

Scaling up microbial fuel cells and other bioelectrochemical systems

Bruce E. Logan

Received: 20 October 2009 / Revised: 20 November 2009 / Accepted: 20 November 2009 / Published online: 15 December 2009
© Springer-Verlag 2009

Abstract Scientific research has advanced on different microbial fuel cell (MFC) technologies in the laboratory at an amazing pace, with power densities having reached over 1 kW/m^3 (reactor volume) and to 6.9 W/m^2 (anode area) under optimal conditions. The main challenge is to bring these technologies out of the laboratory and engineer practical systems for bioenergy production at larger scales. Recent advances in new types of electrodes, a better understanding of the impact of membranes and separators on performance of these systems, and results from several new pilot-scale tests are all good indicators that commercialization of the technology could be possible within a few years. Some of the newest advances and future challenges are reviewed here with respect to practical applications of these MFCs for renewable energy production and other applications.

Keywords MFC · MEC · BES · Bioelectricity · Microbial fuel cell

Introduction

The ability of certain bacteria to produce electrical current in the laboratory was for many decades a scientific curiosity (Potter 1911), with little hope initially for practical applications. Power densities were low, chemical mediators that were toxic and often short-lived had to be added into the medium, and rich media were used to cultivate the

bacteria (Allen 1972). Several events happened around the same time that completely changed the prospects for electrical current generation by microbial fuel cells (MFCs): it was discovered that mediators did not need to be added into solution (Kim et al. 1999); wastewater could be used as a source of fuel, while accomplishing wastewater treatment (Liu et al. 2004); and much higher power densities were attained than in previous tests (Rabaey et al. 2003). Since 1999, power production has continued to increase by five to six orders-of-magnitude (based on projected surface area; Logan 2009). Power densities of MFCs using oxygen have reached 2.7 W/m^2 (cathode limited, power normalized to the cathode; Xing et al. 2008) to 6.9 W/m^2 (much larger cathodes than anodes, power normalized to the anode area; Fan et al. 2008).

Researchers have improved volumetric power densities by increasing the total surface area of the electrodes per volume of reactor and by reducing total reactor volume. Using oxygen and a separator between the electrodes, 1.55 kW/m^3 was produced using a 2.5-mL MFC with a cathode surface area of $280 \text{ m}^2/\text{m}^3$ (Fan et al. 2007b; Fig. 1). With a ferricyanide catholyte, 2.15 kW/m^3 was generated using a 0.335-mL reactor with a cathode surface area of $1,920 \text{ m}^2/\text{m}^3$ (Nevin et al. 2008). While chemical catholytes such as ferricyanide and permanganate are used in the laboratory to test new ideas (Rabaey et al. 2003; You et al. 2006; Zuo et al. 2008b), it has become apparent that practical applications for large systems require sustainable electron acceptors such as oxygen. Thus, most recent work with applications for wastewater treatment has focused on air-cathode designs.

MFCs were first used to produce power from the electrical current generated by bacteria, but there has been an evolution in these systems resulting in applications for other purposes. Additional voltage was added to the potential generated by the bacteria, allowing for various

B. E. Logan (✉)
Department of Civil and Environmental Engineering,
Penn State University,
212 Sackett Building,
University Park, PA 16802, USA
e-mail: blogan@psu.edu

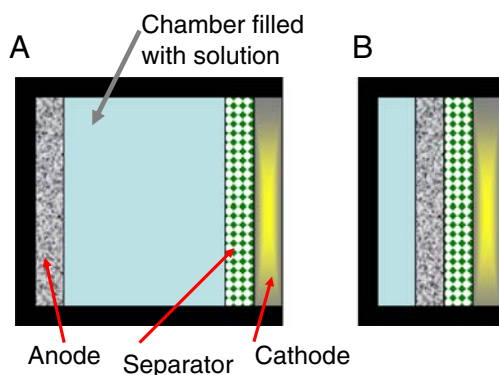


Fig. 1 Microbial fuel cell designs. **a** Anode kept separated from the cathode with a separator (or membrane). **b** When the separator is able to reduce oxygen transfer from the cathode, but allow proton transfer from the liquid, volumetric power density can be increased by moving the anode next to the cathode and reducing the liquid volume (Fan et al. 2007a; Zhang et al. 2009c)

products to be generated at the cathode, such as hydrogen, methane, and hydrogen peroxide (Cheng et al. 2009; Liu et al. 2005; Rozendal et al. 2006a, 2009). Membranes can be used in MFCs in specific ways to allow for water desalination, while simultaneously generating electrical power (Cao et al. 2009). These other systems are no longer strictly fuel cells as electrical power is no longer the primary objective. Thus, the terms such as “MFC technologies”, “MxCs”, and bioelectrochemical systems have been used to describe the suite of possible applications that have evolved from our ability to extract and utilize the current and potential generated by bacteria.

The challenges for bringing MFC technologies out of the lab, that is for practical applications, rest of a number of factors. The cost of the electrode materials must be reduced, precious metals cannot be used, and current densities must be maximized. While these issues can be addressed in laboratory studies, other issues remain that ultimately require field testing. Pilot-scale studies are needed to address how well materials perform at larger scale and their longevity, and they are needed to examine performance of these devices over time with variations in fuel (wastewater) composition, temperature, and as a function of maintenance (for example to control fouling on electrodes). The evolution of these systems also requires a better understanding of the bacteria and the biochemical pathways used by the exoelectrogenic bacteria able to release electrons to acceptors outside the cell. However, there have been several recent reviews on this subject of the bacteria in MFCs (Logan 2009; Lovley 2008) and, thus, this will not be further addressed here. Rather, the focus here is on advances in materials and a review of pilot tests that are being undertaken to understand how to build and operate scalable systems. The types of electrode materials and their surface areas, the importance of current collectors to

improve power production, and the role of separators in construction of the reactor are particularly emphasized as they relate to scaling up MFC systems.

Electrode materials

Various materials have been used in the laboratory as electrodes, but greater attention is now being paid to electrodes that contain current collectors (Zhang et al. 2009a; Zuo et al. 2008a). A piece of carbon cloth or paper, even if highly optimized for bacterial adhesion, still lacks the high electrical conductivity of metals that is needed to transfer electrons over long distances. Thus, many new electrode designs are incorporating metals as current collectors. Chemical treatments and precious metals can improve power production in the laboratory (Cheng and Logan 2007; Liu et al. 2007), but ultimately, these modifications may not be practical due to cost. Thus, there will be compromises on performance based on material costs.

Anodes

Carbon cloth is an excellent substrate for anodic biofilms in MFCs, but fuel cell grade materials can be expensive (approximately \$1,000/m²). Carbon felt is another material that is often used in MFCs (Borole et al. 2009; Deng et al. 2009). Carbon mesh can work as well or better than carbon cloth or paper, and it is much less expensive material (approximately \$10–50/m²; Wang et al. 2009). A high-temperature ammonia gas treatment is useful for increasing bacterial adhesion and power densities (Cheng and Logan 2007), but a simple heat treatment of the carbon mesh is sufficient to produce good performance (Wang et al. 2009). Current collectors have not been used with these materials (except as terminals), and they must be selected with care to avoid corrosion. Copper is not suitable due to high corrosion rates, toxicity to bacteria, and it will give the impression of high power densities due to galvanic corrosion. Many stainless steels also undergo corrosion, but careful selection of chrome content apparently can produce materials stable even in seawater (Dumas et al. 2007).

One of the more promising materials and configurations is graphite fiber brush anodes (Feng et al. 2009; Logan et al. 2007; Nielsen et al. 2007). The core of the brush is made of a non-corrosive metal (certain stainless steels or titanium), and the graphite fibers have very high surface areas based on the small size of the fibers. However, it is not clear what minimal fiber densities could be used to achieve the lowest costs, and to what extent the different parts of the brush contribute to power as the effective

electrode spacing varies for individual fibers that are different distances from the cathode. Early tests with brush anodes used a high-temperature ammonia gas treatment (Logan et al. 2007), but heating alone is sufficient to condition the surface for good bioelectrochemical properties (Feng et al. 2009). Metals such as tungsten and stainless steel also show promise (Dumas et al. 2007; Rosenbaum et al. 2006) and could be used in brush form as well.

MFC Cathodes

The cathode is the most challenging aspect of the MFC design due to the need to have a three-phase interface: air (oxygen), water (protons), and solid (electricity). So far, the cathode is more likely to limit power generation than the anode (Fan et al. 2008; Rismani-Yazdi et al. 2008). Good progress has been made in replacing the platinum catalyst used for oxygen reduction with non-precious metals and metal-organic compounds based on Co and Fe (Cheng et al. 2006; Zhao et al. 2005). Cathodes using only bacteria (biocathodes) for increasing current densities above that of the plain material show great promise, but so far, these systems have required the use of dissolved oxygen rather than air (Bergel et al. 2005; Clauwaert et al. 2007b; He and Angenent 2006). For sediment MFCs, the dissolved oxygen is readily available, but for ex situ reactors such as those planned for wastewater treatment, aeration would be costly and thus likely prohibit use of these cathodes.

A new and interesting material being used for oxygen reduction in MFC cathodes is activated carbon (AC), especially when this material is linked to a metal mesh current collector. AC provides even higher surface specific areas (area per mass) than graphite granules. While AC is relatively poor at oxygen reduction compared to Pt-catalyzed carbon cloth materials, the large AC surface area compensates for this characteristic making AC a useful material in MFCs where overall current densities per projected electrode area are low. An AC cathode impregnated with Fe was recently shown to be capable of producing 23 W/m^3 (Aelterman et al. 2009), but the cathode needed to be sprayed with water, and this design lacked a current collector. Using AC pressed onto a nickel mesh produced a power density of 36 W/m^3 ($1,220 \text{ mW/m}^2$ based on cathode projected surface area; Zhang et al. 2009a). An expensive polytetrafluoroethylene binder was used, resulting in estimated costs of $\$50\text{--}70/\text{m}^2$ for the complete cathode assembly, but it may be possible to reduce the mass of material or use alternative binders in the future. Nickel can be replaced with less expensive stainless steel, as the electrode is cathodically protected from corrosion, reducing the projected cost to $\$20\text{--}40/\text{m}^2$.

MFC cathodes that use nitrate as an electron acceptor are another area of interest for ammonia-rich wastewaters (Clauwaert et al. 2007a; Viridis et al. 2008). Nitrogen

removal is important wastewater treatment as the oxygen demand for ammonia removal during wastewater treatment can be nearly equal to that of the organic matter. After oxidizing ammonia to nitrate through wastewater aeration, the nitrate-rich stream can be fed into a cathode chamber and used as an electron acceptor by denitrifying bacteria on the cathode. The use of this biocathode avoids the need for precious metal catalysts on the cathode.

MEC cathodes

Cathodes used for microbial electrolysis cells (MEC) for hydrogen production have also been steadily improving in terms of reduced cost of materials. Certain stainless steel and nickel sheet metals achieve produce performance similar to or better than that of platinum (Selemba et al. 2009). Additional cathode design configurations are being explored, and there are new advances in catalysts. High surface area stainless steel brush cathodes in MECs produced hydrogen at similar rates to flat carbon cathodes containing nano-sized Pt, although hydrogen gas bubble hold up on the cathode was a concern (Call et al. 2009). NiMo has shown performance only slightly less than that of Pt for hydrogen evolution in MECs (Hu et al. 2009). Tungsten carbide may also be useful, although corrosion can be a problem in phosphate buffered, neutral pH solutions (Harnisch et al. 2009).

Membranes and separators

Many laboratory MFCs have a membrane between two electrode chambers (Logan et al. 2006), and MECs often have a membrane to isolate the hydrogen produced at the cathode from microorganisms on the anode (Logan et al. 2008). The development and success of membraneless MFCs and MECs shows that in some situations, only a single chamber is needed (Call and Logan 2008; Liu and Logan 2004). Membranes can lead to pH gradients between the electrode chambers (Kim et al. 2007; Rozendal et al. 2006b), and membranes can deform leading to additional degradation in performance particularly when the membrane is placed next to the cathode (Zhang et al. 2009b). Ohmic resistance, and therefore internal resistance, decreases and power increases when the membrane is removed. The need to place the electrodes closely together, however, means that modern systems will likely have some type of separator between the electrodes to prevent electrode contact and short circuiting.

Cloth separators were first used to replace membranes in MFCs (Fan et al. 2007a). Later, it was realized that inert and non-biodegradable materials were needed (Zhang et al. 2009c). In general, separators increase ohmic resistance and

reduce power on a surface area basis due to reduced proton transport to the cathode. However, the separator allows closer electrode spacing, and thus improvement in power densities on a volumetric basis if oxygen penetration to the anode can be reduced (Zhang et al. 2009c). These offsetting needs of reducing oxygen transport but facilitating proton transport makes it difficult to design separators. Separator performance also changes over time due to biofilm growth, and thus the presence of the biofilm either in or on the separator needs to be included in the separator design (Zhang et al. 2009c).

Larger laboratory reactors

MFC tests have been conducted in the laboratory with reactors ranging from 1.5 μL (Qian et al. 2009) to several liters (Jang et al. 2004; Li et al. 2008; Scott et al. 2007), with most reactors typically using tens to hundreds of milliliters (Logan 2008; Logan et al. 2006). We can consider “larger” systems as those over 1 l, with only a few systems developed at this scale for laboratory work primarily to avoid either long cycle times or continuous pumping of large volumes of medium. There have been a few lessons learned from using these larger systems in the laboratory. Many of these larger reactors were “underdesigned” in terms of total electrode surface area or electrode spacing. In general, as long as relative electrode size and spacing is preserved, power produced in smaller fed-batch systems seems to be consistent with that obtained in larger systems (Liu et al. 2008). Continuous flow systems where the liquid leaves the anode chamber and flows directly into the aerated cathode have low power but are simple in design (Jang et al. 2004). However, unless the substrate is completely consumed in the anode chamber, there will be excessive biomass production in the cathode chamber.

More data is needed on the performance of these larger systems over time. Stack systems, with ferricyanide in a separate cathode chamber (avoiding problems with biofilm on the cathode), improved performance as the anodic biofilm community changed in composition (Aelterman et al. 2006), but in other studies performance decreases over time (Cheng et al. 2006; Zhang et al. 2009a). Voltage reversal is also a problem in stacked systems due to differences in resistances between stack cells or substrate starvation in cells during operation (Oh and Logan 2007). The possibility for voltage reversal can be minimized by avoiding low substrate concentrations (that occur in fed-batch cycling) using continuous flow and by closely matching internal resistances among cells in the stack. At Penn State, my group has operated several different “demonstration” MFCs, each one operating for over 1 year. The purpose of these reactors was to show an MFC running

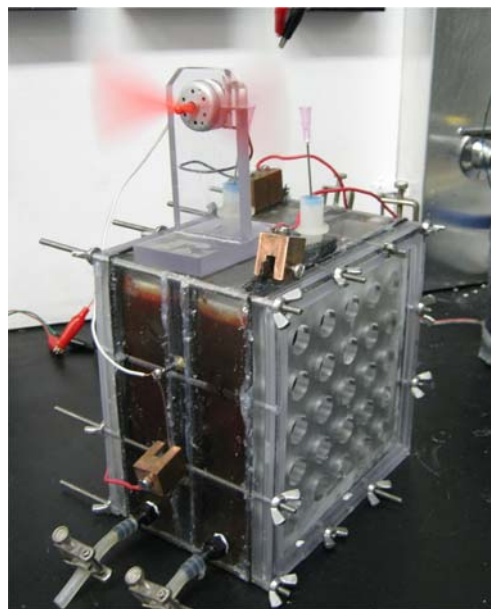


Fig. 2 A larger-volume microbial fuel cell (MFC) running a fan. The MFC contains four brush anodes of the type used in bottle brush MFCs (Logan et al. 2007) and two cathodes (one on each face)

a fan and not for scientific purposes. Our experience was that these reactors could run for more than a year (with neglect in constant feeding) without apparent degradation in performance of the fan operation. The most recent MFC demonstration cell contained approximately 1 l of solution,



Fig. 3 Tubular microbial fuel cells tested for power production using wastewater produced at Foster's brewery in Yatala, Australia (www.microbialfuelcell.org)

Fig. 4 Pilot-scale microbial electrolysis cell being tested for hydrogen production using winery wastewater at the Napa Wine Company in California, USA



four graphite fiber brush anodes, and two cathodes (Fig. 2). After 1.5 years of operation, the fan eventually stopped running. The cathode was cleaned of biofilm, and the performance was mostly restored, although the fan did not run as well as it originally did. This suggests the primary factor in performance was the biofouling of the cathode which has been noted to affect performance over time in smaller laboratory systems (Cheng et al. 2006; Zhang et al. 2009c).

Pilot-scale tests

MFCs have been demonstrated at scales useful for powering remote devices in seawater applications (Tender et al. 2008). There have been no published reports on aboveground pilot-scale tests using MFCs or MECs. However, there is some information available based on internet postings, conference presentations, and through discussions with researchers that indicates there are at least three pilot-scale tests of MFCs or MECs. The first large-scale test of MFCs was conducted at Foster's brewery in Yatala, Queensland (Australia), by the Advanced Water Management Center at the University of Queensland, conducted under the direction of Jurg Keller and Korneel Rabaey (www.microbialfuelcell.org). The reactor consisted of 12 modules, each 3 m high, with a total volume of approximately 1 m³ (Fig. 3). The reactor contained carbon fiber brush anodes inside tubular reactors, with flow up through the tubes and out over the outside of the reactor that was covered with graphite fiber brush cathodes. This design was similar to one tested in the laboratory with a ferricyanide catholyte (Rabaey et al. 2005). Little is known about MFC performance at the site, other than solution conductivity was low, limiting current generation, and that excess biochemical oxygen demand in the wastewater leaving the anode chamber resulted in the buildup of excessive biofilm on the cathodes as the wastewater was exposed to air.

MFC pilot-scale tests are also underway by University of Connecticut researchers and their collaborators (Fuss &

O'Neill, and Hydroqual Inc.) at a site in the USA (Baikun Li, personnel communication). The reactors contain granular graphite as the anode, with Pt-catalyzed carbon cloth cathodes, based on a design published by this group (Jiang and Li 2009). The systems are treating wastewater, removing up to 80% of the chemical oxygen demand present at 300–600 mg/L.

MEC tests

The first demonstration of an MEC for biohydrogen production is being conducted at the Napa Wine Company, in Oakville, CA, USA, by Penn State researchers with engineering services by Brown and Caldwell (Walnut Creek, CA, USA; Fig. 4). The reactor design is based on approach of immersing brush anodes and flat cathodes made of stainless steel into a tank (Call et al. 2009; Logan 2008; Selembo et al. 2009). The reactor contains 24 modules, each with six pairs of electrodes, and is approximately 1 m³ in total volume. Performance of this system will be reported when the system has become fully acclimated and performance is stabilized.

Outlook

MFC and MECs designs have rapidly advanced from low-power laboratory designs made with bottles and expensive materials to higher power densities and designs that appear to be more cost effective. The amount of progress made to date is impressive, especially given the relatively small amount of funding in the area. However, interest in the research topic is high, as evidenced by a growth from 2,415 citations on the topic "MFC" from 1910 to 2002 to 10,700 7 years later in October 2009 (ISI Web of Science database search). Several companies (both start up and large well-established firms) are now looking into commercialization of these systems. It is hoped that with sustained progress and continued research into cost-

effective materials and designs, such systems could become commercially available in only a few years.

Acknowledgements This author is grateful for funding by King Abdullah University of Science and Technology (KAUST; Award KUS-I1-003-13), the National Science Foundation (CBET-0730359 and CBET-0803137), the National Renewable Energy Laboratory (RFH-7-77623-01), and the Paul L. Bush award administered by the Water Environment Research Foundation.

References

- Aelterman P, Rabaey K, Pham TH, Boon N, Verstraete W (2006) Continuous electricity generation at high voltages and currents using stacked microbial fuel cells. *Environ Sci Technol* 40:3388–3394
- Aelterman P, Versichele M, Genettello E, Verbeken K, Verstraete W (2009) Microbial fuel cells operated with iron-chelated air cathodes. *Electrochim Acta* 54:5754–5760
- Allen MJ (1972) In: Norris JR, Ribbon DW (eds) *Methods microbial*. Academic, NY, pp 247–283
- Bergel A, Feron D, Mollica A (2005) Catalysis of oxygen reduction in PEM fuel cell by seawater biofilm. *Electrochem Commun* 7(9):900–904
- Borole AP, Hamilton CY, Vishnivetskaya TA, Leak D, Andras C, Morrell-Falvey J, Keller M, Davison B (2009) Integrating engineering design improvements with exoelectrogen enrichment process to increase power output from microbial fuel cells. *J Power Sources* 191:520–527
- Call D, Logan BE (2008) Hydrogen production in a single chamber microbial electrolysis cell (MEC) lacking a membrane. *Environ Sci Technol* 42(9):3401–3406
- Call D, Merrill MD, Logan BE (2009) High surface area stainless steel brushes as cathodes in microbial electrolysis cells (MECs). *Environ Sci Technol* 43(6):2179–2183
- Cao X, Huang X, Liang P, Xiao K, Zhou Y, Zhang X, Logan BE (2009) A new method for water desalination using microbial desalination cells. *Environ Sci Technol* 43(18):7148–7152
- Cheng S, Logan BE (2007) Ammonia treatment of carbon cloth anodes to enhance power generation of microbial fuel cells. *Electrochem Commun* 9(3):492–496
- Cheng S, Liu H, Logan BE (2006) Power densities using different cathode catalysts (Pt and CoTMPP) and polymer binders (Nafion and PTFE) in single chamber microbial fuel cells. *Environ Sci Technol* 40:364–369
- Cheng S, Xing D, Call DF, Logan BE (2009) Direct biological conversion of electrons into methane by electromethanogenesis. *Environ Sci Technol* 43(10):3953–3958
- Clauwaert P, Rabaey K, Aelterman P, De Schampelaire L, Pham TH, Boeckx P, Boon N, Verstraete W (2007a) Biological denitrification in microbial fuel cells. *Environ Sci Technol* 41(9):3354–3360
- Clauwaert P, Van der Ha D, Boon N, Verbeken K, Verhaege M, Rabaey K, Verstraete W (2007b) Open air biocathode enables effective electricity generation with microbial fuel cells. *Environ Sci Technol* 41(21):7564–7569
- Deng Q, Li X, Zuo JE, Logan BE, Ling A (2009) Power generation using an activated carbon fiber felt (ACFF) cathode in an upflow microbial fuel cell. *J Power Sources* 195(4):1130–1135
- Dumas C, Mollica A, Feron D, Basseguy R, Etcheverry L, Bergel A (2007) Marine microbial fuel cell: use of stainless steel electrodes as anode and cathode materials. *Electrochim Acta* 53:468–473
- Fan Y, Hu H, Liu H (2007a) Enhanced coulombic efficiency and power density of air-cathode microbial fuel cells with an improved cell configuration. *J Power Sources* 171(2):348–354
- Fan Y, Hu H, Liu H (2007b) Sustainable power generation in microbial fuel cells using bicarbonate buffer and proton transfer mechanisms. *Environ Sci Technol* 41(23):8154–8158
- Fan Y, Sharbrough E, Liu H (2008) Quantification of the internal resistance distribution of microbial fuel cells. *Environ Sci Technol* 42(21):8101–8107
- Feng Y, Yang Q, Wang X, Logan BE (2009) Treatment of graphite fiber brush anodes for improving power generation in air-cathode microbial fuel cells. *J Power Sources*. doi:10.1016/j.jpowsour.2009.10.030
- Harnisch F, Sievers G, Schroder U (2009) Tungsten carbide as electrocatalyst for the hydrogen evolution reaction in pH neutral electrolyte solutions. *Appl Catal B Environ* 89:455–458
- He Z, Angenent LT (2006) Application of bacterial biocathodes in microbial fuel cells. *Electroanalysis* 18(19–20):2009–2015
- Hu H, Fan Y, Liu H (2009) Hydrogen production in single-chamber tubular microbial electrolysis cells using non-precious-metal catalyst. *Int J Hydrogen Energy* 34:8535–8542
- Jang JK, Pham TH, Chang IS, Kang KH, Moon H, Cho KS, Kim BH (2004) Construction and operation of a novel mediator- and membrane-less microbial fuel cell. *Process Biochem* 39(8):1007–1012
- Jiang D, Li B (2009) Granular activated carbon single-chamber microbial fuel cells (GAC-SCMFCs): a design suitable for large-scale wastewater treatment processes. *Biochem Eng J* 47:31–37
- Kim BH, Park DH, Shin PK, Chang IS, Kim HJ (1999) Mediator-less biofuel cell. US Patent 5976719
- Kim JR, Cheng S, Oh S-E, Logan BE (2007) Power generation using different cation, anion and ultrafiltration membranes in microbial fuel cells. *Environ Sci Technol* 41(3):1004–1009
- Li Z, Yao L, Kong L, Liu H (2008) Electricity generation using a baffled microbial fuel cell convenient for stacking. *Bioresour Technol* 99:1650–1655
- Liu H, Logan BE (2004) Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. *Environ Sci Technol* 38(14):4040–4046
- Liu H, Ramnarayanan R, Logan BE (2004) Production of electricity during wastewater treatment using a single chamber microbial fuel cell. *Environ Sci Technol* 38(7):2281–2285
- Liu H, Grot S, Logan BE (2005) Electrochemically assisted microbial production of hydrogen from acetate. *Environ Sci Technol* 39(11):4317–4320
- Liu JL, Lowy DA, Baumann RG, Tender LM (2007) Influence of anode pretreatment on its microbial colonization. *J Appl Microbiol* 102:177–183
- Liu H, Cheng S, Huang L, Logan BE (2008) Scale up of a single-chamber microbial fuel cell through optimization of the anode to cathode area ratio. *J Power Sources* 179:274–279
- Logan BE (2008) *Microbial fuel cells*. Wiley, Hoboken
- Logan BE (2009) Exoelectrogenic bacteria that power microbial fuel cells. *Nat Rev Microbiol* 7(5):375–381
- Logan BE, Aelterman P, Hamelers B, Rozendal R, Schröder U, Keller J, Freguicac S, Verstraete W, Rabaey K (2006) Microbial fuel cells: methodology and technology. *Environ Sci Technol* 40(17):5181–5192
- Logan BE, Cheng S, Watson V, Estadt G (2007) Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells. *Environ Sci Technol* 41(9):3341–3346
- Logan BE, Call D, Cheng S, Hamelers HVM, Sleutels THJA, Jeremiasse AW, Rozendal RA (2008) Microbial electrolysis cells

- for high yield hydrogen gas production from organic matter. *Environ Sci Technol* 42(23):8630–8640
- Lovley DR (2008) Extracellular electron transfer: wires, capacitors, iron lungs, and more. *Geobiology* 6:225–231
- Nevin KP, Richter H, Covalla SF, Johnson JP, Woodard TL, Orloff AL, Jia H, Zhang M, Lovley DR (2008) Power output and coulombic efficiencies from biofilms of *Geobacter sulfurreducens* comparable to mixed community microbial fuel cells. *Environ Microbiol* 10(10):2505–2514
- Nielsen K, Reimers CE, Stecher HAI (2007) Enhanced power from chambered benthic microbial fuel cells. *Environ Sci Technol* 41(22):7895–7900
- Oh S-E, Logan BE (2007) Voltage reversal during microbial fuel cell stack operation. *J Power Sources* 167(1):11–17
- Potter MC (1911) Electrical effects accompanying the decomposition of organic compounds. *Proc R Soc Lond Ser B* 84:260–276
- Qian F, Baum M, Gu Q, Morse DE (2009) A 1.5 μ L microbial fuel cell for on-chip bioelectricity generation. *Lab Chip* 9:3076–3081
- Rabaey K, Lissens G, Siciliano SD, Verstraete W (2003) A microbial fuel cell capable of converting glucose to electricity at high rate and efficiency. *Biotechnol Lett* 25(18):1531–1535
- Rabaey K, Clauwaert P, Aelterman P, Verstraete W (2005) Tubular microbial fuel cells for efficient electricity generation. *Environ Sci Technol* 39(20):8077–8082
- Rismani-Yazdi H, Carver SM, Christy AD, Tuovinen OH (2008) Cathodic limitations in microbial fuel cells: an overview. *J Power Sources* 180:683–694
- Rosenbaum M, Zhao F, Schröder U, Scholz F (2006) Interfacing electrocatalysis and biocatalysis with tungsten carbide: a high performance noble-metal-free microbial fuel cell. *Angew Chem (Int Ed)* 45(40):6658–6661
- Rozendal RA, Hamelers HVM, Euverink GJW, Metz SJ, Buisman CJN (2006a) Principle and perspectives of hydrogen production through biocatalyzed electrolysis. *Int J Hydrogen Energy* 31(12):1632–1640
- Rozendal RA, Hamelers HVV, Buisman CJN (2006b) Effects of membrane cation transport on pH and microbial fuel cell performance. *Environ Sci Technol* 40(17):5206–5211
- Rozendal RA, Leone E, Keller J, Rabaey K (2009) Efficient hydrogen peroxide generation from organic matter in a bioelectrochemical system. *Electrochem Commun* 11:1752–1755
- Scott K, Murano C, Rumbu G (2007) A tubular microbial fuel cell. *J Appl Electrochem* 37:1063–1068
- Selemba PA, Merrill MD, Logan BE (2009) The use of stainless steel and nickel alloys as low-cost cathodes in microbial electrolysis cells. *J Power Sources* 190(2):271–278
- Tender LM, Gray SA, Grovemanb E, Lowy DA, Kauffmand P, Melhado J, Tyce RC, Flynn D, Petrecca R, Dobarro J (2008) The first demonstration of a microbial fuel cell as a viable power supply: powering a meteorological buoy. *J Power Sources* 179:571–575
- Virdis B, Rabaey K, Yuan Z, Keller J (2008) Microbial fuel cells for simultaneous carbon and nitrogen removal. *Water Res* 42(12):3013–3024
- Wang X, Cheng S, Feng Y, Merrill MD, Saito T, Logan BE (2009) The use of carbon mesh anodes and the effect of different pretreatment methods on power production in microbial fuel cells. *Environ Sci Technol* 43(17):6870–6874
- Xing D, Zuo Y, Cheng S, Regan JM, Logan BE (2008) Electricity generation by *Rhodospseudomonas palustris* DX-1. *Environ Sci Technol* 42(11):4146–4151
- You S, Zhao Q, Zhang J, Jiang J, Zhao S (2006) A microbial fuel cell using permanganate as the cathodic electron acceptor. *J Power Sources* 162:1409–1415
- Zhang F, Cheng S, Pant D, Bogaert GV, Logan BE (2009a) Power generation using an activated carbon and metal mesh cathode in a microbial fuel cell. *Electrochem Commun* 11:2177–2179
- Zhang X, Cheng S, Huang X, Logan BE (2009b) Improved performance of single-chamber microbial fuel cells through control of membrane deformation. *Biosens Bioelectron*. doi:10.1016/j.bios.2009.11.018
- Zhang X, Cheng S, Wang X, Huang X, Logan BE (2009c) Separator characteristics for increasing performance of microbial fuel cells. *Environ Sci Technol* 43(21):8456–8461
- Zhao F, Harnisch F, Schröder U, Scholz F, Bogdanoff P, Herrmann I (2005) Application of pyrolysed iron (II) phthalocyanine and CoTMPP based oxygen reduction catalysts as cathode materials in microbial fuel cells. *Electrochem Commun* 7:1405–1410
- Zuo Y, Cheng S, Logan BE (2008a) Ion exchange membrane cathodes for scalable microbial fuel cells. *Environ Sci Technol* 42(18):6967–6972
- Zuo Y, Xing D, Regan JM, Logan BE (2008b) Isolation of the exoelectrogenic bacterium *Ochrobactrum anthropi* YZ-1 by using a U-tube microbial fuel cell. *Appl Environ Microbiol* 74(10):3130–3137