Institution:
University of Cambridge

Unit of Assessment:
UoA5

Title of case study:
Biophotovoltaic devices

1. Summary of the impact (indicative maximum 100 words)

Developing renewable sources of energy has to go hand in hand with reducing energy demand through increased energy awareness and behavioural change. To this end a multidisciplinary consortium of researchers, led by Professor Christopher Howe (Biochemistry), have developed several biophotovoltaic (BPV) devices for off-grid electricity generation, and as educational tools. This has resulted in impact on commerce (i.e. the acquisition of a BPV spinout company by Ortus Energy Ltd in 2009 through share exchange), on society and culture (an award-winning 'Moss Table' developed by the consortium, which incorporates BPV technology, has been exhibited internationally since 2011 and has received extensive international media coverage) and on educational practices (a prototype BPV educational tool for schools has been developed by Howe and colleagues in 2013 and trialled with 6th form students).

2. Underpinning research (indicative maximum 500 words)

Finding sustainable ways of harnessing solar power is an imperative if we are to meet present and future energy needs. Conventional photovoltaic (PV) cells are energy-intensive to manufacture, and have end-of-life issues. The concept of 'biophotovoltaic' (BPV) devices was conceived to make use of the highly efficient light harvesting processes in photosynthesis:

Plants are the planet's most prolific collectors of solar energy, turning it into energy-rich compounds. During intense sunlight a significant proportion of the harvested energy has to be dissipated as heat because subsequent light-independent reactions are rate-limiting. In the BPV concept, the photosynthetic electron transfer chain is intercepted before the rate-limiting step and energy-rich electrons are diverted to an electrode, to turn solar energy directly into electricity without affecting the viability of the photosynthetic organism.

The concept was developed from 2006 onwards by a consortium of researchers led by Chris Howe (Professor of Plant and Microbial Biochemistry, Department of Biochemistry, since 2005), and including Alison Smith (Professor of Plant Biochemistry, Plant Sciences, since 2007; previously Lecturer/Reader there since 1983), Dr David Summers (Senior Lecturer, Genetics, since 2000), Dr Adrian Fisher (Reader, Chemical Engineering, since 2005), and Dr Petra Cameron (Physical Chemistry, University of Bath).

The initial proof of concept for BPV showed light-dependent production of a current in a prototype electrochemical device, where parts of photosynthetic cells (isolated thylakoid membranes) were used as the light harvesting material in the anodic chamber. Electrons generated by photosynthetic water splitting were shuttled by a redox mediator from the thylakoids to the anode, from where the current flowed to the cathode. Protons generated from water splitting travelled through a semi-permeable membrane into the cathodic chamber, where water was re-formed at the cathode, closing the circuit. The original experiments, carried out in the Smith laboratory, were not published in a journal, but led to the filing of a patent in 2007 (Ref. 8, Section 5). Isolated thylakoid membranes cannot self-repair, hence further research carried out between 2007 and 2011 in the laboratories of Howe and Fisher replaced them with intact microalgae. The work characterized the performance of BPV devices under varying conditions of microalgal cell density, light levels etc., showing that the electrons generated were ultimately derived from the photosystem I end of the electron transfer chain (Ref. 1, Section 3), and that algal biofilms could form stably on the anode surface and allow current generation in the absence of an exogenously added redox mediator (Ref. 2, Section 3). The last was an important development as it greatly increased the potential for the devices to be sustainable.

A collaboration was set up between Howe, Fisher and Dr Ian Wilson (Reader, Chemical Engineering, since 2005) in 2010 to determine the performance of different anode materials, which showed, importantly, that materials such as carbon and stainless steel could be used as anodes, removing the need to rely on non-sustainable materials such as Indium Tin Oxide (Ref. 3, Section

3).

An additional important development of the project between 2010 and 2013, carried out in the Howe lab, was to broaden the biological material used in the anode of the device to include land plant material (mosses or vascular plants). The plant material in the anode exudes organic matter, which is metabolized by bacteria in the rhizosphere. These bacteria liberate electrons, as in a conventional microbial fuel cell, generating current. Howe and colleagues characterized the power output from rice in comparison with a weed commonly found competing with rice in paddy fields (Ref. 4, Section 3). This work raises the possibility of coupling power generation to large-scale agriculture.

This research, proving that land plants could also be used in the anode of the device, formed the basis of the development in 2011 of an electricity-generating Designer 'Moss Table', in a collaboration between the groups of Howe and of Dr James Moultrie (Senior Lecturer, Institute for Manufacturing, since 2009), which has become an important tool for educating about energy awareness and renewable energy.

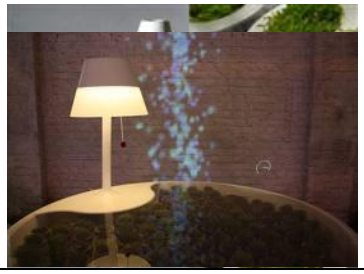
Potential applications of BPV devices have been enhanced by further research in the Howe lab, between 2011 and 2013. Taking advantage of molecular biology tools, photosynthetic bacterial strains were generated which carry mutations that increased the power output of the BPV device ca. 23 times (Ref. 5, Section 3). These findings are all being incorporated into the development of a BPV-based experimental toolkit for use in secondary schools.

3. References to the research (indicative maximum of six references)

1) Bombelli P, Bradley RW, Scott AM, Philips AJ, McCormick AJ, Cruz SM, Anderson A, Yunus K, Bendall DS, Cameron PJ, Davies JM, Smith A, Howe CJ, Fisher AC (2011) Quantitative analysis of the factors limiting solar power transduction by *Synechocystis* sp. PCC6803 in biological photovoltaic devices. Energy & Environmental Science 4:4690-4698 DOI: 10.1039/C1EE02531G
2) McCormick AJ, Bombelli P, Scott AM, Philips AJ, Smith AG, Fisher AC, Howe CJ (2011) Photosynthetic biofilms in pure culture harness solar energy in a mediatorless biophotovoltaic (BPV) system. Energy & Environmental Science 4:4699-4709 DOI: 10.1039/C1EE01965A
3) Bombelli P, Zarrouati M, Thorne RJ, Schneider K, Rowden SJ, Ali A, Yunus K, Cameron PJ, Fisher AC, Ian Wilson D, Howe CJ, McCormick AJ (2012) Surface morphology and surface energy of anode materials influence power outputs in a multi-channel mediatorless bio-photovoltaic (BPV) system. Phys Chem Chem Phys 14:12221-12229 DOI: 10.1039/c2cp42526b
4) Bombelli P, Iyer DM, Covshoff S, McCormick AJ, Yunus K, Hibberd JM, Fisher AC, Howe CJ (2013) Comparison of power output by rice (*Oryza sativa*) and an associated weed (*Echinochloa glabrescens*) in vascular plant bio-photovoltaic (VP-BPV) systems. Appl. Microbiol. Biotechnol. 97:429-438 DOI: 10.1007/s00253-012-4473-6
5) Bradley RW, Bombelli P, Lea-Smith DJ, Howe CJ (2013) Terminal oxidase mutants of the cyanobacterium Synechocystis sp. PCC 6803 show increased electrogenic activity in biological photo-voltaic systems. Phys. Chem. Chem. Phys. DOI: 10.1039/C3CP52438H

Funding:
EPSRC grant "Semibiological photovoltaic cells" £155k; Howe, Fisher; Oct 2007-Mar 2009
EPSRC grant "Advanced biophotovoltaic devices" £1.3M, Fisher, Howe, Smith, Summers; Oct 2008-Mar 2013

4. Details of the impact (indicative maximum 750 words)



Impacts on society, culture and creativity:
Public understanding has improved, and public debate has been stimulated and informed by research
Out of the collaboration between BPV researchers in Biochemistry, Plant Sciences and Chemical Engineering and researchers of the 'Design in Science' project at the Institute for Manufacturing (IfM)

arose the 'Moss Table'. The designers at IfM, Alex Driver and Carlos Peralta, were keen to create an item which the general public could easily relate to, through which they could showcase BPV technology. The table incorporates 112 BPV moss pods where photosynthate of moss leads to generation of current, which aids in powering an integrated table lamp. The Moss Table has become a high profile tool to educate about opportunities for sustainable design, as well as the challenges of generating sufficient renewable energy.

The table and/or the BPV technology has been exhibited at **high profile international design fairs** (*London Design Festival 2011; Salone Satellite of Milan Furniture Fair 2012; ALIVE / En Vie, Paris, 2013*), at national and regional **science exhibitions** (*Royal Society Summer Science Exhibition 2010, Big Bang Fair 2011, National Science Week March 2012 and 2013, EPSO Fascination of Plants Day May 2012 and 2013, National Sciences Week / Bio Biology Day Oct 2012*), and through an event in the 'Living Designs' series of the InCrops Enterprise Hub (*Jan 2013*). The exhibit received extensive **international press coverage** (*including the New York Times, the Financial Times, and Made Magazine;* Refs 1-2, Section 5) and global attention via blogs and newsletters. It has been selected by members of the public as the **"peoples' choice" for the Design Icons Exhibition** organised by Creative Front Cambridgeshire for the Design Council in Feb 2012 (Ref. 3, Section 5). A film about the BPV technology and the Moss Table has been part of the **British Council-sponsored touring exhibition 'Everything – Forever – Now'**, showcasing contemporary approaches to sustainable design coming out of Britain that use new technologies and materials. So far the exhibition has visited Thailand, Malaysia, Vietnam and Poland (Ref. 4, Section 5). The Moss Table Project is featured in the **book** *Bio Design - The Convergence of Science, Technology and Creativity*, by Myers and William, published 2012, which profiles recent works that illustrate the convergence of design and biology (Ref. 5, Section 5). In addition, the Moss Table was included in the technology section of the **Channel 4 program "Sunday Brunch"** on 13/5/12, and the BPV technology was featured by South-African collaborators of the Cambridge consortium on the "Space Life" **radio show** of the Assembly Radio station (based in Cape Town) on 15/2/13 (Ref. 6, Section 5).

Through the exhibitions, fairs and events an estimated minimum of 50,000 people in 7 countries (UK, Italy, France, Thailand, Malaysia, Vietnam, Poland) have interacted directly with the BPV technology (Ref. 7, Section 5)), and millions more have learned about it through the media coverage and online resources (based on their traffic figures). Repeated requests have been received to purchase the moss table or other BPV technologies that have been showcased, which indicates interest and engagement created through the publicity.

Impacts on commerce:

A spin-out company (H+Energy Ltd; Company No. 05942643) was set up in 2006 by members of the consortium led by Howe in order to develop commercial exploitation of the technology, leading in 2007 to the filing of a patent protecting the BPV technology by the company (Ref. 8, Section 5). In 2009 H+Energy became a wholly owned subsidiary of Ortus Energy Ltd (Company No. 06950554); the shareholders exchanged their shares in H+Energy Ltd for shares in Ortus Energy Ltd.

Impacts on schools and creative professions:

Educational practices have changed outside the submitting unit:

Based on the BPV technology, an educational toolkit (for interdisciplinary training in photosynthesis, (electro)chemistry, experimental design, and for raising energy awareness) has been developed, and has been trialled with a group of students at Hills Road 6th Form College, Cambridge, in July 2013. The trial elicited high interest from the students, and Hills Road 6th Form College have decided to use the tool for student group projects (Ref. 9, Section 5).

Professionals have used research findings in conducting their work:

A London-based designer was researching new ways of generating power in 2011. She testifies: "As a designer interested – but not necessarily an expert – in technology, I eagerly delved into the BPV research published by a team around Prof. Chris Howe of the University of Cambridge. I started a collaboration with Paolo Bombelli from the Howe group in 2012, about integrating BPV

into a futuristic scenario of how plants (in this case bryophytes) might be used. This led to us in 2013 jointly developing a moss-powered radio which is now being exhibited." (Ref. 10, Section 5).
A Norfolk-based architect bureau, MCMM Architettura Ltd, has approached the Howe group in 2013 with an interest in integrating the BPV technology into architectural designs. The architect is now working with members of the Howe group on an installation for the e-Luminate Festival 2014 (Ref. 11, Section 5).

5. Sources to corroborate the impact (indicative maximum of 10 references)

1. New York Times, January 17, 2013:
http://www.nytimes.com/2013/01/17/garden/bio-design-in-the-home-the-beauty-of-bacteria.html?pagewanted=all&_r=0
2. Made Magazine, Issue 2, 2013, p40 ff (ISSN 1753-2973):
http://edition.pagesuite-professional.co.uk/launch.aspx?pbid=50949c5d-3390-4162-9834-377a20643383
3. Moss Table winning "People's Choice" at Design Icons exhibition (Cambridge Innovation Festival exhibition at Anglia Ruskin University, 8-10 February 2012)
http://www.businessweekly.co.uk/hi-tech/13426-solar-powered-moss-table-is-peoples-choice-for-design-icons-showcase
4. British Council Tour including film on BPV / Moss Table:
http://backoftheenvelope.britishcouncil.org/2013/feb/07/everything-forever-now-mocak/
5. BPV / Moss Table featured in book:
Myers, William, Bio Design - The Convergence of Science, Technology and Creativity, Thames & Hudson, 2012, ISBN-10: 0500516278l ISBN-13: 978-0500516270 http://www.biology-design.com/#!table-of-contents/ck4v (pdf of relevant chapter in repository)
6. Feature on Space Life radio show, Assembly Radio station, Cape Town, 15 Feb 2013:
http://www.ceber.uct.ac.za/index.php?option=com_k2&view=item&id=65:assembly-radio-station-discuss-vascular-plant-biophotovoltaics-with-prof-harrison-and-durgaprasad&Itemid=11>
7. Breakdown of visitor numbers to the BPV exhibit at the various events
8. Patent details: Title: HYDROGEN AND ELECTRICAL CURRENT PRODUCTION FROM PHOTOSYNTHETICALLY DRIVEN SEMI BIOLOGICAL DEVICES (SBDS)
Inventor: Paolo Bombelli; Applicant: H Plus energy Ltd; Priority date: 28/9/2007
Priority number: GB20070019009 20070928
9. Letter from Head of Biology, Hills Road 6th Form College, Cambridge
10. Letter from Designer, self-employed
11. Letter from Founder, MCMM Architettura Ltd