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Assessing the potential of steel as a substrate for building integrated photovoltaic applications

Laurie Hughes[1], Noel Bristow[2], Tatyana Korochkina[1], Pascal Sanchez[3], David Gomez[3], Jeff Kettle[2], David Gethin[1]

1. Welsh Centre for Printing and Coating (WCPC), College of Engineering, Swansea University Bay Campus, Crymlyn Burrows, Swansea SA1 8EN, Wales, UK

2. School of Electronic Engineering, Bangor University, Dean St., Bangor, Gwynedd, Wales, UK (contact details email: J.Kettle@bangor.ac.uk. Tel.: 01248 382471)

3. Surfaces Department, ITMA Foundation, Calafates s/n (Parcela L.3.4), Avilés, Spain

Abstract

Government edicts and national time bound policy directives are shaping the drive toward cost effective renewables such as photovoltaics (PV). Building Integrated Photovoltaics (BIPV) has the potential to provide significant energy generation by utilising the existing building infrastructure as a power generator, engendering a transformation shift from traditional energy sources. This research presents an innovative study on the industrial viability of utilising "rough" low carbon steel integrated with an Intermediate Layer (IL) to develop lower cost thin film BIPV products and is compared to existing commercial products. Consideration of the final product cost is given and potential business models to enter the BIPV are identified. The lab scale and upscaling elements of the research support the significant benefits of an approach that extends beyond the use of expensive solar grade steel. A state-of-the-art review of existing steel-based BIPV products is given and used as a benchmark to compare the new products. The results demonstrate that a competitively commercial product is viable and also highlight the strong potential for the adoption of a "rough" steel + IL focused approach to BIPV manufacture and a potential new direction to develop cost efficiencies in an increasingly competitive market.

Keywords:, Building Integrated Photovoltaics (BIPV), Solar Energy, Renewable Energy, Low carbon steel, Intermediate Layer (IL).

1. Introduction

The long term aim of the Paris Agreement is to maintain global warming to levels well below 2°C above pre-industrial levels. This requires a global step change in governmental policy and a radical transition toward renewables. One of the significant components in this migration toward cleaner forms of energy is the greater use of photovoltaics (PV). Government edicts and national policy directives are shaping the drive toward PV and engendering a transformation shift from traditional energy sources [1]. One of the key elements of this transition is the emergence of Building Integrated Photovoltaics (BIPV).

Within the European Union (EU), directive 2010/31/EU [2] states that all buildings occupied by public authorities built after 31st December 2018 should be nearly zero energy rated. The 2010/31/EU directive also states that all other new buildings must be nearly zero rated by 31st December 2020. This means that new buildings must generate their own energy from renewable sources and not be wholly reliant on traditional grid based forms of fossil fuel related energy beyond these dates. Utilising the building infrastructure to host PV based generation via BIPV has the potential to provide an important component of this transition and enable organisations to comply with 2010/31/EU. However, as highlighted by the International Energy Authority (IEA) in their 2017 report titled: *Perspectives for the Energy Transition - Investment Needs for a Low-Carbon Energy System*; to meet the targets of the Paris

Agreement would require a significant increase in the use of low carbon technologies within the construction sector [3]. The IEA report also highlights the specific challenges of retrofitting within existing housing stock, highlighting that 70% of the existing infrastructure will exist in 2050 and that robust policy intervention is required in many countries to overcome the many barriers [3].

Traditional building products utilised within the construction industry, have ordinarily fulfilled a single function; namely providing a weatherproofing function in the form of a cladding element, roof, or facade in adherence to specific building regulations. The selection of materials is ordinarily based on physical properties, performance and cost as well as design aesthetics. BIPV differs from traditional PV products that are added after construction or modules that are not integral to the building fabric, in that they offer the advantage of providing the conventional building material with PV generation integrated within the product. The definition generally accepted for BIPV, is contextualising the definition by the product's power generation abilities and impact on the building's integrity if the BIPV product was removed. In contrast, traditional rack mounted modules are not integral to the building's infrastructure and can be removed with minimal impact [4], [5]. BIPV products are considered a functional part of the building structure, or architecturally integrated into the building's design. This key advantage over traditional non-integrated solutions highlights the potential for the initial costs of the PV element to be either partially or fully offset by reducing the costs for the building materials component of construction as well as installation. These aspects have contributed to studies highlighting BIPV as one of the key elements of the zero energy building EU target for 2020 [6]. The planning and development of multi-function buildings with integrated façade and roof elements, capable of fulfilling energy generation as well as technical and legal demands, could become an essential, accepted part of the architectural mainstream [7] and building design [6]. The retrofit of BIPV within existing building infrastructure, exhibits additional challenges over new build BIPV, but greater potential due to the available existing infrastructure. Designers and architects need to consider building form and function as well as impact of additional loading on the building's structural integrity. However, the potential for retrofit BIPV is significant. Studies have highlighted that building rooftops in the US could potentially accommodate up to 660 GW of installed capacity, a substantial contribution to renewable energy requirements [8]. Many cities around the world have substantial existing infrastructure and could benefit greatly from hosting BIPV products that are able to accommodate the design considerations and characteristics of existing buildings [9], [10].

A study from Grand View Research highlights that the global BIPV market is predicted to reach $31.14 billion by 2024, a significant trajectory of growth from the $6.94 billion level in 2015 [11]. Furthermore, the report indicates that thin-film BIPV is expected to witness highest Compound Annual Growth Rate (CAGR) of over 20% from 2016 to 2024 due to superior integration within building envelopes in comparison to crystalline products. The main contributor to these figures is integrated roof systems which account for 61% of the overall revenue for BIPV manufacturers [11].

Thin film BIPV can be layered onto a substrate of only a few µm thick providing a range of applications where the product can be adhered to a variety of building shapes or surfaces. Installation and Balance of System (BoS) costs are reduced for thin film BIPV products [12], [13]. Thin film PV can be bonded to building surfaces using peel and stick technology or separate bonding adhesive, negating any requirement for racking infrastructure or structural support. These attributes lend themselves to BIPV applications where the characteristics of new or existing building infrastructure can be accommodated. The stated performance of c-Si based technologies is greater when compared to thin film technologies such as amorphous silicon (a-Si) or Copper Indium Gallium Selenide (CIGS) [14]. However, thin-film solar products can generate energy in sub optimal spectral conditions and are thereby, capable of producing higher relative real world energy yields in comparison with c-Si based systems [15]. Thin film BIPV can be installed within north facing facades or vertical faces where c-Si modules would provide relatively poor performance [16]. Within higher temperature installations, thin-film technologies exhibit greater performance characteristics negating any requirement for additional cooling mechanisms. Thus, thin film PV can avoid the significant drop in performance (up to 50%) of c-Si modules in tropical and hot regions and maintain performance even in low ventilation scenarios [12]. In cases where modern Roll to Roll (R2R) manufacturing techniques and processes are utilised, thin film BIPV products can offer: less waste, minimal handling and reduced shipping costs.

The advent of thin film PV technologies has transformed the potential for BIPV with many forecasters highlighting the high levels of energy demand that could be fulfilled by this technology [17].

However, market conditions within the PV industry including thin film manufacturers, has been problematic. The targeting of global PV markets by the heavily subsidised Chinese manufacturers since 2007/08 has proved to be the catalyst for a prolonged period of difficult trading conditions. Numerous manufacturers have been unable to trade profitably leading to inevitable bankruptcy or reassessment of business models to focus on more downstream activities [18]. The emergence of new technologies and focus on leading edge thin film products has not been an insulator from the problems within the sector. These issues have impacted firms across the spectrum including thin film specialist Hanergy, which was forced to shed 2000 jobs and reported a $1.6 billion loss for the 2015 financial year [19]. These issues highlight the trend of ongoing price competitiveness amongst PV manufacturers with reports highlighting the continued downward pressure on costs continuing to 2020 and beyond [20], [21]. The ongoing demand for niche targeted PV technologies such as BIPV is clear, as targets such as directive 2010/31/EU [22] facilitate change within the market and drive demand. Manufacturers will need to focus on efficient production methods and analyse all cost elements within the supply chain to retain competitiveness within the industry. Innovation is critical as the BIPV industry matures and establishes itself from its current niche position.

This study reports the market potential and cost effectiveness of BIPV products utilising low cost steel substrates. This entails a market analysis of the current state of the BIPV and thin-film industry. Furthermore, a component costings and manufacturing feasibility modelling is provided to estimate a realistic cost (€) for a competitor BIPV product manufactured onto steel. The strengths of the potential product, business justification and industrial viability is discussed. Such work is imperative for the product development and novel as it has not previously been conducted; to implement such production lines requires multi-million pound investment and careful evaluation is required from early steps in the manufacturing process.

The remainder of this paper is structured as follows: Section 2 outlines the background and aims of the study, Section 3 reviews the relevant BIPV related literature and key aspects of the BIPV market sector and shows how steel based products could compete. Section 4 defines the methodology and process utilised within the cost study to derive the required data. Section 5 shows the results of the product cost model and manufacturing feasibility to arrive at a realistic cost (€) for a competitive BIPV product. Section 6 develops the industrial viability theme in the context of the BIPV market place. The key findings and suggestions for future research are outlined in the Conclusions section. To our knowledge, this is the first extensive study of cost analysis of steel-based PV products with an auditable comparison to state of the art products.

2. Study Aims and Objectives

The main objective of this study is to ascertain the industrial viability of innovative approaches to the design and manufacture of BIPV products utilising low cost steel substrates and an 'Intermediate layer' (IL), in place of expensive solar-grade stainless steel. The study analyses the suitability of utilising a range of "rough" low cost steels suitable for the deposition of a number of thin film PV technologies such as: a-Si and Organic Photovoltaics (OPV). The steel types selected are: AIS430 (stainless not solar grade), DX51D+Z, (galvanised) DX51D+AS (Aluminised), DC01 cold rolled low carbon steel) at thicknesses of 0.05mm to 1mm. This range of steel grades and thicknesses were selected to ascertain the technical feasibility and manufacturing viability of the IL approach for a number of potential substrate options. It is accepted that other steel options are available, however, the range selected for this study is sufficient to ascertain the viability of the steel + IL concept for BIPV. The complexity in seeking to use low cost grades of steel is the inherent roughness of the steel surface. Although not visible to the naked eye, these characteristics of low cost steels would ordinarily exclude their use for PV substrate applications without further refinement and processing.

The key aims and objectives of the study are threefold. Firstly, an analysis of the viability of the progression from initial lab-scale feasibility to production scale research and demonstrate the potential for BIPV product manufacture using modern R2R production techniques. Secondly, the performance/cost of steel-based BIPVs developed using the IL-low cost steel grey approach is benchmarked over existing commercial products. Finally, the paper assesses the industrial viability of using steel-based products and identifies a route to market.

3. BIPV market analysis potential for steel based products

Previous studies have discussed the deposition of thin film PV technologies directly on traditional building materials such as roof tiles and steel based products. Researchers highlight a number of advantages over traditional rigid c-Si based PV products that are directly related to the physical properties and efficiency characteristics of thin film technologies in real world operating conditions [23]. These characteristics together with the abilities of thin film products to be more effectively integrated within building infrastructure, are deemed to compensate for the disparity in efficiencies when compared to c-Si based systems [24], [7]. Studies have assessed the viability of utilising steel as an effective substrate material for PV applications. Ke et al. [25] experimented with steel as a suitable substrate, utilising varying thicknesses for the IL applied to the stainless steel. The study concluded that acceptable efficiencies were possible with a 2µm IL incorporated with an a-Si PV layer [25], but the results are specific to a stainless steel substrate under small scale lab conditions. The feasibility of incorporating an IL onto stainless chromium steel to allow the direct deposition of a CIGS PV layer, was studied by Wuerz et al. [26]. The research supported the potential for utilising sheet steel as a substrate material, however, the results in this study are only applicable to specific stainless steel types. The study by Martinez et al. [23] highlights the technical feasibility of utilising an IL with a steel substrate based on a single junction a-Si PV layer. The research established the technical and lab-scale potential for an IL centric approach using a rough galvanised steel type and their application for BIPV products. The study however, did not extend this approach to ascertaining the upscaled industrial viability of utilising an IL or the use of alternative PV layer technologies such as CIGS or OPV. The ongoing pressure for PV manufacturers to reduce costs at every level highlights the need for ongoing research into the use of low cost materials at all stages of the value chain. This study extends the research in Martinez et al. [23] to evaluate the industrial viability of utilising a steel substrate and IL at production scale level. The high level physical properties of products that utilise a steel substrate are shown in Figure 1 a) OPV based PV product and b) a-Si product. The IL also functions as a smoothing layer between the “rough” steel substrate and active layers.

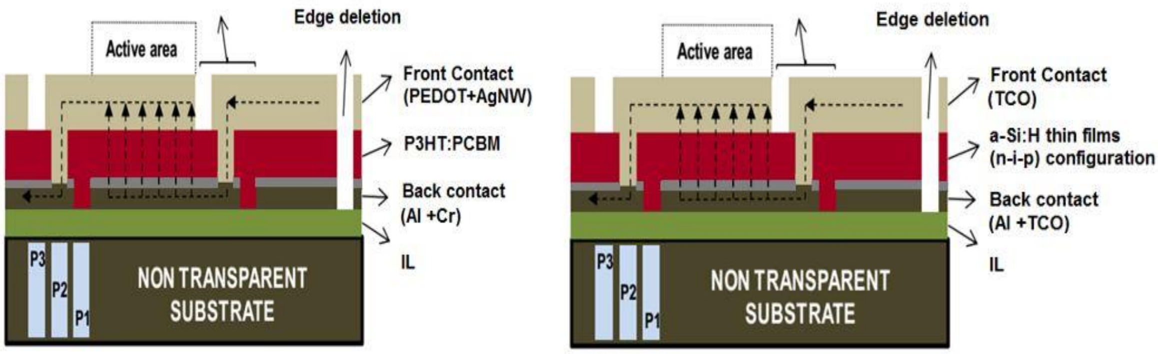

Figure 1: a) PV structure of an OPV example, where PEDOT =poly(3,4-ethylenedioxythiophene), AgNW = silver nanowires, P3HT = Poly(3-hexylthiophene), PCBM =[6,6]-phenyl-C61-butyric acid methyl ester , Al=Aluminium, Cr= Chromium and IL = Intermediate layer and b): PV structure of an a-Si example where TCO = transparent conducting oxide

Studies forecast a rising demand for BIPV, as the increased use of renewables continues and energy production becomes an integral component in combination with architectural design rather than a secondary bolt on addition to the building fabric [27], [28]. The trend toward energy efficient buildings effectively acting as mini power stations [6], incentivized by government directives [2] and a greater awareness of carbon emissions, is likely to drive further innovation and demand within the BIPV industry [12]. In addition to complying with renewable policies such as EU Directive 2010/31/EU, organizations will seek to identify the economic benefits for BIPV and the Return on Investment (ROI) for BIPV solutions. Studies have highlighted payback periods for BIPV installations reaching breakeven points within 10 years , this is critical for further adoption within the industry [29].

The likely long term sustainable success of BIPV is dependent on a number of factors [30]:

- Collaboration between the building industry and PV supply chain to engender a seamless integration between energy generation and building function.
- Clear communication of added value and tangible benefits for consumers and building designers.
- Efficient production methods and processes able to facilitate flexible manufacturing and accommodate changing market conditions.
- Competitive product cost in the form of the solar industry metric of €/W_p and also in the form of the standard building industry metric of €/m^2.

The take up of BIPV is influenced by the criticality of not compromising the load thresholds of building infrastructure. Conventional roofing tiles, typically weigh around 20-30 kg/m^2 whereas fibre reinforced cement tiles can be as high as 60-80 kg/m^2 [28]. The specification of BIPV products needs to accommodate these weight constraints especially in the retrofit context.

The greater availability and lower cost of thin film products are cited as key trigger factors for the success of BIPV, requiring collaboration of all stakeholders, including manufacturers, product designers, marketing, planners, developers, architects and installers [7]. Current levels of thin film production have reduced considerably from the 17% market share in 2009 in part due to the increased competition in the market, continued price reductions for c-Si technologies, and lower costs of c-Si based manufacturing [31]. Although studies articulate the expected increased demand for thin film products within the BIPV sector, the industry faces a number challenges many of which are heavily dependent on strategic, political, social and economic factors [32].

3.1 Thin film BIPV product category analysis

To make the case for the industrial viability of steel substrate + IL based BIPV products, an analysis of prospective competitive products was undertaken from aspects of the literature and available commercial pricing data. The analysis of thin film products specifically targeted at the BIPV market, yields products that can be categorized into three main groups: semi flexible, thin film on glass and thin film foil based products. Semi-flexible thin film BIPV products are generally c-Si based technology exhibiting stated manufacturer efficiency levels of between 19% – 22%.

Although lighter than traditional PV panels, c-Si based semi flexible products are still relatively heavy when compared to foil based products. Modules range between 1.5kg/m^2 to 3.5kg/m^2 depending on panel size and type, thereby limiting their use for some retrofit applications where weight is a key constraint. The SRFM-330 panel shown in Figure 2 from Sopray solar [33] is typical of this style of BIPV product. This category of product generally operates within a flexibility range of 20 - 30 degrees, although some products such as the GH150PF-36 panel from SunPower, claim an operating flexibility range between 30 – 90 degrees [34]. BoS costs for c-Si based semi-flexible BIPV are less than traditional modules, as the standard racking infrastructure is not required. Overall, semi-flexible BIPV products offer a high efficiency product with long lifetime performance but are limited for many applications that require additional flexibility, lighter weight and consistent performance under a range of real world spectral conditions.

Figure 2: Semi flexible c-Si BIPV: Sopray Solar – SRFM-330 panel [33].

Thin film on glass BIPV products effectively replace traditional glazing within buildings, but with the added benefits of semi-transparent PV. BIPV glazing products can be used within a number of application areas such as shelters, facades, cladding, skylights and transparent roofing installations (Figure 3).

Figure 3: Examples of thin film on glass BIPV products [35]

Thin film on glass products generally exhibit stated transparency figures of 10 - 50% and a consistent operating performance in a range of high temperature conditions without requiring additional ventilation [31]. These products can offer advantages where roof space is limited, delivering benefits for large facade installations [36]. Thin film on glass BIPV products however, are limited by their rigid form and inability to be integrated within constructions that are of non-uniform shapes and angles. Although up to 30% lighter than traditional glazing units, thin film BIPV glass is significantly heavier, thicker and less flexible than thin film foil products. BoS costs are likely to be higher than thin film foil BIPV due to the glazing supporting framework required. As such thin film glass BIPV would have limited application for many industrial applications and retrofit installations where weight and low profile are key requirements.

In terms of metallic substrates, including steel, thin film BIPV can be produced as a lightweight flexible foil product (Figure 4). The low profile flexible form, allows efficient manufacturing using R2R techniques where long lengths of sheet product can be accommodated in a step by step continuous process. PV manufacturers - Global Solar, Flisom, and BIPVCo, all produce variations on the thin film foil BIPV theme, where products utilize a thin metal substrate, PV layer and protective encapsulation to form the completed product [37], [38]. Thin film BIPV foil products generally utilize a-Si or CIGS technologies although US based First Solar specializes in cadmium telluride (CdTe) technology. Thin film BIPV can be adhered to building surfaces such as roof's or facades using peel and stick type or adhesive bonding methods. The inherent flexibility of foil type products lends them to be used in a variety of BIPV applications that can include curved construction elements and applications where weight and low profile are key factors.

Figure 4: Thin film BIPV examples manufactured with an underlying foil substrate [39], [38], [40]

Thin film BIPV foil products are often aimed toward the commercial and industrial rooftop market where the installation of PV either in the integrated or retrofitted context can benefit from relatively large areas of available space [41]. This factor has advantages for thin film BIPV products that exhibit low power density characteristics but lower cost/m^2.

Thin film foil BIPV manufacturers generally highlight a number of advantages over competing technologies and traditional BIPV installations, particularly in relation to roof applications [42], [27], [31], [37]:

- Significant weight savings over fixed rigid units and glass based BIPV products. Thin film foils are generally around 3kg/m^2 whereas glass based modules are typically in the range 20-25kg/m^2.
- PV layers, especially a-Si, can be layered onto substrates at levels of thickness of 1µm, up to 100 times thinner than traditional first generation PV.
- Flexibility of steel substrate foil products allows for installation onto a range of non-standard roof shapes even at acute angles.
- Improved performance over a wider range of spectral conditions.
- Higher levels of durability in relation to glass based BIPV in ability to sustain impact and retain performance.
- Low profile and lack of requirement for racking infrastructure allows for withstanding winds of up to 160 mph.
- Individual rolls of thin film can be replaced with minimal risk of damage to surrounding BIPV.
- Ease of installation with peel and stick capability thereby providing savings on BoS costs.
- Wide operating range from -40^o to 85^o C with no additional cooling requirement.

Products such as the Flex-01 series from Miasole, demonstrate the ease of installation of this type of product on existing infrastructure. The BIPV foils are effectively rolled out and secured via a peel and stick method, functioning as an energy generator and watertight roof covering. Manufacturers that operate R2R processes also highlight the efficiencies of production and the ability to automate the various deposition processes to manufacture thin film foil BIPV products within single or linked processes. However, significant challenges remain for many thin film foil BIPV manufacturers. The ever present downward pressure on costs within a competitive market, the high capital cost of market entry and unrealistic business models, can be a significant barrier to potential new BIPV manufacturers.

3.2 Thin film BIPV product pricing

In order to ascertain the industrial viability of steel + IL derived products, a review was undertaken of the relevant literature and comparable product data. However, the analysis of accurate and up to date BIPV product pricing is problematic with a number of conflicting and generalized sources of data.

Many studies reference industry wide reports and surveys by organizations such as NREL [10], International Technology Roadmap for Photovoltaics (ITRPV) [20], as well as periodic spot prices from organizations such as PV Insights [43]. However, although useful as a guideline for pricing and market trends, these industry wide figures are either technology specific (c-Si), extrapolated from limited market sectors or, as is the case for the PV insights spot prices, subject to an element of judgement as an integral element of the pricing process [43]. The Fraunhofer Institute for Solar Energy provides a pricing and trend perspective on global, European and domestic systems comparing thin film technologies with c-Si modules. The 2017 report highlights prices within the German market for rooftop PV at around the €1.2/W_P level for a typical 10 to 100 kW_p rooftop-system [42]. However, the report covers a range of technologies and application types thereby impacting direct comparisons. The \$1/W_P (€0.83/W_P) selling price figure for BIPV products has been cited by some forecasters as a barometer of near grid parity. This was recently reiterated by Anil Vijayendran, Vice President at MiaSole, who stated that a simple CIGS thin-film roof panel is currently within this price range [44]. However, it is not clear if this statement is representative of a specific product type, inclusive of volume discounts, an average price or whether it is for a low specification product.

Obtaining accurate and up to date BIPV product pricing directly from PV manufacturers in general is problematic. Many producers are reluctant to publish their prices unless in response to a formal approach or tender as part of an architectural plan or design. However, the sensitivity of pricing is not universal amongst all manufactures and a number either publish their prices on their websites or include prices within Business to Business (B2B) forums such as Alibaba [45]. The products and prices presented in Table 1 are described as thin film flexible BIPV products, suitable for a range of BIPV applications including retrofit projects. The listed products include thin film foils and semi-flexible BIPV products.

Table 1: BIPV products and prices by category and technology as of March 2018 [45].

Manufacturer	**BIPV Product**	**Category**	**Cost per Area (€/m^2) Range**	**Cost per Watt (€/W_P) Range**
Qingdao Power World	PW100A	a-Si on glass	42.24 – 52.80	0.53 – 0.66
Solar Motion	Black panel 2 or 3 layers	a-Si on glass	59.84 – 100.32	0.60 – 1.00
Solar First Energy	SF-THT-72W,80W,130W	a-Si on glass	61.60 – 88.0	0.62 – 0.88
Hanergy	Oerlikon120W	a-Si on glass	70.40 – 88.0	0.70 – 0.88
henzhen Shine Solar Co	SN-H100/H150	c-Si Semi flexible	157.60 - 227.66	0.70 – 1.06
Ocean Solar	OS100-17MFX	c-Si Semi flexible	157.04 - 164.60	0.73 - 0.77
Sopray Solar	SRFM-330	c-Si Semi flexible	176.0 - 211.20	0.88 - 1.06
GH Solar	GH150PF-36	c-Si Semi flexible	188.32 - 258.72	0.94 - 1.29
CNBM Solar	CNBM135	c-Si Semi flexible	290.40 - 367.84	1.32 - 1.67
Yinxu Solar	SDYX-F360W	CIGS foil	158.40 - 396.00	1.06 - 2.64
Global Solar	PowerFlex 185W/300W	CIGS foil	264.00 - 330.00	1.76 - 2.20
LQ Solar	CIGS75/38W	CIGS foil	299.20 - 403.92	1.76 - 2.46
Miasole	FLEX-02 70/340	CIGS foil	299.20 - 448.80	2.00 - 3.00
Sopray Solar	SRCIGS90/275W	CIGS foil	258.46 - 307.82	2.35 - 2.80
LQ Solar	PVL-31/68/ 72/136/140	a-Si foil	202.40 - 374.0	1.95 - 3.74
LQ Solar	XR36-300	a-Si foil	149.60 - 242.00	1.50 - 2.42
LQ Solar	LQ-XLS22-144	a-Si foil	158.40 - 246.40	1.58 - 2.46
Hangzhou New Energy Co	CTF-68W	a-Si foil	176.00 - 308.00	1.76 - 3.08

The range of products listed in Table 1 are included within the study as a reference point for current BIPV prices and a comparator for potential new steel substrate and IL derived BIPV products. Prices are generally published within a \$/W_P and \$/m^2 price range to reflect variances due to order quantities, product sizes and power outputs. All prices are for product purchase only and do not include any BoS or installation costs. It is assumed that in the event of purchase, the actual price paid would be within the stated range. The product categories within Table 1 reflect the broad thin film BIPV product types available within the marketplace and the categories explored within this paper.

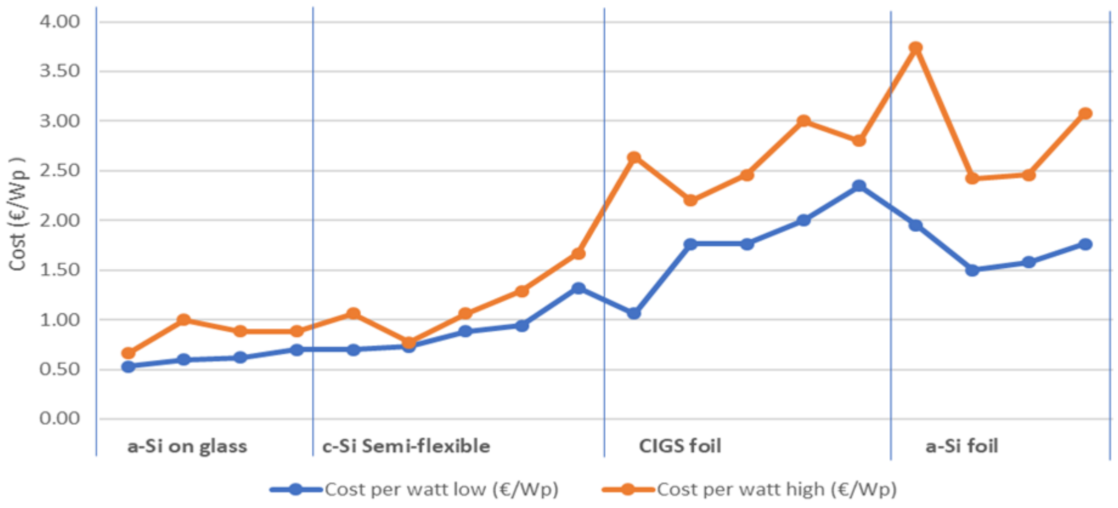

Figure 6: Factory gate price distribution of BIPV by product category in €/W_P as of March 2018

A price distribution by BIPV category is shown in Figure. 6 and technology from the data in Table 1. The data highlights the wide range between low and high \$/W_P figures that reflect the range in prices dependent on volume, discounts and other commercial factors. The manufacturer data positions the CIGS and a-Si foil products at a higher price level than the a-Si on glass and c-Si semi-flexible BIPV products. It is this category of BIPV product that offers the relevant price range to ascertain the industrial viability of any steel + IL derived BIPV product.

The next section describes the process followed in this study to develop the required data from lab to production scale to ascertain the commercial viability of utilising steel substrates and an IL for BIPV products.

4. Process followed to ascertain industrial viability of steel + IL for BIPV

To develop the required data to ascertain the feasibility of utilising steel + IL for BIPV, this study progressed through a number of steps to analyse the key performance data:

1. Undertake the necessary technical assessment of the various steel grade and IL combinations to ensure compatibility and required performance at laboratory scale [ref any relevant publications].
2. Analyse the performance of each of the steel and IL options to production scale.
3. Develop a detailed cost model for the manufacturing of a potential steel + IL derived BIPV product.
4. Ascertain the industrial viability of potential BIPV products against the global market.

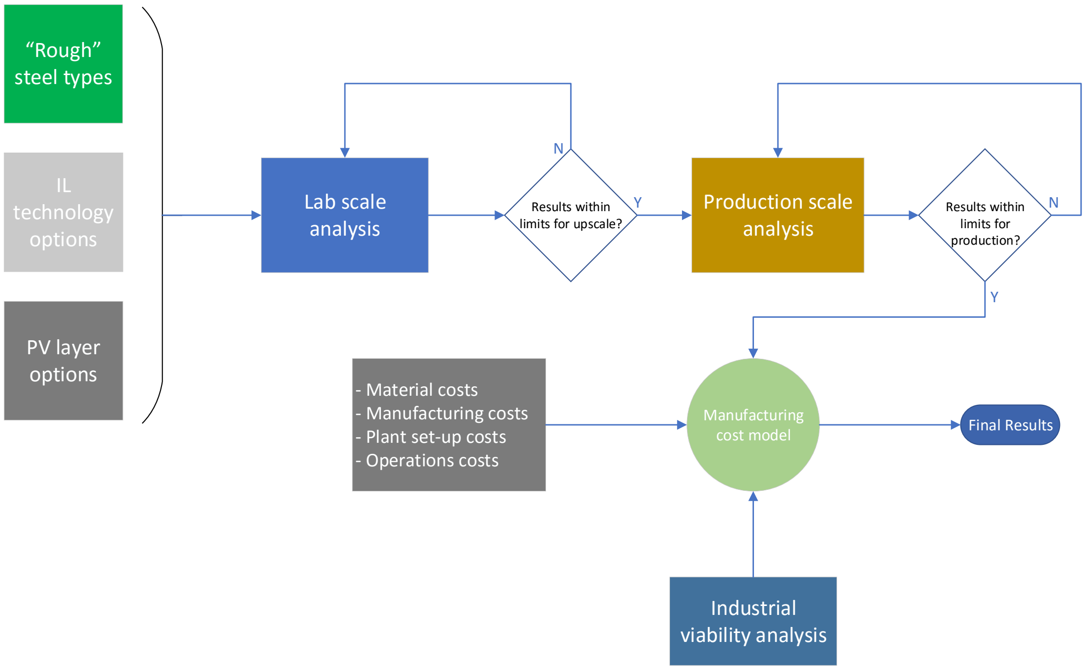

Figure 7: Process to developing industrial viability of steel + IL for BIPV.

The process followed to develop the analysis of steel + IL options for BIPV use is presented in Figure 7. The study iterated through lab scale and production scale analysis to ascertain the working combinations of IL and steel types, capable of R2R manufacture [ref?]. A cost model was developed to categorise and quantify the costs of manufacturing a fully functioning BIPV product in €/m2 units. The industrial viability analysis includes the market assessment and product comparison with commercially available BIPV products.

5. Cost analysis and industrial viability

The process followed to ascertain the costs involved in manufacturing a new BIPV product are set out in Figure 8. The process entailed the development of a cost model that adopted a bottom up approach in alignment with Anderson [46], where each of the individual cost elements were identified and included within the model. The cost analysis was performed at the up-scaling stage of the IL coating processes where the technical viability of each of the IL options was established. All costings are based upon calculations relevant as from March 2018. In particular, steel prices have shown significant fluctuations over the past 8 years with around 55% variation in base steel prices. The cost analysis assumes the utilisation of a modern R2R production facility to assure the most efficient and cost effective means to develop the BIPV products.

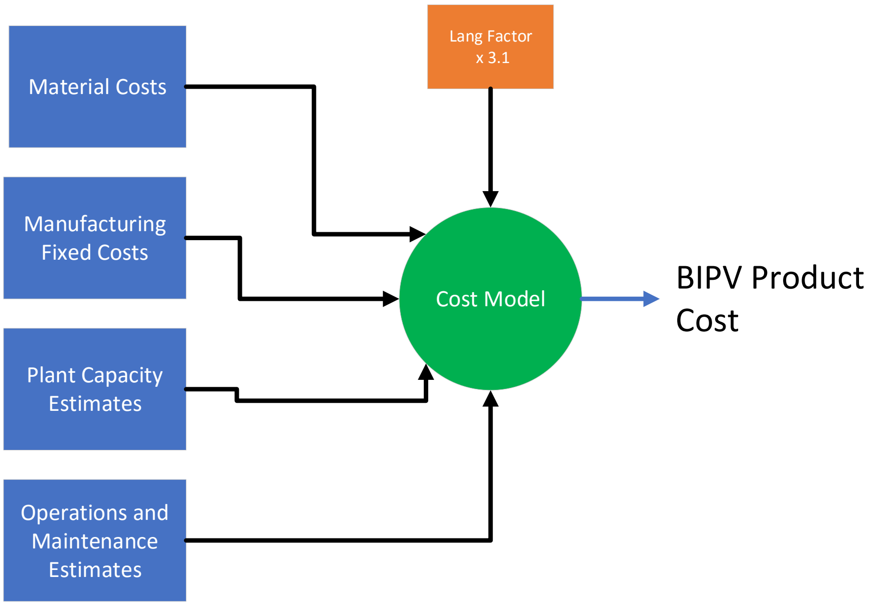

Figure 8: Cost model development process

The methodology and approach selected for the manufacturing cost estimation within this study was based on the methods outlined in Anderson (2009)[46]. This approach separates costs into variable and fixed cost components as detailed in see Table 2). In the context of the cost categories as defined by the Association for the Advancement of Cost Estimate, AACE, International this research resides within Class 4 (Feasibility Study) [47].

Table 2: Manufacturing Costs (fixed and variable)

Variable Costs	Fixed Costs

• Materials
  ○ Raw materials (and processing costs if required)
  ○ Material quantity, quality and manufacture timeframe
  ○ Transport costs
  ○ Wastage
  ○ Materials balance and flow.
• Waste Treatment
• Utilities (for large volume processes)
	• Capital Depreciation
	• Labour (operations and supervisory)
	• Utilities (for small volume processes)
	• Operations & Maintenance
	• Plant Support (e.g. R&D personnel dedicated to plant troubleshooting)
	• Site Services (e.g. plant security, support of plant infrastructure)
	• Supplies (office, janitorial etc.)

The underlying calculation for total plant cost is defined in Eq. (1), where the sum of the costs of the main equipment are multiplied by the Lang factor [48]. Lang factors were originally incorporated within industrial engineering and are widely utilized as a method for estimating the total installation cost based on the cost of the major technical components. The Lang factor approach allows for site, construction, materials, installation, engineering, training and other costs [49] and is considered as an appropriate tool for AACE class 4 and class 5 estimates [50,51]. The Total Plant Cost figure incorporates a Lang factor multiplier of x3.1, in alignment with the recommended solids processing figure [48].

$$Total\ Plant\ Cost = Lang\ Factor \times \sum Principle\ Equipment\ Costs \tag{1}$$

To estimate the levelized capital investment costs per square metre produced over the lifetime of the plant we take into account the Capital Recovery Factor (CRF) using Eq. (2):

$$C_{Investment} = \frac{Total\ Plant\ Cost\ \times CRF + Operations\ \&\ Maintenance}{Yearly\ Output\ Rate\ \times Plant\ Lifetime} \tag{2}$$

CRF is defined in Eq. (3), where *D* is the discount rate (allowing for interest and inflation) and *n* is the plant lifetime in years.

$$CRF = \frac{D(1+D)^n}{(1+D)^n - 1} \tag{3}$$

The calculation of the total plant cost and subsequent capital investment cost is based on a number of underlying assumptions. These assumptions have been incorporated within the cost model utilised to develop the product costs:

- Discount rate is based on the 30 year figure of 3.5% (UK Green Book [52]).
- Plant lifetime is 10 years, resulting CRF is 0.12.
- Annual operations & maintenance is estimated at 4% of annual plant cost.
- Miscellaneous plant costs is 5% of annual plant cost [53].
- Material costs are calculated for non-EU prices and subject to additional transport costs.
- Chemical supplies are almost exclusively sourced from outside the EU and subject to 5.5% import duty.
- Exchange rates are valid for the date: 22/09/2017.
- Waste treatment costs have been estimated at €1.18/kg (based on high temperature incineration of hazardous waste) and have been included in the total material cost (based on the estimated wastage levels). Waste treatment includes the recovery of volatile solvents lost during the coating process.
- Labour costs are considered as fixed, as they are not easily adjusted with fluctuating demand.
- Each R2R line is manned by one supervisor and three operatives and that the plant will be run by a manager with two support staff.
- Each R2R line will have a labour cost of €0.52/m^2 and with three R2R lines the total labour cost will be €1.03/m^2 (assuming production of 300,000 m^2/year).
- IL costs are based on R2R production plant.
- Equipment costs are based on the pilot-scale R2R plant at SPECIFIC [54].
- Substrate pre-processing costs prior to R2R are set at 10%.
- Substrates require degreasing and cleaning before IL processing, set at 15% [55]

5.1 Plant capacity

Manufacturing plant capacity calculations are based on a facility that can accommodate minimum BIPV production volumes of 30 MW/year [11], [12]. This aligns with capacities of peer group manufacturers such as: Energy Conversion Devices Inc, (traded as Uni-Solar) that produced a-Si PV on flexible stainless steel substrates using a R2R process. Energy Conversion Devices operated a 30MW plant in 2003 [12]–[14]. At 10% efficiency 30 MW/year equates to approximately 1500m^2/day of production (assuming 4 production days per week and 1 day of maintenance). This equates to 300,000 m^2 of annual production. Production line throughput is dependent on feed rate. Assuming a web width of 30 cm and a roll area of 500 m^2 (length≈1700 m), a feed rate of 5 m/min would take nearly six hours to process the roll, compared to approximately 1 hour at a feed rate of 30 m/min. For the IL coating processes, feed rate is largely determined by curing time and it is assumed that only one R2R line would be required for the coating process.

5.2 Raw steel pricing

Solar grade stainless steel is an established material for PV substrates but is expensive due to both the high quality of steel used and the extra processing required to provide a clean smooth substrate suitable for PV fabrication. Costs for this grade of steel are quoted as high as €36/kg at a thickness of 25 µm, equivalent to €8/m^2 [55]. These figures represent a significant cost component of the overall PV system. This study analysed the potential for a number of less refined "rough" steels as substrates for PV modules. By utilising an IL to provide insulation combined with a smooth surface suitable for PV fabrication, the study was able to assess the efficiency and suitability of four less refined and cheaper steel grades: AISI430, DX51D+Z, DX51SD+AS, and DC01, at lab and production scale. The prices of each of the steel types in the context of €/kg and €/m^2 are presented in Figure 9.

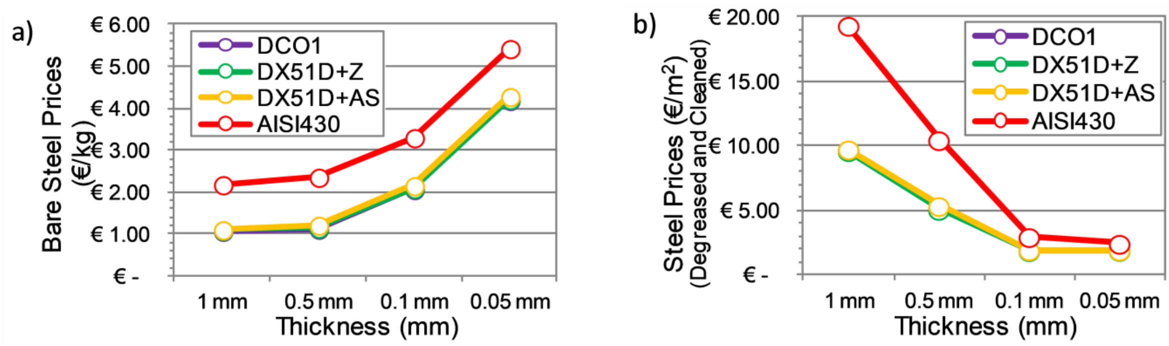

Figure 9: Steel prices [55]: a) Price per kg for bare steel; and b) Price per m^2 for prepared steel ready for IL processing.

5.3 Intermediate Layer processing and pricing

The final product integrity relies on the concept of utilising an IL with the cheaper lower grade steel substrate as presented in Figure 10. The IL is required to insulate the solar cell from the steel substrate and to provide a planarised layer suitable for solar cell fabrication. The IL also functions as an additional barrier to prevent the migration of impurities from the steel substrate through to the solar cell (especially during elevated temperatures encountered during fabrication processing). It is critical for the IL to exhibit similar thermal expansion properties to the specific steel type to mitigate the potential for delamination or cracking during processing at higher temperatures. The ILs must also remain chemically inert during PV processing with no degassing, degradation or adverse reaction with either the steel or the PV materials.

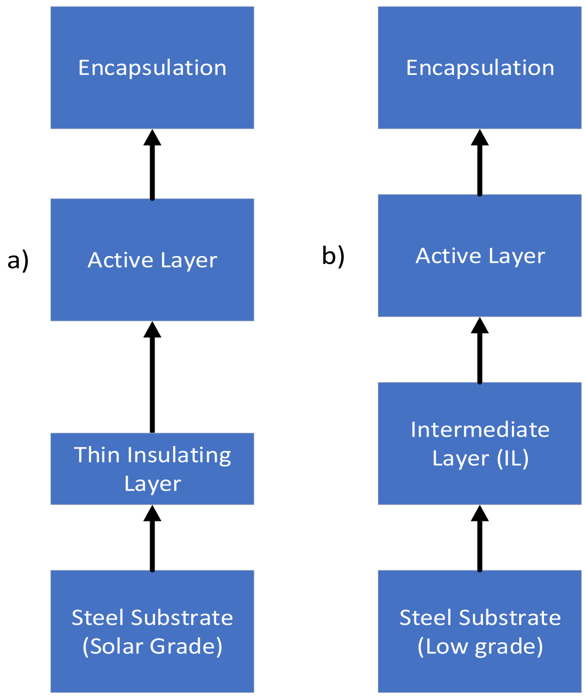

Figure 10: PV component architecture a) traditional approach using solar grade steel, b) steel + IL product

A number of different ILs were considered for this study: polymeric ink; epoxy; and SiOx deposited either by evaporation or from solgel (hydrolysis-condensation from precursors). Following detailed analysis at both laboratory and pilot-scale two successful candidates emerged: polymeric Blue Ink (D2140114D5, Gwent Electronic Materials Ltd) and SiO_X deposited by sol-gel to an in-house formulation (SolGel F1) [ref did we publish?].

5.3.1 Intermediate Layer material costs

Table 3 presents the material costs and usage of Blue Ink and SolGel F1. After testing a wide range of IL materials, these two were identified as the best materials to develop into steel BIPV products as they show a combination of 1) good technical properties (low surface roughness, high electrical insulation), 2) relatively low cost in small volume lab-based tests and 3) can be deposited by a R2R compatible upscale process that could be applied into a steel coating line. Blue Ink is an expensive commercial product (although good volume discounts are available) whereas SolGel F1 is an in-house mixed and prepared option [56]. Blue Ink is applied by screen printing and has a low wastage, whereas SolGel F1 is applied by spray coating, which can be a wasteful process. SolGel F1 has a high proportion of volatile solvents, equating to a loss factor of 93%. The final materials costs are calculated as €1.80/m^2 for Blue Ink and €0.33/m^2 for SolGel F1.

Table 3: IL material costs and usage.

IL Material	Coating thickness (μm)	Raw Material Cost (€/kg)	Wastage (coating process)	Volatile Loss	Material Usage (g/m^2)	Material Cost (€/kg)[b]	Material Cost (€/m^2)
Blue Ink	8	52.14	4%	30%	35.7	50.31	1.80
SolGel F1	3	3.04[a]	45%	93%	79.8	4.13	0.33

[a] including material processing costs (estimated at €1/kg).
[b] including waste treatment costs (€1.18/kg, based on high temperature incineration of hazardous waste).

5.3.2 Intermediate Layer processing costs

The sheet based process for Blue Ink IL is applied to the cleaned and degreased steel substrates using the following process:

1. Steel substrate is divided into sheets (30cm x 30cm) suitable for screen printing
2. Blue Ink is applied by screen printing
3. Soft bake – wicket dryer at 150°C for 20 minutes
4. Hard bake – wicket dryer at 200°C for 10 minutes

The 30 minute curing time dominates the processing costs and determines the maximum throughput. Faster throughput would require longer ovens and therefore, greater capital cost. The use of wicket ovens, with the sheets held vertically and in close proximity, allows shorter length ovens to be used.

The second IL considered for upscale development was SolGel F1. SolGel F1 is suitable for R2R spray coating and can be applied directly to the cleaned and degreased steel substrates using the following process:

1. SolGel F1 is applied via spray coating process
2. Multiple stage curing is then processed via a hotplate:
   a. 60°C for 30 minutes to remove the solvent
   b. 100°C for 15 minutes to gradually raise the temperature
   c. 150°C for 15 minutes to gradually raise the temperature
   d. 210°C for 30 minutes for high sintering of the sol-gel layer
3. Alternatively - curing can be done using a near infra-red (NIR) oven
   a. 2 minutes at 93% max power (5.92kW)

The feed rate for both IL materials has been estimated at 12m/min, taking 6.9 hours to process a 1500m^2 roll, or 2.3 hours for a 500m^2 roll (roll size dependent on material thickness). Table 4 shows the processing costs for the ILs, including capital investment, labour and electricity and gives total processing costs (including materials) of €2.60/m^2 for Blue Ink and €1.24/m^2 for SolGel F1.

Table 4: IL processing costs.

IL Material	Capital Investment (€M)	Capital Investment (€/m^2)	Labour Cost (€/m^2)	Electricity Cost (€/m^2)	Processing Cost (€/m^2)	Total Processing Cost (including materials) (€/m^2)
Blue Ink	2.8	0.12	0.52	0.15	0.80	2.60
SolGel F1	5.3	0.23	0.52	0.15	0.91	1.24

5.4 PV manufacturing costs

Two PV technologies were evaluated for the study: OPV and a-Si. PV technology has a high learning rate (18-22%), with cumulative capacity doubling every two years [57]. This has led to a downward price pressures on thin film products and a continued emphasis on lower costs and efficient manufacturing processes.

5.4.1 OPV Costs

The costs for OPV are based on an inverted structure (see figure 1(a)): steel, IL, printed silver back electrode, ZnO electron transporting layer, P3HT:PC$_{61}$BM active layer, PEDOT:PSS hole transporting layer and transparent top electrode of silver nanowires (AgNWs). OPVs are a relatively new technology with limited commercial products available in the market. The cost figures used are derived from the academic literature, specifically the ProcessOne method pioneered by Krebs et al. [58,59]. ProcessOne is based on ITO as the transparent electrode and work by Emmott et al. suggests that replacing this with AgNWs could reduce the energy requirement by 50% and the overall cost of the electrode by between 64% and 73% with minimal effect on efficiency [60].

5.4.2 a-Si Costs

Modern commercial a-Si modules are based on the triple junction design in order to maximise light capture and this architecture has been used in this study and the structure is shown in figure 1(b). The commercial sensitivity surrounding detailed a-Si production costs necessitates that these costs be based on available module manufacturing costs with an allowance for substrate costs. These costs are widely available within the public domain [18]–[20]. A report by the US Department of Energy suggests that substrate costs makes up between 16% and 25% of the total module cost [21]. In order to estimate module fabrication costs module prices have been adjusted to allow for high and low substrate costs to generate a maximum and minimum cost.

5.4.3 PV Costs and target prices

Table 5 presents the power conversion efficiencies (PCEs) and manufacturing costs for OPV and a-Si. The PCEs used reflect current commercial module specifications [58]and are significantly lower than the maximum PCEs attained in laboratories conditions as highlighted in Green et al 2017 [61]. The costings exhibit a much wider price range for OPVs and this reflects the commercial immaturity of this technology and uncertainty in material costs [62]. The substrate component contributes about 20% of the final manufactured cost of the cell. Considering the PCEs in Table 2 and global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3:2003), maximum affordable substrate costs (Steel+IL) would be €6/m^2 for OPV and €10/m^2 for a-Si technologies. The Steel + IL target price referenced in Table 5. This represents the PCE and existing cost level to ensure competitive OPV and a-Si BIPV products.

Table 5: Performance characteristics, manufacturing costs and target Steel + IL substrate costs for various thin film solar technologies.

PV Technology	PCE	Manufacturing Cost per Area (€/m^2)	Manufacturing Cost per Watt peak (€/W_P)	Steel+IL Substrate Target Price (€/m^2)
OPV	6%	53.15 – 130.53	0.89 – 2.18	6
a-Si	10%	54.60 – 71.40	0.55 – 0.71	10

5.5 Steel+IL Substrate Price Summary

Figure 11 presents the processed Steel+IL prices for Blue Ink and SolGel F1 for the different steel types and thicknesses. The target prices for suitable PV technologies are also shown, which gives an indication of which thicknesses would be financially viable. Blue Ink is not suitable for OPVs as the roughness is too high (R_a=35-60nm, R_z=320-450nm). Table 5 summarises the maximum viable steel thicknesses for each of the steel types, IL materials and PV technologies (based on a target PV module price of €1/W_P). Using this data, it is possible to estimate the maximum possible substrate thickness for each steel type and PV technology. This is presented in Table 6.

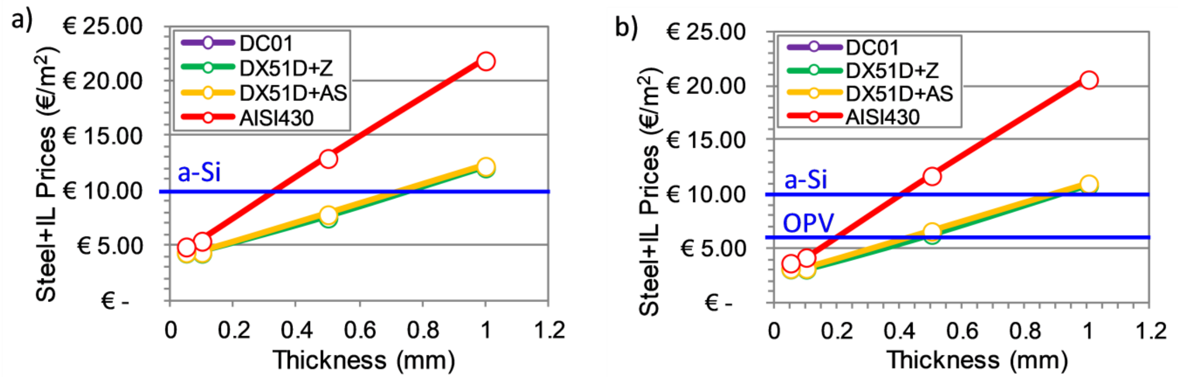

Figure 11: Processed Steel+IL substrate prices showing the target prices for PV technologies: a) Blue Ink (a-Si only); b) SolGel F1 (OPV & a-Si).

Table 6: Maximum viable steel thicknesses for the different IL coatings and suitable PV technologies

IL Material	PV Technology	Steel Type			
		DC01	DX51D+Z	DX51D+AS	AISI430
Blue Ink	a-Si (€10/m^2)	0.75 mm	0.75 mm	0.75 mm	0.35 mm
SolGel F1	OPV (€6/m^2)	0.45 mm	0.45 mm	0.45 mm	0.2 mm
	a-Si (€10/m^2)	0.9 mm	0.9 mm	0.9 mm	0.45 mm

5.6 PV module prices

Table 7 presents PV module prices for the target thicknesses of each steel type. A profit margin of 10% has been applied to the final PV module prices to allow for a suitable comparison with existing commercial BIPV products. The nominal price for the completed BIPV product is set at €1/W_P as this has been judged to be a level where a new BIPV product would be competitive [56].

Table 7: PV module prices (including 10% profit margin €/W_P). Maximum and minimum prices are shown.

IL Coating + PV Technology	Steel Thickness	Steel type			
		DC01	DX51D+Z	DX51D+AS	AISI430
Blue Ink + a-Si	1 mm	€0.74 - €0.92	€0.73 - €0.92	€0.74 - €0.92	€0.84 - €1.03
	0.5 mm	€0.68 - €0.87	€0.68 - €0.87	€0.69 - €0.87	€0.74 - €0.93
	0.1 mm	€0.65 - €0.83	€0.65 - €0.83	€0.65 - €0.83	€0.66 - €0.85
	0.05 mm	€0.65 - €0.83	€0.65 - €0.83	€0.65 - €0.83	€0.66 - €0.84
SolGel F1 + OPV	1 mm	€1.17 - €2.59	€1.17 - €2.59	€1.18 - €2.59	€1.35 - €2.77
	0.5 mm	€1.09 - €2.51	€1.09 - €2.51	€1.09 - €2.51	€1.19 - €2.61
	0.1 mm	€1.03 - €2.45	€1.03 - €2.45	€1.03 - €2.45	€1.05 - €2.47
	0.05 mm	€1.03 - €2.45	€1.03 - €2.45	€1.03 - €2.45	€1.04 - €2.46
SolGel F1 + a-Si	1 mm	€0.72 - €0.91	€0.72 - €0.9	€0.72 - €0.91	€0.83 - €1.01
	0.5 mm	€0.67 - €0.85	€0.67 - €0.85	€0.67 - €0.86	€0.73 - €0.91
	0.1 mm	€0.63 - €0.82	€0.63 - €0.82	€0.64 - €0.82	€0.65 - €0.83
	0.05 mm	€0.64 - €0.82	€0.63 - €0.82	€0.63 - €0.82	€0.64 - €0.83

The steel substrate thicknesses shown in Table 7 lend themselves to a number of categories of BIPV applications. As presented in Table 8, Blue Ink and SolGel F1 IL coatings on all steel types are suitable for flexible foil (thickness ≤ 0.1mm) and semi-flexible modules (thickness >0.1mm, ≤0.5mm) for all suitable PV technologies and IL materials (Blue Ink: a-Si, SolGel F1: OPV & a-Si). For the DC01, DX51D+Z & DX51D+AS steels types both ILs with a-Si PV were suitable for semi-rigid modules (thickness >0.5mm).

Table 8: Suitability of different IL coatings for BIPV module production

IL Material	PV Technology	Steel Type			
		DC01	DX51D+Z	DX51D+AS	AISI430
Blue Ink	a-Si	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible
SolGel F1	OPV	flexible foil semi-flexible	flexible foil semi-flexible	flexible foil semi-flexible	flexible foil semi-flexible
	a-Si	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible semi-rigid	flexible foil semi-flexible

6. Discussion - Industrial viability within the BIPV market

The potential BIPV product prices highlighted in the previous section, presented a varied product cost depending on steel type: DC01, DX51D+Z & DX51D+AS, thickness: (0.05mm to 1mm), IL material and PV technology. All the steel options offer cost advantages when compared to commercially sourced solar grade stainless steel at €8/m^2 [55]. The industrial viability and potential business case for a steel + IL derived product is reliant on product price competitiveness within an evolving global PV industry. The technologies analysed within this study highlight the potential for the development of products oriented toward the BIPV market. By utilising the different steel thickness and IL options, there is the potential to cater for a number of BIPV and Business to Business (B2B) interim product categories as shown in Figure 12.

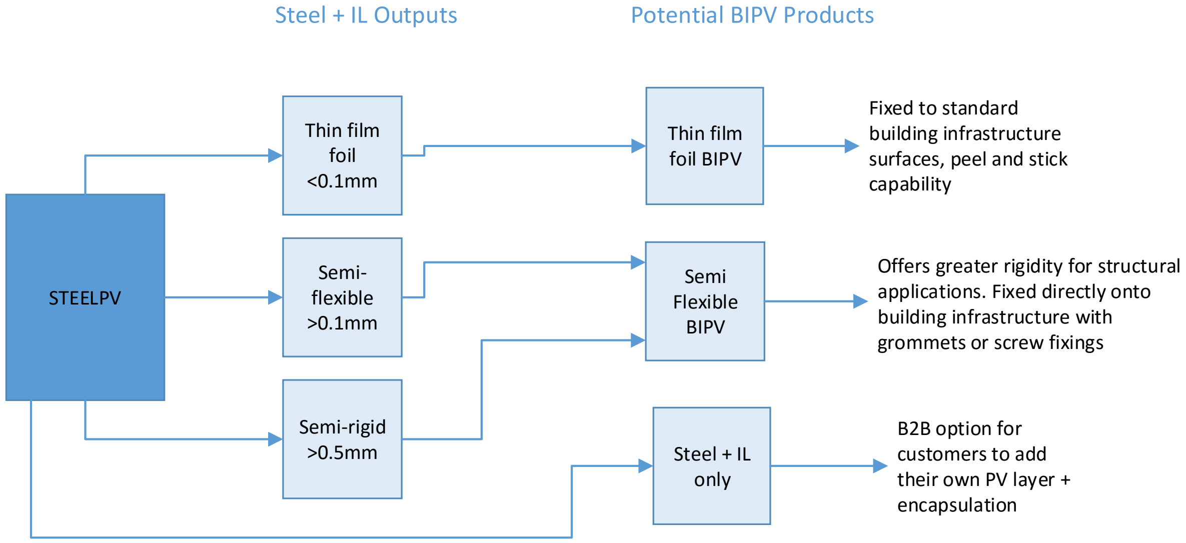

Figure 12: Potential steel + IL products

The IL and PV combinations from Tables 7 and 8 that are the most likely to achieve the greatest potential for BIPV products are based on the cost model analysis.

- Blue Ink + a-Si: 0.65-1.03 (€/W_P)
- SolGel F1 + OPV: 1.03-2.77 (€/W_P)
- SolGel F1 + a-Si: 0.63-1.01 (€/W_P)

The assessment of market price competitiveness is problematic in that many factors such as order quantity, product discounts and country of origin can impact PV product prices. BIPV manufacturers tend to publish their product prices in a high-low range format in the absence of a detailed specification. The price €/W_P ranges identified in Table 7 across the range of steel types and thicknesses will be used in the comparison with existing BIPV products. Two main BIPV product categories are relevant: semi-flexible and thin foil film BIPV. Thin film on glass is not compared in this section as it is out of scope in the context of comparable product types. These two BIPV product categories represent the bulk of the non-glass PV products that can be installed on rooftops, facades and sunshades as well as specialised building infrastructure and retrofit applications. The €/W_P price ranges for the thicker steels for each of the IL + PV combinations will be compared to the semi-flexible BIPV product prices. The <0.1mm combinations will be compared to the thin film foil BIPV products. It is assumed that the thinner steels and IL + PV combinations would also be suitable for retrofit BIPV applications due to the lighter weight of these potential products.

A comparison of semi-flexible BIPV products from Table 1 is shown in Figure. 13 and the applicable product combinations as shown in Tables 7 and 8. The prices shown do not include BoS or installation costs. Generally, the market prices for semi-flexible BIPV products are less than those of thin film products. The five manufacturers and products shown in Figure 13 are all based on c-Si technologies. The range of the SolGel F1 + OPV product is wide in comparison with the other products, highlighting that further research is required to refine this disparity. The Blue Ink + a-Si and SolGel F1 + a-Si products are competitive with the existing range of semi-flexible BIPV products and are within the €1/W_P target price level for all but the most expensive steel types (AISI430). The Blue Ink and SolGel F1 a-Si products range from 0.67 and 1.03 €/W_P depending on grade of steel. This demonstrates the competitiveness of this approach for semi-flexible BIPV applications and the margin of safety between the lower price range and the desired €1/W_P figure.

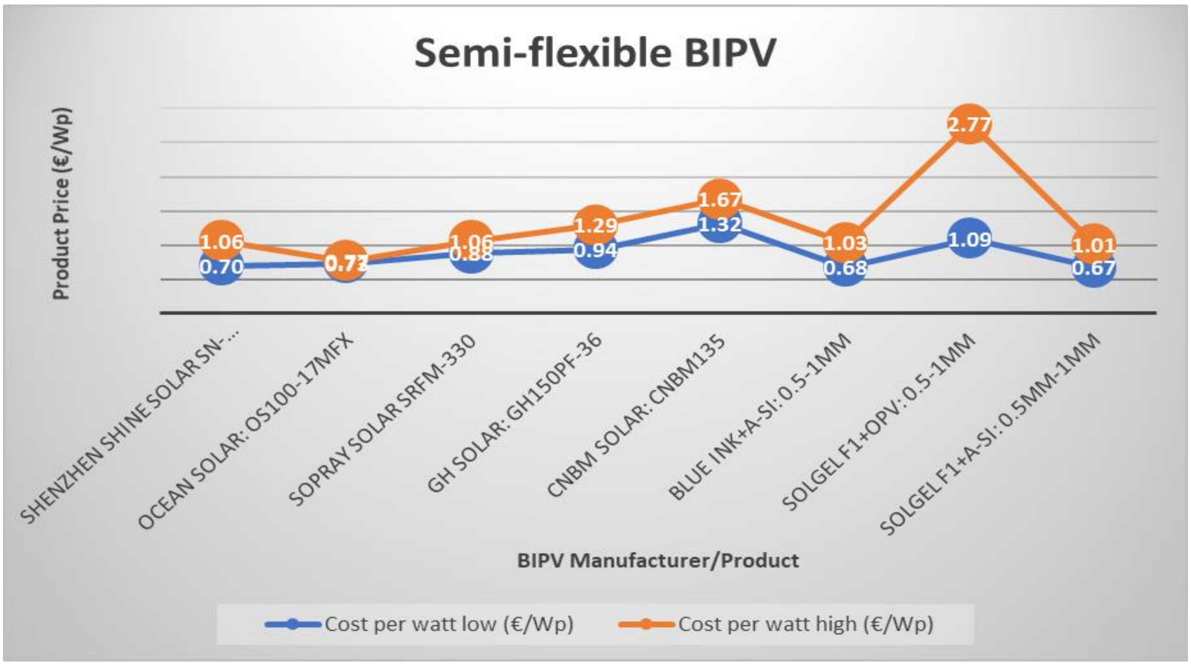

Figure 13: BIPV semi-flexible products vs steel + IL (0.5-1mm)

A comparison of thin film foil BIPV products vs comparable steel + IL products is shown in Figure. 14. The €/W_P prices for thin film BIPV are generally significantly higher than the equivalent semi-flexible products with a wide range between the low and high figures in some instances. As the thin film foil BIPV market is relatively immature, it is difficult to ascertain if the market will support this level of price variation over the medium and longer term. As with the semi-flexible products, the SolGel F1 + OPV has a wide variation in prices between 1.03 - 2.47 €/W_P. The SolGel F1 + a-Si and Blue Ink + a-Si products seem very competitive at 0.63 – 0.83 €/W_P and 0.65 – 0.85 €/W_P respectively.

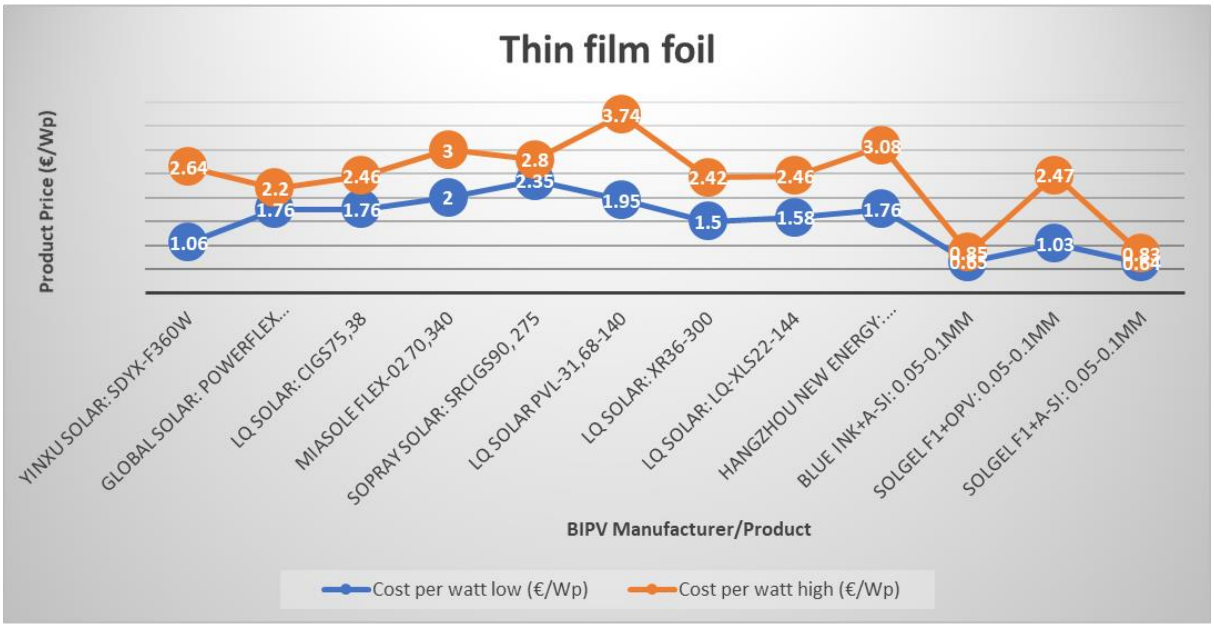

Figure 14: BIPV thin-film foil products vs steel + IL (0.05 – 0.1mm)

The results show that the SolGel F1 + a-Si and Blue Ink + a-Si prices across the full range of steel grades (DC01, DX51D+Z, DX51D+AS, AISI430) are competitive with existing commercial BIPV offerings. The price differential is particularly significant for the lower grades of steel where the range of prices starts from 0.63 – 0.66 €/W_P . These figures highlight the price competitiveness of steel + IL products within this specific BIPV category, demonstrating the industrial viability of this type of product. The margin of safety exhibited by the thin film foil steel + IL prices, highlights the potential scope to withstand further market pressures. Reports highlight the likelihood of further price pressures in the PV market through 2020 and beyond as the levels of oversupply continue and global uncertainty impacts market confidence.

The costs for upscaling to a fully operational BIPV manufacturing facility are significant. Bottom up estimates for the capital costs for an IL coating facility, based on full plant and equipment assuming a full R2R capability are in the range of €2.84m (Blue Ink) and €5.3m (SolGel) depending on selection of IL layer technology. Estimated plant specific annual levelized capital investment costs allowing for maintenance and support as well as consumables renewal are in the range of €37k - €70k, again depending on technology choices. These costs are a significant barrier to market entry and require the implementation of a strategic business model where significant levels of cash flow are available to maintain production during the early stages of operations when the pipeline of orders is weak.

The opportunities in developing a sustainable and effective manufacturing capability supported by an effective business model are many and varied, as the PV industry supports the transition to renewables. A report from the advanced materials research group n-tech highlighted that the BIPV market could be worth more than $9 billion by 2019 and as high as $26 billion by 2022 [63]. This, together with initiatives such as 2010/31/EU, presents significant potential opportunities for new market entrants that are not encumbered with legacy technologies, outdated processes or manufacturing methods able to create a cost effective, lean operational model targeted at key market sectors. However, outlining new and innovative business models is problematic, in that the PV industry is still undergoing significant change and consolidation. Even large established manufacturers such as Hanergy and First Solar are suffering from the current difficult trading period as market consolidation and the continuation of pressures on margins is likely to be an ongoing feature for the next five years or more [64], [20].

6.1 Business model options for steel + IL derived products

The industrial viability of utilising steel + IL for PV can be further enhanced by exploring a number of potential business models that can exploit the use both the interim and final PV technologies. Figure 15 presents three potential options: Option A: Full scale thin film BIPV manufacturer; Option B: Production of steel substrate with IL bonded to a PV layer supplied by a third party; Option C: Interim product - manufacture of steel + IL for sale to 3rd party to complete the thin film PV product manufacture. (Option C could in practice be a sub product of either option A or B).

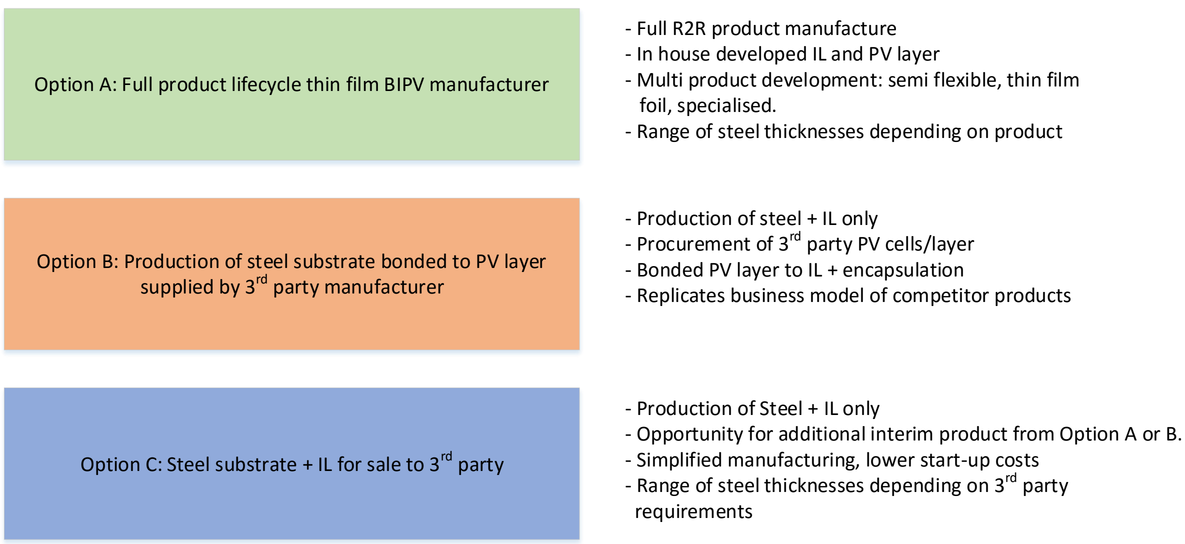

Figure 15: Business model options for use of steel + IL for BIPV

Option A: Full scale thin film BIPV manufacturer:
Steel + IL derived products could offer cost efficiencies over competing BIPV products, assuming that full R2R product manufacturing was undertaken in house. The key innovation in the driving down of costs is the use of non-solar grade steel in the development of BIPV products. This range of alternative steel substrates offers significant cost savings when compared to competing manufacturers that utilise more expensive solar grade steel types. This innovation could provide greater opportunity for more efficient cost control and greater scope to sustain downward market pressures over the short and medium term. The cost model developed in this study is based on the fit out and availability of a modern R2R manufacturing facility. This would entail a manufacturing process, whereby selected grade of coiled steel (AIS430, DX51D+Z, DX51D+AS and DC01) is processed/cleaned and effectively fed in at the start of the R2R process and a thin film PV product is "laid down/printed" and cured/dried at the end of the R2R process. The assumption here is that this process is managed in-house and that the required manufacturing facility is structured to perform all the necessary functions required for thin film BIPV production. The PV product will need to be accredited for stability, which would be a risk and cost borne by the manufacturer.

Option B: Production of steel substrate and IL bonded to 3rd party PV
This option entails procuring the PV layer from a 3rd party manufacturer that would be integrated onto the steel + IL to form the completed product by bonding. As this type of BIPV product would be utilising cheaper grades of steel, the additional cost of the procured PV layer could be mitigated whilst still producing a competitive product. The opportunities in this area and assessment of potential demand would require further analysis to ascertain the cost/benefit of this specific route to market. This business model option is currently used by PV product manufacturer BIPVco Ltd. BIPVco currently process their own substrate within their manufacturing facility and procure its PV cells from Hanergy subsidiary Miasole that are bonded to the substrate to form a complete PV product. The advantage to BIPVco is the utilisation of a known and industry tested technology and a simplified manufacturing process. Option B could present less risk for a new PV manufacturer with reduced costs and potentially faster time to market. However, the ability to control cost within the value chain in a very competitive market could be a significant constraint as PV prices continue to fall. The Option A model would be better able to compete in a cost constrained market but is likely to require higher initial investment than Option B for the additional components of the manufacturing process and resulting time to market.

Option C: Manufacture of steel + IL for sale to 3rd party Manufacturer
This business model options entails producing a steel + IL product for 3rd party PV organisations. PV manufacturers would procure the steel + IL interim product under license and add their own PV layer and encapsulation to complete the product manufacture. The benefit to 3rd party PV manufacturers could be a reduced R&D spend, simplified manufacturing process and more timely route to market. Adequately protecting IPR would need to be considered during the feasibility analysis of this option, but could offer an alternative funding stream for this business model. Option C could potentially be an alternative product offering for Options A and B as long as the manufacturing process is not unnecessarily complex, the technology can be adequately protected and the market exists for this interim type of product. This route to market provides the manufacturer with the lowest associated risk.

7. Conclusions

This paper considers the industrial viability of utilising a number of low cost "rough" steel types as a potential substrate for BIPV. The study developed a number of IL options utilising BlueInk and SolGel F1 and researched the feasibility of each at laboratory and production scale to identify validity of the technology and costs of manufacture. The costs of manufacture and full product pricing were estimated via a methodical bottom up approach where the total plan cost and levelized capital investment costs per m^2 formed an integral element of the model. The resulting BIPV prices developed in this study were tested against comparable BIPV products for the semi-flexible and thin film foil category of products. Results show that the steel + IL derived product are competitive against existing BIPV product offerings from a range of manufacturers. Furthermore, the price ranges for steel + IL products demonstrate a significant margin of safety able to withstand further price pressures in the short to medium term.

This study is limited by focusing on a single case study approach and would benefit from alignment of the results against comparable studies to test outcomes and conclusions. It is recommended that future research is directed toward the validation of the results and business model options presented in this study to further demonstrate the potential impact the results of this study could make within the BIPV sector. Furthermore, the results for the SolGel F1 + OPV option across all steel grades where the range in €/W_P prices substantially deviated from the a-Si options, it is recommended for further research as this PV technology becomes more mature and the costs of PV production reduce.

This study is timely because there are a number of major international projects whereby solar cells are being integrated into steel products which are generally noted by steel companies. The results could also inform other growing PV areas such as vehicle integrated PV, which are likely to have a similar structure to the PV module set out in this study.

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