Electricity production by photosynthetic microorganisms

Christopher J. Howe[1] and Paolo Bombelli[1,2]

[1]Department of Biochemistry, University of Cambridge, Tennis Court Road,
Cambridge, CB2 1QW, UK

[2]Dipartimento di Scienze e Politiche Ambientali Università degli Studi di Milano
Milan, Italy

Correspondence to ch26@cam.ac.uk

Introduction

Biophotovoltaics (BPV) is the light-dependent production of external electrical current (extracellular electron transfer, or EET) by photosynthetic microorganisms. The current can be harvested by an anode in a suitable bioelectrochemical system (**Figure 1)**, and used to power small electronic devices[1]. BPV systems usually utilise bacteria that carry out oxygen-producing photosynthesis (cyanobacteria) or unicellular eukaryotic algae (organisms whose photosynthesis takes place in a discrete subcellular compartment, the chloroplast). BPV can also refer to the use of subcellular fractions, such as isolated chloroplasts, photosynthetic membranes (thylakoids), or photosystems (multiprotein complexes that carry out the primary photochemical reactions of photosynthesis). Although systems based on subcellular fractions can give higher current densities than intact cells, we concentrate here on the latter. These are self-propagating and self-repairing, and therefore of greater interest for large-scale and long-term implementation. BPV systems are also sometimes referred to as photosynthetic microbial fuel cells, emphasising their similarity to the well-established microbial fuel cells (MFCs), where heterotrophic bacteria metabolise exogenous organic nutrients and generate external electrical currents - another example of EET. However, BPV systems differ from MFCs in that in BPVs the electrical current ultimately does not come from heterotrophic metabolism but rather from electrons generated by the light-driven oxidation of water and passed through the photosynthetic electron transfer chain. (This chain is organised according to the Z scheme proposed by Hill and Bendall 60 years ago this year[2].) The first BPV systems were described nearly 50 years ago, using chloroplast thylakoids, and in 1985, Tanaka et al. described light-stimulated current production from intact cyanobacterial cells[3].

BPV systems have some attractive advantages over other power generation systems. MFCs require supply of an added organic substrate, and mass transfer to the organisms generating extracellular electrons from the substrate may limit current. Mass transfer of organic substrate is not a limitation for BPV devices, as they use water as the electron source (expected to be available in excess) and light (although shading of photosynthetic cells by their neighbours may be a limitation). In contrast to conventional photovoltaic systems, BPV systems based on whole cells continue to produce some current in the dark. This current probably results from the metabolism of photosynthetically-derived organic compounds synthesised and stored during the light. (In mixed cultures, organic matter released from photosynthetic microorganisms could be metabolised by heterotrophs to give current output in the dark. In effect, this would be a MFC powered by photosynthetic organisms[4].) BPV systems also have the advantage over conventional photovoltaic systems of using electron-generating material (i.e. photosynthetic micro-organisms) that does not require a great deal of energy to produce and is self-renewing. These attractions of BPV systems have contributed to a marked increase in research into them in recent years, to understand more of the underlying biology and enhance power generation (**Figure 2**).

Design of biophotovoltaic systems

The simplest BPV devices are two-electrode systems (**Figure 1**). The photosynthetic cells are associated with the anode, where they may form a layer that can transfer electrons to the electrode without need for addition of any redox mediator. (This is often referred to as a biofilm, although the cell-cell and cell-electrode interactions are not necessarily as close and complex as in many classical biofilms.) Alternatively, cells may be in suspension, with a redox mediator transferring electrons from cells to the electrode. The cathode uses the electrons generated at the anode to reduce oxygen, usually with a platinum-based catalyst. Three-electrode systems incorporate in addition a reference electrode, allowing the potential of the working electrode to be measured or manipulated with reference to a standard electrode. A three-electrode system allows analytical electrochemical measurements to be made that are not possible, or are less reliable, with a two-electrode system. Two-electrode systems can provide information on the total power output from a BPV device, and parameters that affect it (reviewed in ref 1). For ‘real-life’ applications rather than analytical ones, two-electrode systems are likely to be desirable, being simpler.

Biology of biophotovoltaics

BPV systems may be useful as an experimental tool for studying cell metabolism, as well as the biological and electrochemical processes that determine the availability of electrons for export. That photosynthetic microorganisms can interact electrically with their environment is itself of fundamental biological interest. Perhaps even more exciting is the likely importance of electrical interaction between microorganisms. We are used to thinking of microorganisms as communicating by chemical signals, as in quorum sensing, but electrical communication may well be just as important. Direct metabolic interactions between cells based on electron transfer also occur and can be syntrophic (mutually beneficial)[5], or might be a means of competition. If a cell could interfere with the redox machinery of a competitor, perhaps by feeding electrons into its electron transfer chain, it might be able to generate reactive oxygen species in the competitor, damaging it.

BPV devices are also of interest as an educational tool. Simple ones are in principle cheap to construct, and can be used experimentally in the classroom. Students can design experiments to measure the electrical output from strains isolated from the environment, or to study the effects of environmental changes or pollutants on output. In this way, they can learn about experimental design, photosynthesis, sustainable energy production, and environmental pollution.

Biophotovoltaics for energy

BPV systems are also of great interest as possible energy sources, but how do they compare with established systems in terms of power density? McCormick et al.[4] estimated that an average power density between 0.7 and 3 W m^{-2} is feasible from BPV in northern Europe, with proportionately greater values in locations with higher average intensities of photosynthetically active radiation (e.g. 7 W m^{-2} in Riyadh). The main uncertainties in this estimate were the fraction of photosynthetically derived electrons remaining after essential metabolic requirements of the cell had been satisfied, and the fraction of that surplus that might in principle be exported (assumed to be 67% or more and 60% or more respectively). Actual power output values for commercial and domestic photovoltaic installations for comparison are not easy to obtain. Nominal values are often measured under non-representative conditions for most locations of the panels (e.g. temperature of 25 ^{o}C, irradiance of 1000 W m^{-2}). However, MacKay[6] suggested around 5-10 Wm^{-2} is reasonable under northern European sunlight for photovoltaic systems, while biofuel crops provide on average up to around 1 W m^{-2}.

The predicted values of 3 Wm^{-2} have not yet been achieved for BPV systems, but several approaches have been taken to increase power output. These include genetic modification to enhance the amount of electrons available or their export from the cell. There are many electron sinks inside algal and cyanobacterial cells, and inactivation of these individually or in combination can increase output[1,4]. Little is known about how electrons leave photosynthetic cells, but some enhancement in output has been reported by heterologous expression of proteins implicated in extracellular electron transfer in other organisms[7]. Genetically modified microorganisms may pose problems of public acceptability, and a better route may be to screen algal/cyanobacterial strains or spontaneous mutants for elevated power production. Enhancing electron transfer to the electrode, and the performance of the electrode itself, should also be beneficial[1]. Kim et al. reported that addition of iron oxide nanoparticles and neodymium iron boride magnet complexes (enhancing stage 3 in Figure 1) allowed power output of 0.8 W m^{-2} from a species of the cyanobacterium *Synechococcus* with a light intensity of about 50 W m^{-2} [8].

Novel configurations of BPV devices may also be useful. For example, Saar et al. obtained what was then the highest power density reported (0.5 W m^{-2}) from a device that (in addition to using cells with some of the electron sinks inactivated) separated electron 'generating' and 'harvesting' stages (in effect interrupting stage 3 in Figure 1)[9]. Cells were incubated with potassium ferricyanide under illumination for a period of time, and then the suspension, containing ferrocyanide, was passed over the anode for electron 'harvesting'. Separating phases in this way would allow separate optimisation of conditions for both. It could also enhance the system's ability to generate power in the dark, by accumulating reduced mediator in the light and harvesting electrons in the dark. Consortia with photosynthetic microorganisms providing fixed carbon for heterotrophs that are potent electrogens are also of interest[10].

Scale-up and applications

Will BPV technology ever be feasible as a power source at scale? In high-income and densely populated countries (e.g., Germany, Japan, South Korea, UK) average electrical power consumption is approx. 0.5-2 kW per capita (**Figure 3**). In those countries, the total cultivated land is approximately 0.05-0.15 ha per capita. If an area, say, one tenth the size of the currently cultivated area were set aside for biological power generation, a power output of 5-30 Wm^{-2} would be required to satisfy electrical power consumption, which is unlikely to be feasible. By contrast, for some low- and middle-income countries, with large populations but also larger cultivated land area and lower per capita power demands (e.g., Brazil, India, Indonesia, Mexico), a similar calculation suggests power output of <1 W m^{-2} would be required if one tenth that land area were used (**Figure 3**). It therefore seems unlikely that BPV systems could make a significant contribution to power production in high-income countries with relatively restricted land areas and established grid supply systems. In contrast, BPV systems (or others, such as MFCs using human waste[11]) might make a useful contribution for countries with lower per capita power requirements and greater land area, especially where there is no grid supply system for much of the population. (In Africa alone, an estimated 600 million people live unconnected to the grid, a situation set to persist for many years, as predicted by the 2019 World Energy Outlook.)

Comparing life cycle and cost cycle analyses for BPV and other systems would be very informative, but is difficult at present with little understanding of how BPV systems would be scaled up. Would they be scaled up as one large unit, or as a set of smaller modules, as often the case for MFCs[11]? In the absence of detailed analyses, it is worth noting that BPV systems have the advantage that the energy-generating material (the photosynthetic organisms) are self-propagating, requiring relatively simple mineral nutrients, unlike photovoltaic systems. The microorganisms could be grown on site, and be local strains that are well adapted to the conditions of use. Moreover, BPV systems can in principle be built using simple protocols, without expensive and sophisticated manufacturing facilities, and perhaps using recycled materials for some components[12]. Repair and/or disposal of defective units may be easier for BPV systems than for photovoltaic ones. Furthermore, all those steps (building, repairing, disposing/recycling) could be implemented locally within regional facilities, fuelling local economies. By contrast, production and disposal of photovoltaic panels typically depend on large facilities located far away from where the panels are used. However, it will certainly be important to develop cheap BPV electrodes – both anode and cathode - that do not use rare or expensive materials. It might also be possible to exploit the metabolism of the microorganisms used for co-production of valuable chemicals, enhancing the financial outcome.

As well as having possible use for general power production in some countries, BPV devices may be particularly useful in certain specific applications, especially in remote areas or in environmentally sensitive areas where batteries or conventional photovoltaic systems might be considered invasive or not very effective (e.g. under the dense canopy of tropical forest). The power densities provided at the moment mean that BPV systems can already be used for running low power LEDs and environmental sensors. So BPV systems might be used for powering devices such as water quality sensors. The fact that power is generated biologically may be an advantage for environmental sensors, when the parameter being measured (such as herbicides or other toxins) may have a direct effect on the organisms generating the power[13]. Thus the power generated in, and driving, the device could itself be a measure of the level of environmental pollutant. It would be exciting to see a device which generated and stored power that was then used periodically to transmit a signal reporting on the state of the sensor. In the future BPV systems might be used for charging mobile phones. This could be of particular value in, for example, parts of sub-Saharan Africa where mobile phone coverage is good (and increasingly used for healthcare delivery as well as domestic and commercial activities).

Although biophotovoltaic systems for generation of electricity have improved dramatically over the last few years in power output (**Figure 2B**), they are still at an early stage compared to their conventional photovoltaic counterparts. However, the latter have taken decades of major research and investment to reach their current performance. We predict major developments in BPVs over the next few years, particularly in the development of cheap but efficient electrodes, the identification of strains or consortia of microorganisms that are stable and have good power output, and in scale-up. Proof-of-principle demonstration of real-world implementation of BPV systems will also be needed, to persuade more sceptical researchers, investors and the public that technologies should not be judged simply on the basis of the size of their power density, and that simple biological devices functioning in off-grid and low-resource environments have a useful role in providing energy needs.

Declaration of interests

The authors hold patent GB2466415 - Hydrogen and electrical current production from photosynthetically driven semibiological devices

1. Wey, L.T., Bombelli, P., Chen, X., Lawrence, J.M., Rabideau, C.M., Rowden, S.J.L., Zhang, J.Z., and Howe, C.J. (2019) The development of biophotovoltaic systems for power generation and biological analysis. ChemElectroChem 6, 5375-5386.

2. Hill, R., and Bendall, F. (1960) Function of the two cytochrome components in chloroplasts: a working hypothesis. Nature 186, 136-137.

3. Tanaka, K., Tamamushi, R., and Ogawa, T. (1985) Bioelectrochemical fuel-cells operated by the cyanobacterium *Anabaena variabilis.* Journal of Chemical Technology and Biotechnology. Biotechnology 35, 191-197

4. McCormick, A.J., Bombelli, P., Bradley, R.W., Thorne, R., Wenzel, T., and Howe, C.J. (2015) Biophotovoltaics: oxygenic photosynthetic organisms in the world of bioelectrochemical systems. Energy & Environmental Science 8, 1092.

5. Summers, Z.M., Fogarty, H.E., Leang, C., Franks, A.E., Malvankar N.S., and Lovley, D.R. (2010) Direct exchange of electrons within aggregates of an evolved syntrophic coculture of anaerobic bacteria. Science 330:1413-1415.

6. MacKay D.J.C. (2009) Sustainable energy – without the hot air. 365pp. UIT, Cambridge.

7. Sekar, S., Jain, R., Yan, Y., and Ramasamy, R. (2016) Enhanced photo-bioelectrochemical energy conversion by genetically engineered cyanobacteria. Biotechnology and Bioengineering 113, 675-679.

8. Kim, M.J., Bai, S.J., Youn, J.R., and Song, Y.S. (2019) Anomalous power enhancement of biophotovoltaic cell. Journal of Power Sources 412, 301-310.

9. Saar K.L., Bombelli, P., Lea-Smith, D.J., Call, T., Aro, E-M., Mueller, T., Howe, C.J., and Knowles, T.P.J. (2018) Enhancing power density of biophotovoltaics by decoupling storage and delivery. Nature Energy 3, 75-81

10. Zhu, H., Meng, H., Zhang, W., Gao, H., Zhou, J., Zhang, Y., and Li, Y. (2019) Development of a longevous two-species biophotovoltaics with constrained electron flow. Nature Communications 10, 4282.

11. Walter, X.A., Merino-Jiménez, I., Greenman, J., and Ieropoulos, I. (2018) PEE POWER® urinal II – Urinal scale-up with microbial fuel cell scale-down for improved lighting. Journal of Power Sources 392, 150-158.

12. Bateson, P., Fleet, J.E.H., Riseley, A.S., Janeva, E., Marcella, A.S., Farinea, C., Kuptsova, M., Pueyo, N.C., Howe, C.J., Bombelli, P., and Parker, B.M. (2018) Electrochemical characterisation of bio-bottle-voltaic (BBV) systems operated with algae and built with recycled materials. Biology 7, 26.

13. Chouler, J., Monti, M.D., Morgan, W.J., Cameron, P.J., and Di Lorenzo, M. (2019). A photosynthetic toxicity biosensor for water. Electrochimica Acta 309, 392-401.

Figure Legends

Figure 1. Schematic diagram (not to scale) of a biophotovoltaic system. Photosynthetic microorganisms (green ovals) absorb light energy (1) and oxidise water (2), liberating molecular oxygen and electrons. The latter would typically be used for carbon dioxide fixation, but in a BPV some are passed (in some instances via an electron carrier, EC) to the anode (3). The electrons then pass through an external circuit (4) to the cathode, driven by the difference in redox potential between the electrodes, where they recombine with protons and oxygen (5). In some

instances the anode and cathode are separated by a proton permeable membrane. In a microbial fuel cell, the electrons are generated by heterotrophic metabolism of organic matter, rather than light-driven water oxidation.

Figure 2. Growth in studies and outcomes for biophotovoltaic research. **A**) shows the cumulative number of experimental studies published on BPV from years 2000 to 2019. Data were obtained by searching for "biophotovoltaic" in Google Scholar. Publications based on sub-cellular photosynthetic components (e.g. Photosystem II), anoxygenic photosynthetic microorganism (e.g. *Rhodopseudomonas palustris*), systems with photosynthetic organisms at the cathode, plant-based systems, reviews, book chapters and patents were excluded from this figure. **B**) shows the power densities reported in experimental studies as listed by Wey et al.[1] and McCormick et al.[4]. See Supplementary Information, Table 1.

Figure 3. Electrical power density required if 10% of cultivated land were used for power generation, in the 20 most populated countries worldwide. Data are obtained from the online pages (retrieved March 2020):
https://en.wikipedia.org/wiki/List_of_countries_by_electricity_consumption
https://en.wikipedia.org/wiki/Land_use_statistics_by_country
See Supplementary Information, Table 2.

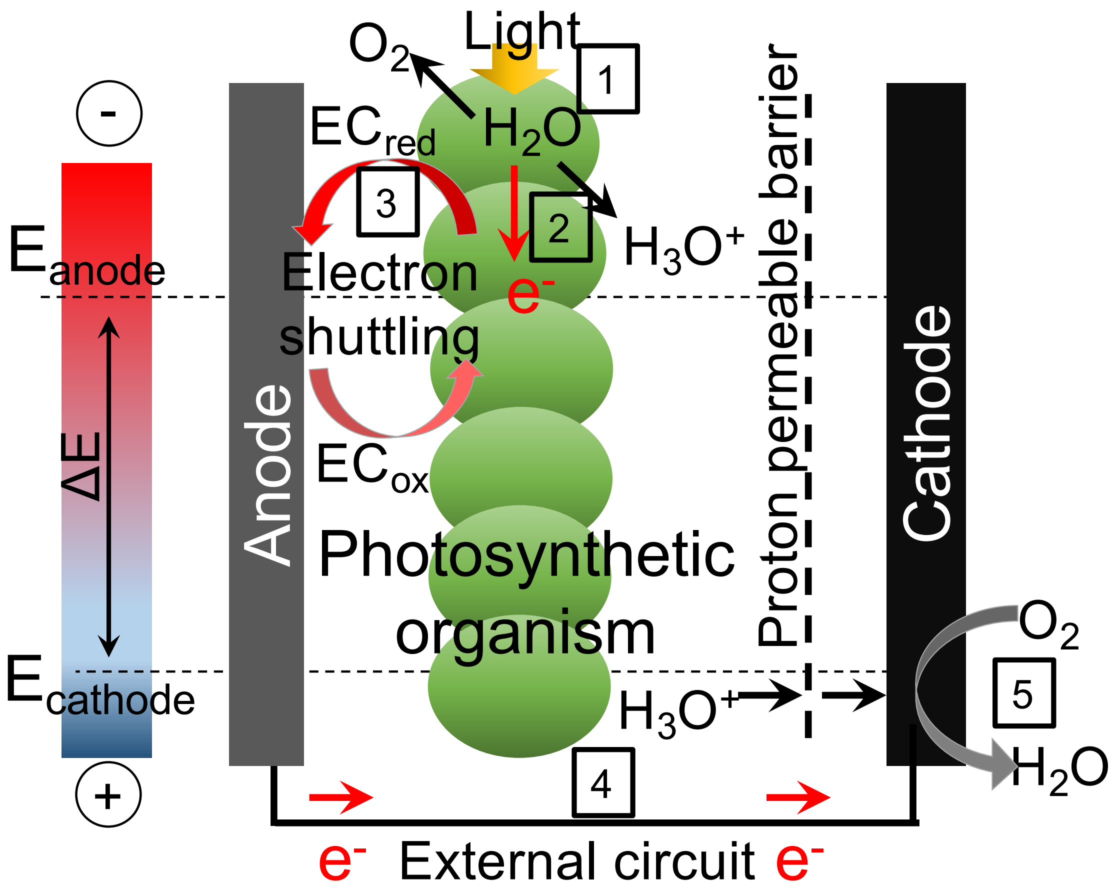
eTOC Blurb

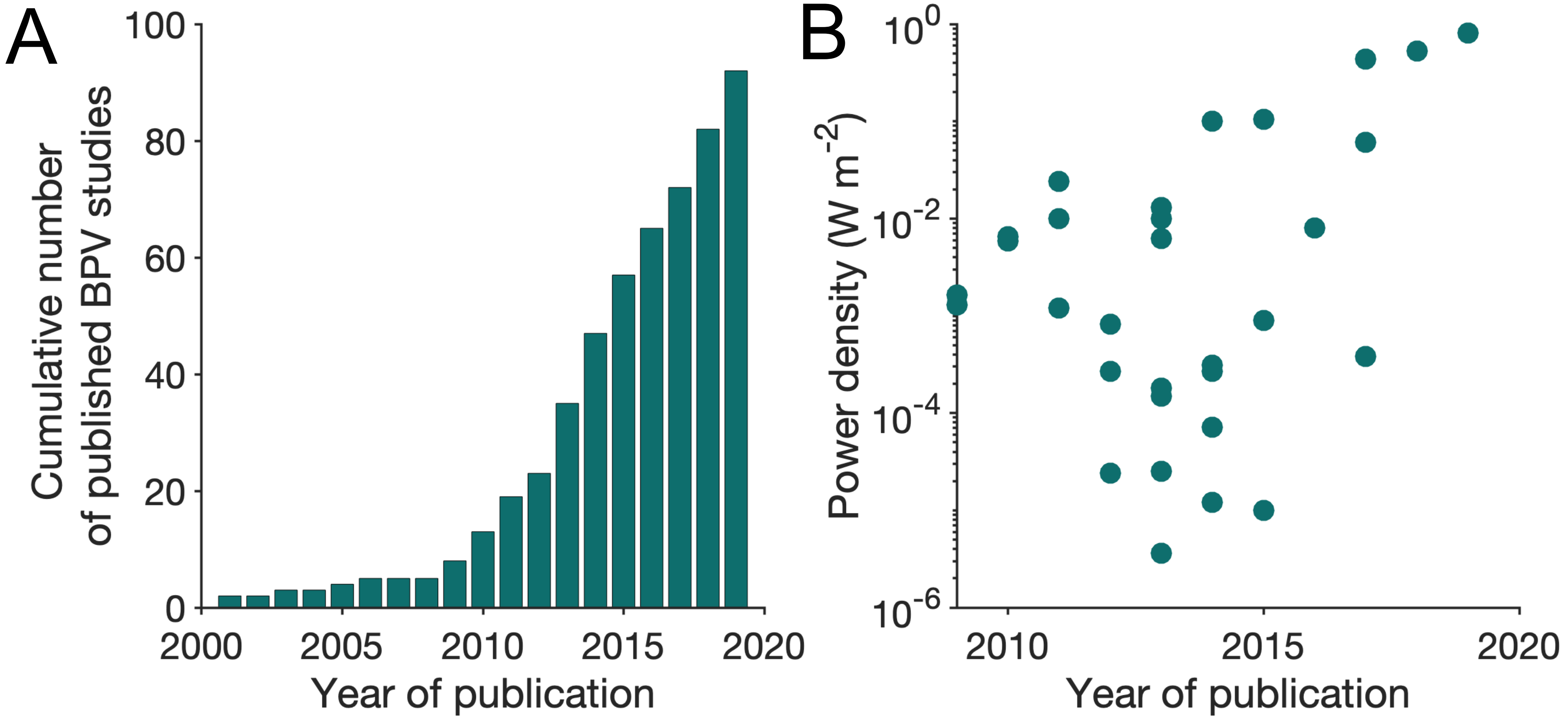
We describe the production of external electric current from photosynthetic microorganisms (biophotovoltaics) and compare the power output expected from devices exploiting this with the output of conventional photovoltaic systems. We discuss possible advantages of biophotovoltaic systems over conventional photovoltaic ones, and suggest areas where future work should lead to enhancement of power output from biophotovoltaic systems. We argue that they may be particularly useful in low-resource and off-grid situations.

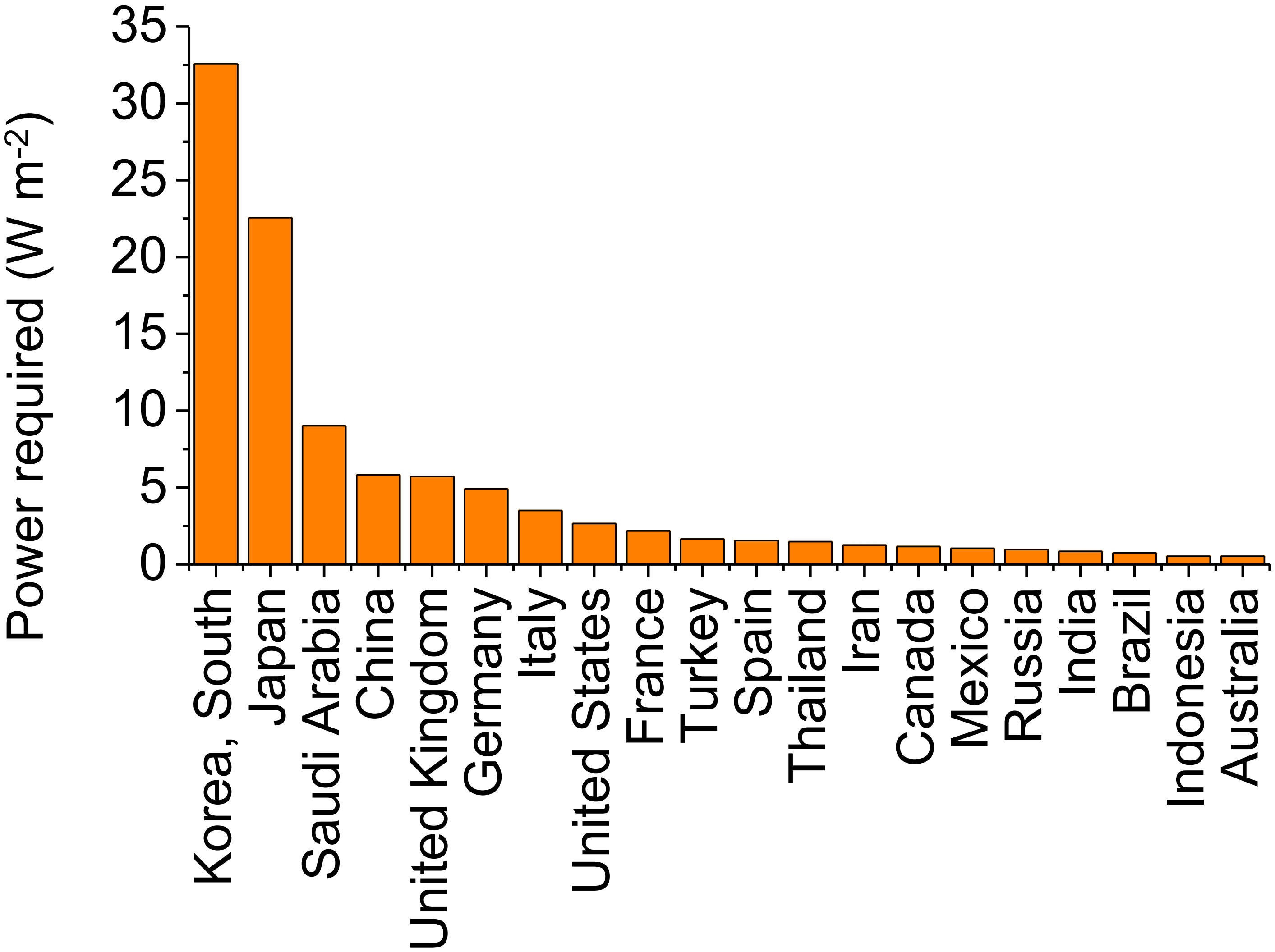
Bios

Christopher Howe is Professor of Plant and Microbial Biochemistry at the University of Cambridge. He received his PhD from the University of Cambridge in 1983 for work on the chloroplast genome of wheat. His lab continues to study chloroplast genomes, especially those of unicellular eukaryotes, but also works on photosynthetic electron transfer chains and the biotechnological exploitation of photosynthetic microorganisms. The lab has worked on direct electricity production by photosynthetic microorganisms since the early 2000s, with the joint aims of enhancing power output for real-world applications and understanding the underlying biology of the systems.

Paolo Bombelli is a Research Scientist in the Department of Science and Political Environment at the University of Milan (Italy) and a visiting researcher in the Department of Biochemistry at the University of Cambridge (UK). He obtained his PhD from the University of Cambridge in 2012 for work on the fundamental principles of photo-bio-electrochemistry. Since then, he has gathered around him a team of collaborators from several leading research groups, industrial partners and non-profit organizations. By combining biology, materials science and engineering, his long-term goal is to translate the fundamental principles of photo-bio-electrochemistry into practical applications.


-
+
E_{anode}
ΔE
$E_{cathode}$
Anode
O_2
Light
1
EC_{red}
H_2O
3
2
H_3O^+
Electron shuttling
e^-
EC_{ox}
Photosynthetic organism
Proton permeable barrier
Cathode
O_2
5
H_3O^+
H_2O
4
e^- External circuit e^-


A
Cumulative number of published BPV studies
0
20
40
60
80
100
2000
2005
2010
2015
2020
Year of publication
B
Power density (W m^{-2})
10^{-6}
10^{-4}
10^{-2}
10^{0}
2010
2015
2020
Year of publication


Power required (W m-2)
35
30
25
20
15
10
5
0
Korea, South
Japan
Saudi Arabia
China
United Kingdom
Germany
Italy
United States
France
Turkey
Spain
Thailand
Iran
Canada
Mexico
Russia
India
Brazil
Indonesia
Australia

Supplementary Table 1 - Publications used for compiling Figure 2B

Title	Journal	Author	Date	mW m^{-2}
Effects of biomass weight and light intensity on the performance of photosynthetic microbial fuel cells with Spirulina platensis	Bioresource Technology 100 (2009) 4183–4186	Chun-Chong Fu, Chia-Hung Su, Tien-Chieh Hung, Chih-Hung Hsieh, Devi Suryani, Wen-Teng Wua	2009	**1.64**
Photosynthetic Microbial Fuel Cells With Positive Light Response	Biotechnology and Bioengineering, Vol. 104, No. 5, December 1, 2009	Yongjin Zou, John Pisciotta, R. Blake Billmyre, Ilia V. Baskakov	2009	**1.3**
Current and voltage responses in instant photosynthetic microbial cells with Spirulina platensis	Biochemical Engineering Journal 52 (2010) 175–180	Chun-Chong Fu, Tien-Chieh Hung, Wen-Teng Wu, Ten-Chin Wen, Chia-Hung Su	2010	**6.5**
Light-Dependent Electrogenic Activity of Cyanobacteria	PloS ONE May 2010 | Volume 5 | Issue 5 | e10821	John M. Pisciotta, Yongjin Zou, Ilia V. Baskakov	2010	**5.9**
Nanostructured polypyrrole-coated anode for sun-powered microbial fuel cells	Bioelectrochemistry 79 (2010) 50–56	Yongjin Zou, John Pisciotta, Ilia V. Baskakov	2010	**5.9**
Quantitative analysis of the factors limiting solar power transduction by Synechocystis sp. PCC 6803 in biological photovoltaic devices	Energy Environ. Sci	Paolo Bombelli, Robert W. Bradley, Amanda M. Scott, Alexander J. Philips, Alistair J. McCormick, Sonia M. Cruz, Alexander Anderson, Kamran Yunus, Derek S. Bendall, Petra J. Cameron, Julia M. Davies, Alison G. Smith, Christopher J. Howe and Adrian	2011	**1.2**
Photosynthetic biofilms in pure culture harness solar energy in a mediatorless bio-photovoltaic cell (BPV) system	Energy Environ. Sci	Alistair J. McCormick, Paolo Bombelli, Amanda M. Scott, Alexander J. Philips, Alison G. Smith, Adrian C. Fisherb and Christopher J. Howe	2011	**10**
Porous ceramic anode materials for photo-microbial fuel cells	J. Mater. Chem., 2011, 21, 18055	Rebecca Thorne, Huaining Hu, Kenneth Schneider, Paolo Bombelli, Adrian Fisher, Laurence M. Peter, Andrew Dent and Petra J. Cameron	2011	**24**
Surface morphology and surface energy of anode materials influence power outputs in a multi-channel mediatorless bio-photovoltaic (BPV) system	Phys. Chem. Chem. Phys., 2012, 14, 12221–12229	Paolo Bombelli, Marie Zarrouati, Rebecca J. Thorne, Kenneth Schneider, Stephen J. L. Rowden, Akin Ali, Kamran Yunus, Petra J. Cameron, Adrian C. Fisher, Ian Wilson, Christopher J. Howe and Alistair J.	2012	**0.024**
Carbon neutral electricity production by Synechocystis sp. PCC6803 in a microbial fuel cell	Bioresource Technology 110 (2012) 214–218	Kartik S. Madiraju, Darwin Lyew, Robert Kok, Vijaya Raghavan	2012	**0.27**
Performance and kinetic study of photo microbial fuel cells (PMFCs) with different electrode distances	Applied Energy 100 (2012) 100–105	Kumaran Raman, John Chi-Wei Lan	2012	**0.82**
Terminal oxidase mutants of the cyanobacterium Synechocystis sp. PCC 6803 show increased electrogenic activity in biological photo-voltaic systems	Phys. Chem. Chem. Phys	Robert W. Bradley, Paolo Bombelli, David J. Lea-Smith and Christopher J. Howe	2013	**0.181**
Microcontact Imprinting of Algae on Poly(ethylene-co-vinyl alcohol) for Biofuel Cells	ACS Appl. Mater. Interfaces 2013, 5, 11123−11128	Wen-Janq Chen, Mei-Hwa Lee, James L. Thomas, Po-Hsun Lu, Ming-Huan Li, and Hung-Yin Lin	2013	**0.15**
In situ fluorescence and electrochemical monitoring of a photosynthetic microbial fuel cell	Phys. Chem. Chem. Phys	Alister E. Inglesby, Kamran Yunus and Adrian C. Fisher	2013	**0.025**
The impact of monochromatic blue and red LED light upon performance of photo microbial fuel cells (PMFCs) using	Biochemical Engineering Journal 78 (2013) 39– 43	John Chi-Wei Lan, Kumaran Raman, Chun-Mao Huang, Chung-Ming Chang	2013	**12.95**
Characteristics of the photosynthesis microbial fuel cell with a Spirulina platensis biofilm	Bioresource Technology 135 (2013) 640–643	Chia-Chi Lin, Chih-Hsun Wei, Chih-I Chen, Chwen-Jen Shieh, Yung-Chuan Liu	2013	**10**
A cost-effective microbial fuel cell to detect and select for photosynthetic electrogenic activity in algae and cyanobacteria	J Appl Phycol DOI 10.1007/s10811-013-0051-2	Veerle M. Luimstra & Sophie-Jean Kennedy & Johanna Güttler & Susanna A. Wood & David E. Williams & Michael A. Packer	2013	**6.2**
Microalgae mediated bio-electrocatalytic fuel cell facilitates bioelectricity generation through oxygenic photomixotrophic	Bioresource Technology 136 (2013)644–653	G. Venkata Subhash,Rashmi Chandra,S.Venkata Mohan	2013	**0.0036**
A photosynthetic-plasmonic-voltaic cell: Excitation of photosynthetic bacteria and current collection through a plasmonic substrate	APPLIED PHYSICS LETTERS 104, 043704 (2014)	Nathan Samsonoff, Matthew D. Ooms, and David Sinton	2014	**0.012**
Photocurrent generation by immobilized cyanobacteria via direct electron transport in photo-bioelectrochemical cells	Phys. Chem. Chem. Phys., 2014, 16, 7862--7871	Narendran Sekar, Yogeswaran Umasankar and Ramaraja P. Ramasamy	2014	**100**
Evaluation of Algal Biofilms on Indium Tin Oxide (ITO) for Use in Biophotovoltaic Platforms Based on Photosynthetic Performance	PloS ONE May 2014 | Volume 9 | Issue 5 | e97643	Fong-Lee Ng, Siew-Moi Phang, Vengadesh Periasamy, Kamran Yunus, Adrian C. Fisher	2014	**0.31**
Reduced Graphene Oxide Anodes for Potential Application in Algae Biophotovoltaic Platforms	SCIENTIFIC REPORTS | 4 : 7562 | DOI: 10.1038/srep07562	Fong-Lee Ng, Muhammad Musoddiq Jaafar, Siew-Moi Phang, Zhijian Chan3, Nurul Anati Salleh, Siti Zulfikriyah Azmi, Kamran Yunus, Adrian C. Fisher & Vengadesh Periasamy	2014	**0.27**
A Micro-Sized Microbial Solar Cell	IEEE nanotechnology magazine | March 2014	SAN YOON, HANKEUN LEE, ARWA FRAIWAN, CHUNHUI DAI, and SEOKHEUN CHOI	2014	**0.071**
A High Power-Density, Mediator-Free, Microfluidic Biophotovoltaic Device for Cyanobacterial Cells	Adv. Energy Mater. 2014, 1401299	Paolo Bombelli , Thomas Müller , Therese W. Herling , Christopher J. Howe , and Tuomas P. J. Knowles	2015	**105**
Overexpressing Ferredoxins in Chlamydomonas reinhardtii Increase Starch and Oil Yields and Enhance Electric Power	Int. J. Mol. Sci. 2015, 16, 19308-19325	Li-Fen Huang , Ji-Yu Lin, Kui-You Pan, Chun-Kai Huang and Ying-Kai Chu	2015	**0.01**
A micro-sized bio-solar cell for self-sustaining power generation	Lab Chip, 2015, 15, 391–398	Hankeun Lee and Seokheun Choi	2015	**0.9**
Biopower generation in a microfluidic bio-solar panel	Sensors and Actuators B 228 (2016) 151–155	panelXuejian Wei, Hankeun Lee, Seokheun Choi	2016	**8**
Electricity generation from digitally printed cyanobacteria	NATURE COMMUNICATIONS | DOI: 10.1038/s41467-017-01084-4	Marin Sawa, Andrea Fantuzzi, Paolo Bombelli, Christopher J. Howe, Klaus Hellgardt & Peter J. Nixon	2017	**0.38**
Self-sustainable, high-power-density bio-solar cells for lab-on-a-chip applications	Lab. Chip, 2017, 17, 3817–3825	Lin Liu and Seokheun Choi	2017	**438**
A Microscale Biophotovoltaic Device	Proc. IEEE Sensors	X. Wei, M. Mohammadifar, W. Yang, and S. Choi	2017	**60.5**
Enhancing power density of biophotovoltaics by decoupling storage and power delivery	Nat ure Energy | VOL 3 | JANUARY 2018 | 75–81 |	Kadi L. Saar, Paolo Bombelli, David J. Lea-Smith, Toby Call, Eva-Mari Aro, Thomas Müller, Christopher J. Howe and Tuomas P. J. Knowles	2018	**530**
Anomalous performance enhancement effects in Ruthenium-based Dye Sensitized Solar Cells	Journal of Power Sources 412, 301-310	Kim, M.J., Bai, S.J., Youn, J.R., and Song, Y.S	2019	**806**

Supplementary Table 2 - Data and spreadsheet used for calculating Figure 3

	Country/Region	Yearly electrical energy consumption	Population	Yearly electrical energy consumption per capita	Electrical power consumption per capita	Cultivated land	Yearly electrical energy consumption per m2 of 10% cultivated land	Electrical power consumption per m2 of 10% cultivated land
		kWh y-1		kWh p-1 y-1	kW p-1	km²	kWh m-2 y-1	W m-2
1	China	6,310,000,000,000	1,403,500,365	4,496	0.51	1,238,013	50.97	5.8
2	United States	3,911,000,000,000	323,995,528	12,071	1.38	1,681,826	23.25	2.7
3	India	1,408,624,400,000	1,266,883,598	1,112	0.13	1,891,761	7.45	0.9
4	Russia	1,065,000,000,000	142,355,415	7,481	0.85	1,265,267	8.42	1.0
5	Japan	934,000,000,000	126,702,133	7,372	0.84	47,250	197.67	22.6
6	Germany	533,000,000,000	80,722,792	6,603	0.75	123,879	43.03	4.9
7	Canada	528,000,000,000	35,362,905	14,931	1.70	519,205	10.17	1.2
8	Brazil	518,000,000,000	205,823,665	2,517	0.29	800,485	6.47	0.7
9	Korea, South	495,000,000,000	50,924,172	9,720	1.11	17,347	285.35	32.6
10	France	431,000,000,000	66,836,154	6,449	0.74	226,617	19.02	2.2
11	Turkey	347,400,000,000	80,274,604	4,328	0.49	240,553	14.44	1.6
12	United Kingdom	309,000,000,000	64,430,428	4,796	0.55	61,631	50.14	5.7
13	Italy	291,000,000,000	62,007,540	4,693	0.54	94,609	30.76	3.5
14	Saudi Arabia	272,000,000,000	28,160,273	9,659	1.10	34,400	79.07	9.0
15	Thailand	264,000,000,000	68,200,824	3,871	0.44	203,188	12.99	1.5
16	Mexico	238,000,000,000	123,166,749	1,932	0.22	259,301	9.18	1.0
17	Spain	234,000,000,000	48,563,476	4,818	0.55	171,836	13.62	1.6
18	Australia	224,000,000,000	22,992,654	9,742	1.11	487,695	4.59	0.5
19	Indonesia	221,070,000,000	258,316,051	856	0.10	478,055	4.62	0.5
20	Iran	218,000,000,000	82,801,633	2,633	0.30	197,794	11.02	1.3

Korea, South	32.6
Japan	22.6
Saudi Arabia	9.0
China	5.8
United Kingdom	5.7
Germany	4.9
Italy	3.5
United States	2.7
France	2.2
Turkey	1.6
Spain	1.6
Thailand	1.5
Iran	1.3
Canada	1.2
Mexico	1.0
Russia	1.0
India	0.9
Brazil	0.7
Indonesia	0.5
Australia	0.5

Figures are taken from Wikipedia page https://en.wikipedia.org/wiki/List_of_countries_by_electricity_consumption

Figures are taken from CIA World Factbook - Wi https://en.wikipedia.org/wiki/Land_use_statistics_by_country