Institution: Swansea University

Unit of Assessment: 12 – Engineering

Title of case study: Enabling building integrated photovoltaics for solar energy generation using functional coatings.

Period when the underpinning research was undertaken: 2009 – 2019

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Trystan Watson	Professor	2007 to present
David Worsley	Professor	1992 to present
James Durrant	Professor	2013 to present
Matthew Carnie	Associate Professor	2008 to present
Cecile Charbonneau	Senior Lecturer	2011 to present
Matthew Davies	Associate Professor	2014 to present

Period when the claimed impact occurred: 1 August 2013 – present

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

A building-integrated photovoltaics (PV) business, BIPVCo, has resulted from collaborative research on functional coatings at Swansea University (SU). The underpinning research and development of a low-cost, lightweight, and flexible metal-mounted PV coating was the fundamental aspect of creating the company. BIPVCo is now a manufacturing organisation that has a production capability per annum that equates to 20 megawatts (MW). BIPVCo received GBP5,000,000 in private sector investment in 2017 and moved to full scale manufacturing in Newport (2018), gaining full TUV (Technischer Überwachungsverin) and MCS (Microgeneration Certification Scheme) approval. BIPVCo's increase in manufacturing capability created 30 new jobs and is supporting an innovation pipeline for steel building materials through continued collaborative research with Tata Steel and SU. In addition to the key impacts Swansea's research has had upon BIPVCo, the concepts and products derived from Swansea's research have influenced the shaping of the construction strategy for the UKs largest steel manufacturer, Tata Steel to include Active Building products.

2. Underpinning research

Conventional solar panels, based on silicon technology sandwiched between glass coverings, are now widely deployed and are one of the cheapest renewable energy sources worldwide. However, the manufacturing processes are complex and require ultra-clean manufacturing environments. Solar panel modules can be mounted on top of a roof or wall structure, however there are emerging opportunities for solar technologies to be integrated into the building fabric. So-called 'building-integrated photovoltaics' (BIPV) as an alternative to traditional silicon panels, offer the opportunity for the whole roof of a building to generate power. It also offers an opportunity to make the material more lightweight and flexible to allow for curved surfaces. An additional challenge for silicon PV is that the high capital costs of manufacturing plants and very high-energy consumption is centring the manufacturing in Asia and thus is not supporting local manufacturing supply chains.

Direct integration of the photovoltaic material with steel roofing is an attractive opportunity, given the current production of 100,000,000m^2 of coated steel for buildings that is manufactured by Tata Steel in the UK annually. Approximately 60% of this output is used in the UK, providing a significant opportunity to produce more sustainable energy at scale.

Since 2007 SU materials scientists **[G1]**, Worsley's team, tackled these issues to develop an inexpensive, ambient printable photovoltaic device that could be integrated directly into the fabric of the building at large scale. This work was initially funded by the EPSRC "Metal substrate mounted flexible dye sensitised semiconductor solar cells" project, which became one of the forerunners to the SPECIFIC Innovation and Knowledge Centre (IKC) **[G2, G3]**. SPECIFIC now covers work on PV manufacturing and electrical storage, thermal generation and storage, and building integration and design in support of the transition to solar powered buildings.

Initial research published in 2011 **[R1]** led to the development of a prototype metal-mounted dye-sensitized solar cell in collaboration with Tata Steel, and this work highlighted the potential for building-integrated PV on sheet steel roofing materials. A number of key technical breakthroughs were made in lightweight flexible metal mounted PV at Swansea during this pre-commercial, early adoption period, which underpinned the initial technology demonstration of the BIPV concept on steel products supported by collaborative research grants alongside the IKC core team.

In 2011, Watson's research team at Swansea produced the world's first dye-sensitized solar cell deposited directly onto a steel substrate, a critical enabler to large-scale roll-to-roll manufacture **[G1, R1]**. In particular, the work probed the influence of direct integration of the PV device stack through multi-layer deposition onto a pre-painted construction substrate. The method was based around chemically isolating the underlying substrate using a dual high temperature-stable organic coating combined with an electrically conductive metal layer. Though the work illustrated the issues of substrate expansion during long-term high-temperature processing, it paved the way for the development of post-processed layers rather than direct deposition.

A major bottleneck in the manufacture of low-cost solution-processable PV is the time required to manufacture the device which prior to our research was known to be 30 minutes. The Swansea team has developed alternative heating and curing methods using near-infrared radiation and photonic techniques that can achieve the same result in just 12.5 seconds **[G2, G4]**. When these technologies are applied to the dye-sensitized solar cell, such as those developed in **[R1]**, the manufacturing time is reduced from many hours to under 2 minutes. This means that the manufacturing process shifts from being a costly batch process to a higher volume, cheaper and continuous process. In 2014, Carnie and Charbonneau sought to understand the influences of short process times on the performance of PV devices and found that rapid processing could be undertaken without detriment to material behaviour or performance **[R2, P1]**. Despite the dye-sensitized technology forming only the pre-commercial prototype, the work provided a benchmark for the evolution from slow and expensive batch processes to continuous fabrication.

To enable the translation of conventional glass-mounted, solution-deposited solar cells onto a flexible but opaque surface such as steel, a transparent top electrode is required. Under normal circumstances, this would be applied via a low volume, costly vacuum process. In 2015 **[G3, G4]**, the team developed a, low-cost and transparent laminate electrode, requiring only finger pressure for application, that not only performs comparably to vacuum-evaporated metallic contacts but also provides mechanical adhesion that the evaporated material does not **[R3]**, **[P2, P3]**. This product was developed for solution-processed PV technology and acted as the forerunner for the incumbent commercially-deployed CIGS (Copper, Indium, Gallium, Selenium) product.

In 2015 members of the Tata Steel research team at Shotton established BIPVCo as a spinout in partnership with Swansea Innovations (the university commercialisation team). The team helped BIPVCo with both the legal structuring for the creation of the separate entity, negotiations, and support to gain private sector investment. The SPECIFIC IKC team worked closely to help scope and design the manufacturing unit, establish local lab testing facilities, and support key aspects of the work on adhesion and lifetime prediction required to integrate photovoltaic (CIGS) foils into premium steel coated roofing products co-developed with Tata. Once established the Tata team took on permanent roles with BIPVCo to drive it forward leaving their positions in Tata but continuing to operate on the Shotton site.

In order to develop greater understanding of in-service performance and provide evidence that the commercial product can be deployed successfully in demanding environments, the research team at SPECIFIC, analysed the performance of the first trial production BIPVCo mounted product applied to an Active Classroom building located at SU's Bay Campus **[G3, G5]**, **[R4]**. Using data collected during a twelve-month period on SU's Active Classroom (a purpose-built showcase for several solar-based technologies), the research showed that, in the oceanic climate of SU, which is defined by a narrow annual temperature range and a high level of precipitation, there is significant fluctuation in PV performance of the BIPVCo product throughout the year. This evolved into an understanding of the link between the Active Classroom battery system and the point at which the PV power output drops to the base load of the building when the battery is full. The work fed data back to BIPVCo and illustrated the product stability and performance variation over the twelve-month period. Recommendations on how to link the product with smart control algorithms to optimise future PV-battery systems were made.

Durrant and Watson has also established a weathering and stability capability at SU **[G3, G6]** which allows extensive monitoring of PV devices both at lab-scale (in the development phase) and in-service on our fully monitored active buildings **[R5]**. These capabilities support product development by enabling standardised test conditions to be run on both developmental prototypes and complete products. This work builds on our historical experience in monitoring the stability of organic coatings and enables more accurate projections of product lifetimes from laboratory experiments. The BIPVCo materials are also part of the international exposure testing programme with Tata group and five Indian Institutes of Technology in the SUNRISE programme **[G7]**.

3. References to the research

The outputs below include five peer reviewed journal papers, two in Q1 and two in Q2 journals (JCR). One has national academic collaboration with Oxford University, and another has industrial collaboration with industry (CPI Ltd). Three of the outputs were supported by funding from EPSRC, one of which also acknowledges Welsh Government and ESF funding. Seven competitively won grants from EPSRC support the body of work totalling GBP18,039,725. This research has made important contributions to the discipline internationally and contributes important knowledge to the field likely to have a lasting influence.

[R1] Watson, T., Reynolds, G., & **Worsley, D.** (2011). Painted steel mounted dye sensitised solar cells: Titanium metallisation using magnetron sputtering. *Ironmaking and Steelmaking,* 38 (3), 168–172. doi.org/10.1179/1743281210Y.0000000003

[R2] Carnie, M., **Charbonneau, C.**, Barnes, P., **Davies, M.**, Mabbett, I., **Watson, T.**, O'Regan, B., & **Worsley, D**. (2013). Ultra-fast sintered TiO_2 films in dye-sensitized solar cells: phase variation, electron transport and recombination. *Journal of Materials Chemistry A*, 1 (5), 2225–2230. doi.org/10.1039/C2TA01005D

[R3] Bryant, D., Greenwood, P., Troughton, J., Wijdekop, M., **Carnie, M.**, **Davies, M.**, Wojciechowski, K., Snaith, H.J., **Watson, T.,** & **Worsley, D.** (2014). A Transparent Conductive Adhesive Laminate Electrode for High-Efficiency Organic-Inorganic Lead Halide Perovskite Solar Cells. *Advanced Materials,* 26 (44), 7499–7504. doi.org/10.1002/adma.201403939

[R4] Brennan, D.A., White, C., Barclay, M., Griffiths, T., & Lewis, R.P. (2019). Performance Characterisation and Optimisation of a Building Integrated Photovoltaic (BIPV) System in a Maritime Climate. *Future Cities and Environment,* 5 (1), 8. doi.org/10.5334/fce.62

[R5] Wilderspin, T., De Rossi, F., & **Watson, T.** (2016). A simple method to evaluate the effectiveness of encapsulation materials for perovskite solar cells. *Solar Energy,* 139, 426–432. doi.org/10.1016/j.solener.2016.09.038

Grants

[G1] Worsley, D. [Principal Investigator]. (2007-2010). Metal substrate mounted flexible dye sensitised semiconductor solar cells. [EP/E035205/1]. EPSRC. GBP307,934.

[G2] Worsley, D. [Principal Investigator]. (2011-2016). Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings – SPECIFIC. [EP/I019278/1]. EPSRC. GBP5,012,105.

[G3] Worsley, D. [Principal Investigator]. **Durrant, J., Watson, T., Carnie, M., Davies, M., & Charbonneau, C.** [Co-Investigators]. (2016-2021). SPECIFIC IKC Phase 2. [EP/N020863/1]. EPSRC. GBP1,998,339.

[G4] Worsley, D., & Watson, T. [Co-Investigators]. (2014-2018). Photovoltaic Technology based on Earth Abundant Materials – PVTEAM. [EP/L017792/1]. EPSRC. GBP2,012,697.

[G5] Watson, T. [Co-Investigator]. (2016-2019). HI-PROSPECTS - HIgh resolution PRinting Of Solar Photovoltaic EleCTrode Structures. [EP/N509905/1]. EPSRC. GBP300,702.
[G6] Watson, T., & Worsley, D. [Co-Investigators]. (2017-2020). Self-assembling Perovskite Absorbers - Cells Engineered into Modules (SPACE-Modules). [EP/M015254/2]. EPSRC. GBP1,827,825.
[G7] Worsley, D. [Principal Investigator]. **Watson, T., Durrant, J., Carnie, M., Davies, M., & Charbonneau, C.** [Co-Investigators]. Strategic University Network to Revolutionise Indian Solar Energy (SUNRISE). [EP-P032591]. GCRF EPSRC. GBP6,580,123.

Patents
[P1] Watson, T., & Worsley, D. (Published 2010). Method for the manufacture of a photovoltaic device. [WO2010/115584].
[P2] McGettrick, J., & **Bryant, D.T.J.** (Published 2014). An opto-electronic device and method for manufacturing the same. [WO2014/095060].
[P3] Bryant, D. (Published 2015). An opto-electronic device and method for manufacturing the same. [WO2015/033088].

4. Details of the impact

Swansea University research into steel mounted building integrated photovoltaics (BIPV), its manufacture, lifetime stability and encapsulation methods and real-world performance of precommercial products has contributed to the creation of a new strip steel PV product, the creation and growth of a spin-out company, GBP5,000,000 of private investment and the creation of 30 jobs through the expansion of manufacturing capability. In addition, the research and critical customer engagement through two award winning demonstration buildings has influenced the shaping of the construction strategy for the UKs largest steel manufacturer to include Active Building products.

The journey to creating BIPVCo began in 2008 as a research project initiated by Tata Steel in collaboration with Worsley and Watson at SU and Durrant then at Imperial College London. The project sought to explore new opportunities to functionalise the steel roofing sector following successful research collaborations to produce extremely long-term guarantees on pre-painted steels by creating new-to-market products, with a unique opportunity for a truly building-integrated solar roof offering. The technology agnostic approach of the team at SU towards the particular PV technology has been key with research work focussed on the manufacturing challenges and key roadblocks, lifetime and stability issues as well as proof of concept buildings to showcase and demonstrate beyond doubt the capability of the new technologies. Throughout, staff from Tata Steel and SU have co-developed the technologies **[P1-P3]** supported by SPECIFIC IKC **[G2 & G3]**, with particular developments on different PV technologies covered by allied research grants Dye sensitised solar cells **[G1]**, perovskite **[G5 & G6]** and broader inorganic absorbers **[G4]** latterly with international collaborations on multiple PV technologies in India **[G7]**. Through this approach the team have provided underpinning research on the technologies of dye sensitised solar cells which were the first demonstration of steel integrated BIPV **[R1]**, new materials **[R3]**, processing methods **[R2]** and encapsulation techniques **[R4]** which can be applied to multiple BIPV systems with the first of a kind second generation CIGS steel integrated PV incorporating learnings from all of these studies trialled using the award winning Swansea Active Classroom **[R5]**.

BIPVCo is a new company founded in 2015 on the underpinning research performed by SU into functional coatings for solar energy generation applied to steel-based construction material substrates. BIPVCo produces unique flexible, building-integrated and lightweight PV products that form part of the building envelope. Through incorporation into steel roofing, these PV systems can form a portion, or even the entirety, of the roof structure without the need for additional strength in the roofing frame **[R5], [G2 & G3]**. In 2016 and, in conjunction with SPECIFIC, BIPVCo's Metektron product was first trialled using a 17kWp roof installed on the pioneering Swansea Bay Campus Active Classroom. The research from SU not only enabled BIPVCo to first showcase their integrated PV product but also (with help from SPECIFIC), led to them securing initial private sector investment of GBP1,000,000, which has subsequently increased by a further GBP4,000,000 to establish the full-scale manufacturing capability **[C1]**.

BIPVCo started with two staff, has grown and now employs >30 skilled staff. In the Spring of 2017 after a successful twelve-month trial at Swansea's Active Classroom, BIPVCo achieved another milestone in its development and were granted TUV accreditation and MCS certification, which represent industry lifetime standards. This accreditation and Swansea's research to demonstrator pathway was critical to launching a credible product into the highly competitive solar marketplace **[C1]**. The CEO of BIPVCo states:

"*The support of Swansea University and the photovoltaics research was absolutely crucial in the setup phase as a spin-out company from the University and the continued support of the research team is critical in making our new Metektron product and indeed the company* [is] *unique within the solar market place*" **[C1]**.

In 2018, BIPVCo moved to larger manufacturing facilities in Newport in South Wales where the company now has a production capability equivalent to 20MW per annum. Within the same year an additional 22kWp of curved PV was installed on Swansea's Active Office, a larger building with higher energy demands, providing a total PV area of over 300m^2. This subsequently contributed to a reduction in carbon footprint compared to similar buildings without the integrated technology and showcased the architectural flexibility of the product without any loss in performance. The Active Office received an EPC rating of A+ recognising that in an annual cycle it was predicted to be energy positive. The BIPVCo roof is the main energy source providing 78% of the power use on an annual cycle (generating 18MWh in 2020). This represents a carbon saving of 5.5 tonnes (based on the average grid intensity for carbon of 306 g/kWh in 2020). The design of the building supports a low energy consumption of 61 kWh/m^2 compared to a typical office 220 kWh/m^2.

The Metektron product has now been adopted by several developers and installed on approximately 200 buildings including private and social housing, hospitals and commercial buildings internationally **[C1 & C3]**, where a lightweight, flexible and non-reflective PV solution is desirable. In a supporting letter, the CEO of BIPVCo states:

"*The research to demonstrator pathway developed at Swansea University has been a success for BIPVCo, leading us to a commercially viable product, and subsequently a relocation to larger premises in Newport where we have expanded our facilities and production capability*" **[C1]**.

This is further reinforced by the Managing Director of Tata Steel Strip Products UK who states:

"*…the commercial development of BIPVCo was only possible with the support of the* [Swansea] *university and we are very proud to have supported our own staff to transition in setting up this new business*" **[C2]**.

Tata supply the pre-painted coated steel (co-developed with SU) and the back-to-back warranties of 30-40 years with the BIPVCo PV integration and so remain a key element of the BIPVCo development story. In addition to the key impacts Swansea's research has had upon BIPVCo, the concepts and products have also influenced the shaping of the construction strategy for the UKs largest steel manufacturer to include Active Building products. This change in strategy has enabled Tata Steel to offer and provide sustainable building solutions to meet the increasing demand on the construction industry to develop the UK's low carbon infrastructure into the future. The impact on Tata Steel's construction strategy is noted in a letter of support by the Managing Director Tata Steel Strip Products UK:

"*The demonstration of the first and second generation products [BIPV] on the Active Classroom and Office by the Swansea University team has also been extremely important in shaping our own construction strategy with Active Buildings now being a major theme with some of our biggest clients*" **[C2]**.

5. Sources to corroborate the impact

Where organisations provide testimonials below, in what capacity they are involved with the impact follows in brackets:

[C1] Letter of Support: CEO, BIPVCo Ltd. (Reporter)

[C2] Letter of Support: Managing Director Strip Steel Products, Tata Steel UK. (Reporter)

[C3] BIPVCo website, www.bipvco.com