final product. The laminate was then heated above the melting point of EVA to 90 °C, as recommended by the manufacturer. This temperature was held for 20 minutes, before the laminate was transferred to the hot plate press, and heated to 135 °C, under a pressure of approximately 100 kPa. After 30 minutes in the press, the laminate was removed and allowed to cool to room temperature on a rack. Test laminates were then cut into 25 mm strips on a guillotine, and the unbonded regions were bent 90° to form a T-shaped sample, as pictured in Figure 63.

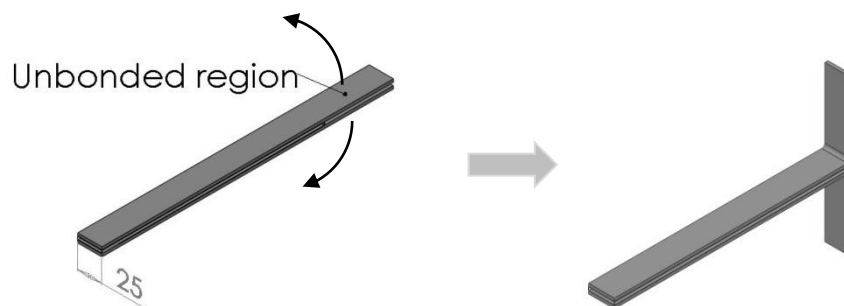


Figure 63 - Strips of laminate bent to T-shape

Ten samples were then tested in a tensile tested using a rate of 254 mm/min, adhering as close as possible to ASTM D1876.

The procedure was then repeated, except using COLORSTEEL which had been flame treated on the side which bonds to the EVA. Flame treatment was achieved by running the flame from a small butane hand torch over the surface of the COLORSTEEL. The COLORSTEEL was then dyne tested to see whether the surface wetted and if there were any spots which were not adequately treated.

5.2.4 Results

The average peeling force was taken across the length of the bond. ASTM D1876 was followed as closely as possible, however many samples exhibited weak areas in the bond meaning in some cases the tested bonded area was less than the recommended 127 mm of bonding.

Figure 64 shows the results typical of an untreated specimen - note that the graph is for a 25 mm sample, so does not represent the force per cm. These samples averaged only 8 N/cm. The average peak force required to separate the sample was 26 N/cm. Note that the entire sample was not able to be tested due to the weak bond. Once peeling had started, the rest of the sample simply peeled away with very minimal force required.

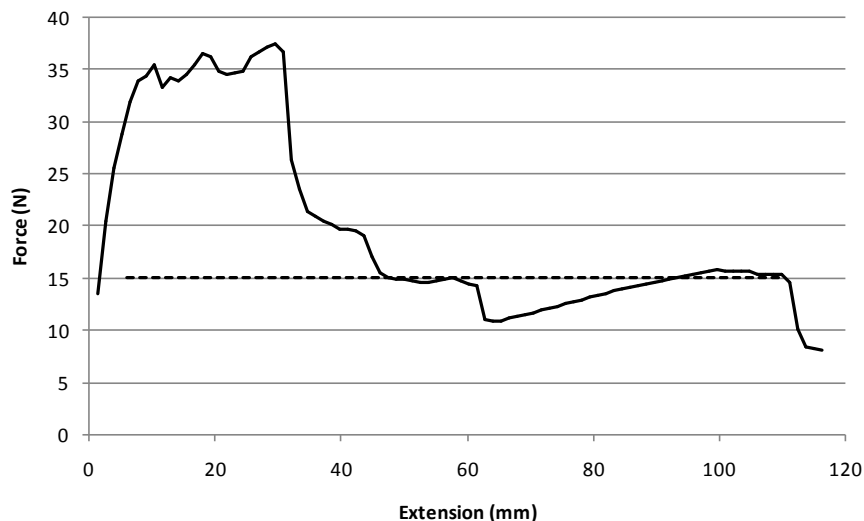


Figure 64 - Peel test typical of an untreated sample

Figure 65 shows the results typical of a flame treated specimen - note that the graph is for a 25 mm sample, so does not represent the force per cm. These samples averaged 56 N/cm. The average peak force required to separate the

sample was 94 N/cm. Most of the flamed samples did not exhibit constant adhesion strength across the length of the bond.

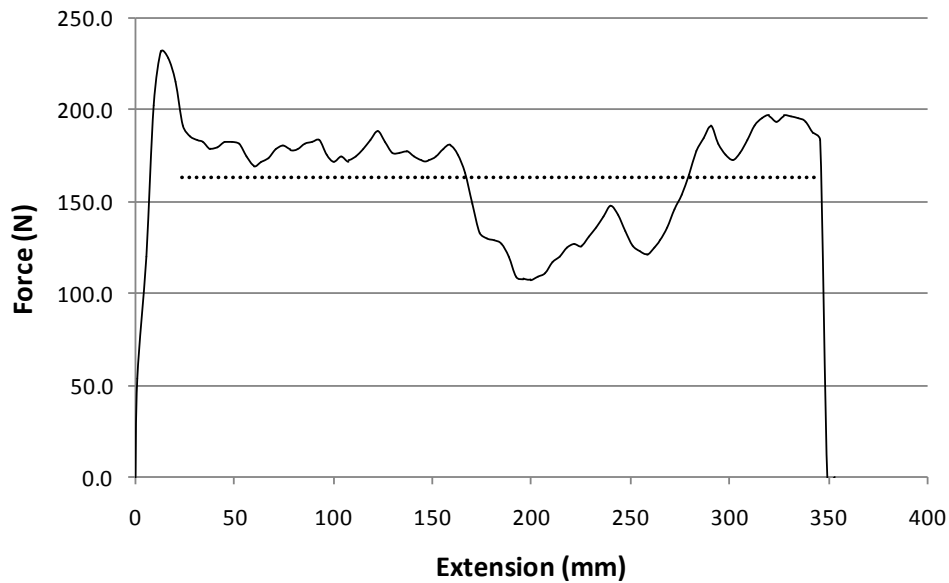


Figure 65 - Peel test typical of a flame treated sample

5.2.5 Discussion

There is a clear difference in adhesion strength between the treated and untreated samples. The treated samples were on average 7 times stronger than the untreated samples. The untreated samples had an average adhesion strength of 7 N/cm, which falls below the generally accepted standard to be used in PV modules, which was determined to be 20 N/cm. However, the treated samples were far stronger, with an average of 56 N/cm. This suggests that some form of surface treatment is necessary if COLORSTEEL is to be used in PV laminates.

Samples did not exhibit consistent adhesion strength across the bond. The main factor contributing to this is likely to be the inclusion of air bubbles in the laminate, and hence areas of poor adhesion, as the samples were not under constant vacuum throughout the entire process. Additionally, the flame treatment may not have been applied consistently across the entire sample. With stricter control over the flaming process, it is estimated that the average bond strength will increase further to around the 80 N/cm. This would place the adhesion strength of COLORSTEEL to EVA at the higher end the range when compared to

other back sheet materials. It is unsure whether there is any degradation in the surface if the COLORSTEEL is left to sit for a long period of time before it is laminated.

5.3 Fabrication of Laminating Unit

5.3.1 Background

It was necessary to produce small PV laminates for folding purposes to prove whether or not the concept is feasible. Several methods were trialed in an attempt to produce a laminates of adequate quality, however initial attempts produced laminates of poor quality. These involved combinations using the vacuum oven and heated press. Laminates were placed in the vacuum oven, and heated to 90 °C, and held there for 20 mins. Subsequently, heat was increased to 135 °C and held there for 30 mins. Such conditions meant that air was included in the laminate as bubbles, and when vacuum was applied the entire time, but adequate pressure was not applied, ripples were formed in the laminate.

The decision was made to fabricate equipment to simulate the flatbed lamination process on a small scale, based on drawings found in an article published by NASA. The design by NASA closely replicates the true conditions found in flat bed photovoltaic laminators. The basic apparatus is pictured below in Figure 66. Aluminium frames create two chambers when separated by a flexible membrane. Vacuum fittings allow both chambers to be under vacuum, with valves for releasing vacuum (not pictured), and isolating the two chambers. The assembly is placed into the hot plate press to provide heating. The frames, top plate and membrane are bolted together, while the bottom plate is kept as a separate piece. This allows easy insertion and removal of the PV laminate.

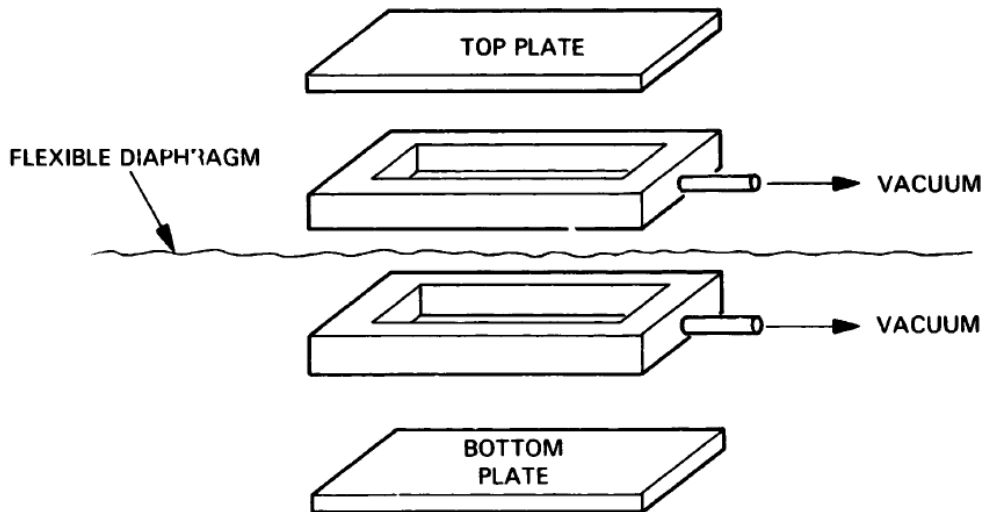


Figure 66 - Basic principle of laminating unit (NASA)

5.3.2 Materials

Materials in the direct vicinity of the hot press need to be able to withstand temperatures of up to 135 °C. A selection of vacuum tubing was found in the workshop, but it was unsure whether it would withstand the required temperatures. These were placed in the oven at 135 °C, and subsequently increased to 200 °C to ensure they would withstand the elevated temperatures. The nylon samples were able to withstand these temperatures easily without softening or melting. Push in vacuum fittings were sourced, along with valves for isolating the top chamber and releasing the vacuum.

The largest width mild steel sheet readily available was 300 mm, so this was selected as the overall width for the laminating unit, in 5 mm thickness. No steel bar was available in the appropriate length or size, however 20 x 20 mm solid aluminium was on hand. This was selected despite the fact that it would be more difficult to weld into a frame.

Several materials were identified as being possible for the membrane - these included Teflon, silicone and nylon based films. Teflon film of 0.25 mm thickness was readily available from a local supplier, so this was chosen. All purpose silicone sealant rated to 150 °C was used to ensure a leak-free rig. Countersunk allen key screws were sourced, to be used to bolt the frame together.

5.3.3 Manufacture

1. The aluminium bar was cut on a band saw at 45 ° angles to form miter joins.
2. The edges of the weld surface were chamfered using a file in preparation for welding.
3. Aluminium welding was outsourced to a local workshop.
4. Frames were surface milled to ensure a flat, smooth surface.
5. Two 5 mm steel sheets were cut at 350 mm on the band saw.
6. 6.5 mm holes were drilled through the top plate and top frame to allow it to be bolted together.
7. The bottom frame was drilled and tapped M6.
8. The top and bottom frames were drilled and tapped in order to screw in the vacuum fittings
9. Parts were thoroughly cleaned and a silicone sealant was applied between the top plate and top frame.
10. Vacuum grease was used on the frame surfaces which would mate with the membrane.
11. The top sheet, frames and membrane were then bolted together using the countersunk M6 screws
12. Vacuum fittings and lines were attached
13. A silicone bead was deposited on the bottom sheet and allowed to dry. This will provide the sealing to the bottom frame when put in the press.
14. Spacers were cut from steel sheet on the band saw to raise the laminate
15. An adapter was machined so that the vacuum hose could be attached to the vacuum pump.

5.3.4 Operation

Laminates were layered and placed in the bottom chamber, on top of steel spacers so that the top surface of the laminate sat just below the flexible membrane. The laminates were layered COLORSTEEL, EVA, cell, EVA, ETFE, with the ribbons feeding out the edge of the laminate.

The steps followed for producing laminates are as follows:

1. Vacuum was applied for 15 minutes with no heating applied.

2. Temperature was increased to 90 degrees.
3. The top chamber was then isolated from vacuum, and the air allowed to slowly enter.
4. The temperature was held at 90 °C for 15 minutes.
5. Temperature was increased to 135 degrees, and held once again for 15 minutes.
6. Heat elements were turned off, and air allowed slowly back into the bottom chamber.
7. The press was released and the apparatus removed.
8. The laminate was then allowed to cool to room temperature on a cooling rack.

An approximation of the lamination temperature and pressure profiles is given below in Figure 67.

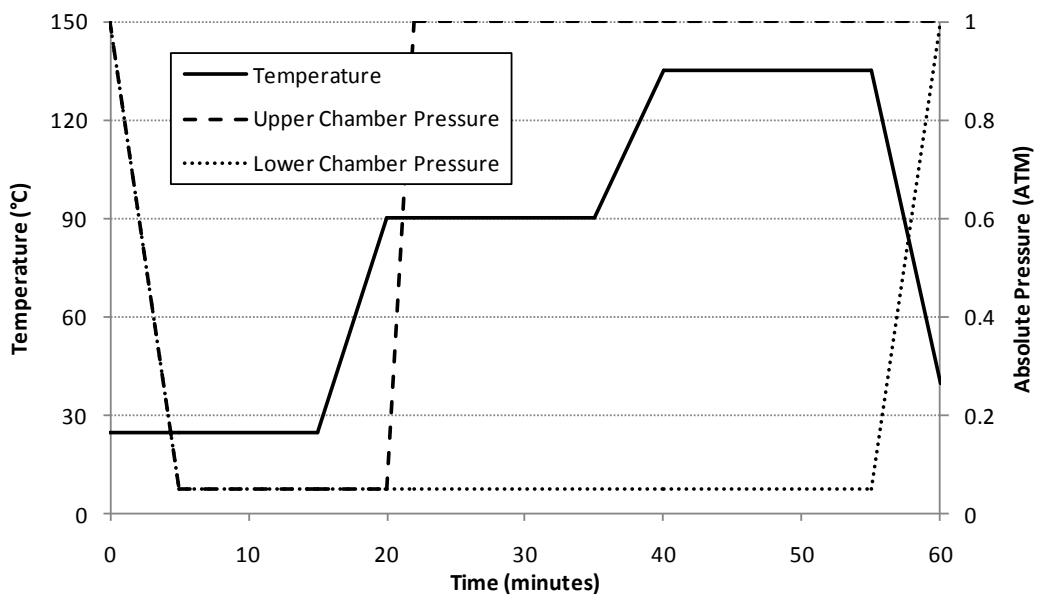


Figure 67 - Temperature and pressure profile used for producing PV laminates

5.3.5 Discussion

The lamination rig performed well, however it was found that the Teflon sheet stretched somewhat and had to be replaced periodically as the seal was broken between the upper and lower chambers. The lamination process was far from optimized in terms of processing times, however this was of little consequence for experimental purposes as it was only necessary to produce a few laminates of high quality.

5.4 Forming PV laminates with COLORSTEEL Back Sheets

5.4.1 Background

Crystalline silicon PV cells are very brittle, and risk breakage during the folding operation. Additionally, the ribbon wire could potentially become damaged during the process. It is also important that the surface of the module is not damaged in any way, as this will accelerate corrosion and failure of the module.

The design of modern folding machines results in very little, if any, surface damage to the work piece. The material is positioned and clamped between upper and lower clamping beams before a folding beam sweeps upward (or downward on up and down folders) to form the pre-programmed flange angle. Parts with numerous bends and different bend angles, open or closed hems, and bends inside of the part can be finished with one setup and one handling. Systems incorporate automatic gauging, clamping, and pivot bending for accurate, versatile part production with repeat precision. It is predicted that the cells will not be damaged, as the deformation caused when folding is extremely localised, so if the cells are positioned correctly there should be no issues. Roll forming or pressing could be options for shaping the PV laminate; however, due to the extremely delicate nature of the cells, it is most likely that the cells would be damaged.

5.4.2 Experimental Method

Laminate layers were first cut to size. COLORSTEEL was flame treated as in the preceding section. Ribbon was soldered to the front and rear of the PV cells. Laminates were layered COLORSTEEL-EVA-PV-EVA-ETFE ensuring the treated ETFE surface was facing the EVA. The ribbon was fed out the edge of the

module, and the procedure described in the previous section was used to form the laminate.

Laminates were then folded into a trapezoidal profile using a hand brake. First they were inspected for any initial damage. Folds were initially made approximately 6 mm from the cell edge. On the subsequent samples this distance was gradually decreased, ending up as close as 1 mm from the cell edge. As folds were performed on a hand brake with only up folding capabilities, the laminate needed to be turned over when folds were required in the opposite direction. Once folded, the laminates were photographed and examined for any signs of damage. This included damage to the cell, top sheet, and ribbons. The power output of the folded laminates was then tested, and compared to a control cell (unfolded laminate), making sure that both were in the same plane, will full sunlight across the cell.

5.4.3 Results

The figures below show the laminates after they have been folded. As pictured, there is no visible damage to cells at the edge. Additionally, there is no degradation in the power generated between the control cell and the folded laminates. Similarly, there appears to be no damage to the ribbons due to folding of the laminates. There is also no damage to the ETFE surface - even the EVA showed no damage. Figure 68 shows a laminate which was subject to folding of the worst case scenario, with the folds beginning as close as 1 mm to the edge of the cell.

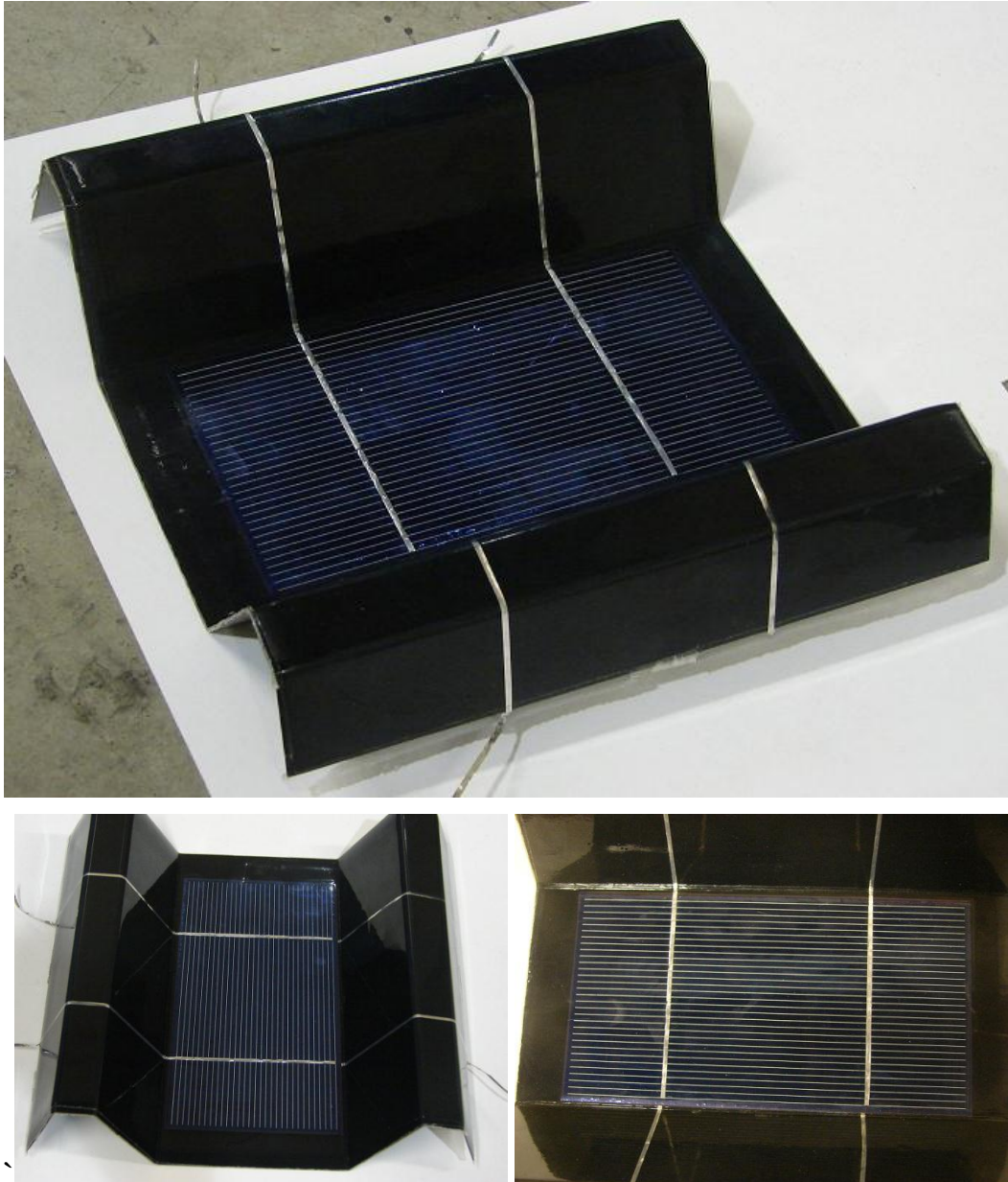


Figure 68 - Photos of small scale folded laminate

5.5 Conclusions from Concept Verification

Through experimentation it has been proven that the chosen concept is viable, both in terms of adhesion of EVA to a COLORSTEEL substrate, and more importantly, the ability to fold PV laminates post lamination into roofing profiles.

Some form of surface treatment is required in order to provide adequate adhesion between EVA and COLORSTEEL. Treated samples showed similar adhesion to other PV products already on the market, and with process optimisation it is expected to perform at the higher end of the range.

PV laminates of high quality were able to be produced on a lamination device fabricated at the university, however there is still room for optimisation of the lamination cycle, and modifications to the rig. PV laminates based on a COLORSTEEL substrate are able to be folded with no damage to the cell or other laminate material to form smart building materials which act as both the building structure, and a power generation source.

Chapter 6: Discussion

6.1 Introduction

The preceding chapters developed a design for an innovative PV product, integrated into long run metal roofing, designed to fit into the current market.

It is important to evaluate the chosen design, to ensure it meets all the design requirements, and gauge it's suitability for production. This chapter evaluates the design based on the requirements stated in the PDS, discusses the potential for development of the product, and provides recommendations for future work.

6.2 Evaluation of Design

It is important that the BIPV product meets the design requirements specified in the PDS, and that the design has not digressed from these. One of the most important requirements of the design is that it must be an integrated solution and not infringe on the aesthetics of the roof. The design generated in this thesis integrates well into the Speed Deck profile, and is not a bulky add-on, as most other PV products are. The design merges well into the roofline, maintaining the aesthetics of the structure. This is a truly integrated solution, no extra framing, brackets or supports are necessary, the BIPV product acts as the roofing surface, and all wiring is hidden from view. However, the concept does require the continuity of the roof to be broken, resulting in laps in the roof. This is not a huge negative, as it has little impact on the aesthetics of the roof.

The generated concept exhibits a high degree of innovation, and as such it is differentiated from other products on the market. It incorporates two new ideas, the first being using COLORSTEEL as the back sheet for PV laminates. More importantly, it proposes the idea of forming PV laminates into roofing profiles. This thesis has gone beyond the generation of an innovative idea, and has actually provided the basis to prove that the concept will work in practice. The idea of folding PV laminates into roofing profiles could be valuable in terms of IP, and has the potential to be patented.

Utilizing a modular design means that every panel can be made identical and the length of the panel does not depend on the specific application. Modular design means thermal expansion becomes less of an issue, as panels are now short, discrete lengths. Installation and handling will also be easier as panels are only a few metres in length. There may be a small degree of difficulty in handling the panels up until the folding step, as the thin laminate will lack stiffness, however this should be able to be easily overcome by implementing the correct handling procedures.

The main competitor to the BIPV product is UNI-SOLAR laminates, which are applied to metal roofing in a peel and stick manner. This product goes one step further and provides a fully integrated solution, where the PV laminate actually acts as the roof surface. UNI-SOLAR is currently limited to profiles which have large pans of around 400 mm, so it is only suited to large commercial and industrial buildings. The BIPV product which is the topic of the thesis fits into a much more attractive profile, and can theoretically be adapted to a variety of profiles, which opens up a much larger market. Comparing output per m² of roofing, this product performs in the middle range, it would be near the higher end, however, space is lost due to the ribs which do not have PV cells covering them.

Ideally the product would have retained the clip in functionality of Speed Deck, however the folding process did not allow this, however this is not a big issue. The fixing of the product to the roof uses standard roofing practices, meaning there will be no issues with leakage. It uses a similar fixing method to translucent sheeting which is currently used with Speed Deck. The translucent sheeting also has a trapezoidal profile, and standard fasteners are used to fix it to the roof as it does not have clip in functionality. Installation of panels will be very straightforward, with no specialized labour required to install the panels. It is recommended, however, that the system design be undertaken by a PV designer, and wiring of the panels to the inverter and grid be performed by qualified persons as normal.

The product has been designed to be able to meet all of the relevant IEC standards by using standard products which have already been proven in the solar industry. Specifically, the most common encapsulant, EVA, has been chosen, along with an ETFE cover which is already used in crystalline silicon products on the market. Additionally, an in-laminate butyl seal will be used at the edges - this has been proven in thin film applications due to the strict sealing requirements, however it does not find regular use in crystalline silicon modules as these typically use edge tape and aluminium frames. This means that the product will be able to withstand damp heat tests, and when the thickness of EVA is optimized, it will be able to withstand hail. The roof life will even be extended due to the extra protection from having the protective coverings. This BIPV product will be able to produce approximately 200 W peak per panel, in a safe and reliable manner. The use of standard junction boxes means there will be no issues with electrical safety or performance with connecting of adjacent modules. Also, junction boxes are now isolated from the environment so they can be expected to last a lot longer. They can even be substituted for cheaper items which do not need to meet the strict requirements of IP65.

The product has been designed to be low cost. Measures which ensure it will be competitive on the market include:

- Integrated design - product is dual purpose and serves as both roof surface and power generation, no additional frames supports or mounting structures are required
- Low cost materials - common materials have been chosen - COLORSTEEL, EVA, ETFE, butyl etc.
- Installation - installation is very simple and will not require a great deal of labour

The issue of oil canning in the BIPV product resulting from the lack of swages in the profile has been raised on several occasions by those who work in the roofing industry at Dimond. Swages are typically incorporated into roofing profiles to prevent this phenomenon - without these a standard roof is likely to be susceptible to a perceived waviness in the flat areas of metal panels. Longitudinal thermal expansion is a significant contributor to the degree of oil canning. With the

profiled laminate concept, panels are fabricated in short lengths, which means longitudinal expansion is of little consequence. Additionally, the combination of EVA, cells and FEP will make a small contribution in providing strength to prevent oil canning.

6.3 Potential for Product Development

Once a product is entered into the market, the design process is not over. It must be continually developed as adapted to the changing market place, or else it will eventually become outdated. This section reviews the products adaptability to other roofing profiles, other PV technology, and to BIPVT.

6.3.1 Adaptability to Alternative Roofing Profiles

The product concept is not dependent on the choice of roofing profile. It could easily be adapted to a wide range of other roofing profiles which have a rib and pan design. It be advantageous to incorporate it into a corrugate profile, however this is not feasible, as there are no flat portions of roofing in which to incorporate the brittle crystalline silicon cells. This would increase the uptake of the technology, as it would become more of a ‘designer’ product, giving users the option of multiple architectural styles. Architects would be more willing to incorporate the BIPV technology into their designs. Speed Deck is predominately a commercial profile, so incorporating into residential profiles would definitely open up a large and expanding market opportunity.

As described in Chapter 3, c-Si cells are most commonly produced as 125 and 156 mm (pseudo) squares. Profiles with a pan width of over 125 mm are obvious candidates for the integration of solar cells. Clearly, it would be desirable to enter the BIPV corrugate market, as this is by far the largest. However, the aesthetic value of a BIPV corrugate product is currently limited due to reasons already mentioned.

The product could potentially be integrated into a number of profiles produced by Dimond. Of the residential profiles, Styleline would be the obvious choice, as it has the second highest market share behind corrugate. The pan width of Styleline is only 127 mm, and would not be able to take the 156 mm cells which are used in

the Speed Deck design. However, there is the possibility of integrating 125 mm cells, or even laser cutting larger cells to the appropriate size. It has been proven that the cells can be as close as 1 mm to the fold line, so if the string of cells was placed accurately there should not be a problem. Alternatively, the pan of the BIPV could be made slightly wider to allow incorporation of the cells if damaging the cells is of concern. This would not compromise the aesthetics of the product. The same would apply to the Veedek profile.

Of the low rib commercial profiles Pacific and Sahara would not be suitable for this application, due to their similarities with corrugate. However Metric and Windek have a pan width of 188 mm, which would be well suited to the integration of 156 mm cells, leaving around 16 mm free on either side of the cell. Of the high rib profiles, only DP955 and Topspan have pans wide enough to allow integration of PV cells. All the other profiles have trough widths ranging from 25 - 110 mm, while DP955 has a massive 239 mm wide trough, and Topspan has 127 mm. It would be preferable to integrate cells into the most popular commercial profile, Brown Built 900, however, a meager 75 mm profile would mean the cells would need to be laser cut in half, and would not utilize a high proportion of the roofing area. The Dimondek range all have pans wide enough to allow the incorporation of cells, however there may be difficulties in folding the panel to these profiles. An alternative would be to perform the first fold on the CNC folder (the one closest to the cells), and then run the edge of the panel through a roll former to create the rib, and only have panels spanning one pan.

Similarly, the product could be integrated into a variety of profiles from Stramit's range under the same principles described above, including CapacityPLUS and Megaclad, among others.

6.3.2 Adaptability to Alternative PV Technologies

It was illustrated in Chapter 3 that solar cell technologies are evolving rapidly, and while crystalline silicon may currently be the most sensible solar cell of choice for the product, it is not likely that this will be the case in the long term. Crystalline silicon cells are unlikely to be rivaled in efficiency by competing technologies anytime in the foreseeable future, however, the cost per peak Watt of silicon cells

is likely to be significantly undercut by upcoming technologies in the medium term. It is important that the BIPV product is able to adapt and evolve in tandem with evolving PV technologies. It is evident that many second generation technologies, such as CI(G)S, a-Si and CdTe, will be able to be integrated into the product with little consequence. Power generation per panel would be decreased, along with the cost per panel. The lower power generation results in larger installation size on the roof. In situations where the desired installation size is limited by available roof space, it would be desirable to use crystalline silicon to boost the power output.

The time at which the product becomes outdated would most likely occur only if certain technologies attained a degree market success, such as a 'paint on' solar cell, as envisioned by Dyesol Ltd. However, there are still multiple technical hurdles with such technologies, and it is predicted that these are still years away from production.

6.3.3 Incorporation of thermal to form BIPVT

The UoW is currently investigating BIPVT and BIT products in addition to the BIPV product proposed in this thesis, as summarised in Chapter 1. It would be desirable to adapt the BIPV design to BIPVT by incorporating fluid channels into the design.

The easiest way to incorporate thermal into the design would be to simply attach a fluid channel to the back of the roofing sheet using a thermally conductive adhesive. The channels would then be connected via a manifold. This would be beneficial in terms of strength of the final product, as it would have extra reinforcing on the back. It is likely that the profile would be changed slightly, so that the fluid channel would be able to sit on top of the purlins. This would involve raising the pan by the thickness of the fluid channel, as pictured below in Figure 69.

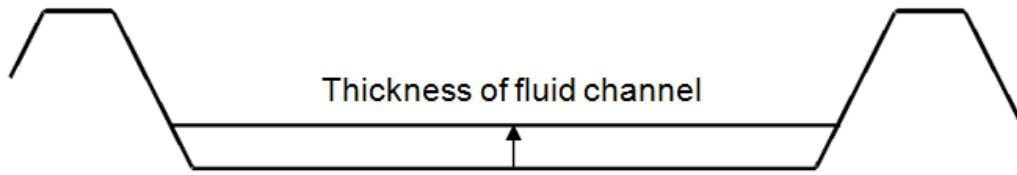


Figure 69 - Modification of profile for BIPVT

There would be a number of extra steps associated with creating a BIPVT product, including, sealing of channels and mounting fittings for inlet and outlet manifolds. However, it is more likely that another avenue be explored for creating a BIPVT product, such as producing an extrusion which acts as the PV backsheet, with fluid channels already incorporated into it.

6.4 Recommendations for Future Work

A strong basis for the production of a BIPV product has already been established, however, there are still certain details to be specified, and additional investigations and testing which would be of benefit. More detailed analysis of certain aspects of the design is recommended. Full scale prototypes would be the next logical step in the development of the product, which can then be tested on site at the university (or elsewhere), and eventually be submitted for IEC certification.

The product is at the point where a full scale prototype is necessary so that it can be folded using the CNC folder. These can either be made offshore, or the laminator constructed in Chapter 5 could be upscaled. It would be advantageous to have in house lamination capabilities. This is because all product knowledge would be able to be kept in-house, avoiding the risk of any third party being able to replicate the idea. Also, if laminates are to be outsourced, there is no way of controlling the process, and therefore the quality of the final product. In-house lamination opens up the opportunity for a multitude of testing options, and optimization of the lamination process. The quality of PV laminate produced is highly dependent on numerous variables, including temperature, heating rate, hold times, pressure, etc. Research is necessary to optimise these variables to reduce the lamination cycle time as much as possible, and still produce a high quality product. Lamination parameters will then be able to be specified to the laminators

when the time comes to produce the product commercially. The unit does not need to be made large enough to fabricate full sized panels; prototypes could be made which only span one pan instead of three. This would also provide an insight into any difficulties encountered when handling the product. These prototypes could then be trialed on the solar testing rig at the UoW. It would be subjected to a variety of tests, including evaluating the performance and power output, its resistance to the environment, and strength testing to see whether it can be walked on, and to formulate guidelines for handling etc.

It is estimated that the lamination unit could cost anywhere up to 10,000 NZD⁶², however this is a ball-park figure, and more detailed analysis would be required to provide a more accurate estimate. Items contributing to the total cost of the rig include, among others:

- Thermocouples
- Vacuum gauges
- Frame to hold lamination unit
- Frame to form lamination chambers (does not need to be aluminium as used in this study, could be cheaper mild steel)
- Membrane
- Top and bottom plates
- Temperature control
- Vacuum pump (possibly sourced from the university, or hired)
- Heating elements
- Labour
- Sealants

There are other factors of the design which need further investigation. A study into surface treatment would be desirable to optimize this process, and determine the best course of action. Corona treatment may well end up being the treatment of choice in the long term. It may be desirable to build a flame treatment rig which is capable of treating the COLORSTEEL in a reliable, controlled, and repeatable manner.

Another aspect which still remains unanswered is how thick the front EVA sheet will need to be in order to provide adequate impact resistance to meet the requirements laid out in IEC 61215. To evaluate this it is recommended that an apparatus is fabricated which replicates the conditions specified by IEC 61215. The apparatus will be used on small scale laminates, which are grouped depending on the thickness of the front EVA sheet. Pass criteria will then be applied to determine the minimum thickness required to pass the certification.

Chapter 7: Conclusions

An innovative concept for a BIPV product for long run metal roofing was successfully generated, verified and evaluated. The concept has the potential to be patented, and can therefore be valuable in terms of IP. There are no other products like it on the market, so it is likely to find its place in the market.

PV laminates are able to be constructed using COLORSTEEL back sheets; however appropriate surface treatment is necessary to ensure adequate adhesion. This study used flame treating to achieve this, which provided a 7 fold increase in adhesion strength over the non-treated sample. Other methods of treatment may be suited, in particular corona treatment. Untreated COLORSTEEL is not suitable for use in PV laminates.

Additionally, flat PV laminates having a COLORSTEEL substrate, (and likely any metal substrate), are able to be folded into shapes capable of mating with existing metal roofing profiles without damaging the cells. The PV laminate then becomes a ‘smart’ building product, serving a dual purpose of generating power and acting as a building material. Folds can be made as close as 1 mm to the cell without affecting the performance of the PV laminate.

The product is best targeted first in Australia, after a small amount of test installations have been performed in New Zealand. Specifically, this product would target the commercial market in A.C.T., where FiTs for medium and large scale producers have been announced. The Speed Deck Ultra profile produced by Stramit, a division of Fletcher Building, was identified as the most suitable profile to integrate the product into. The product is able to utilize existing roofing practices in order to provide a fully sealed roof. It can be easily installed and will be able to be added to Dimond’s product range in order to branch out and target a more diversified market. The most sensible choice of PV technology at this time is first generation crystalline silicon cells.

There is much potential for development of the product and integration into a variety of roofing profiles to create a range of BIPV products. This thesis has

demonstrated that the BIPV product presented is worth further investigation, and it would be beneficial to produce full scale laminates for further research and development. It would be desirable to fabricate an in-house laminator capable of producing full scale laminates. This would allow research to be undertaken to specify the final details of the design. All IP could be kept confidential, and lamination conditions and treatment processes could be optimized. Also a variety of different tests could be performed on the product to ensure it would pass IEC certification.

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