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Energy Sustainability of the Water Infrastructure

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Abstract

The next century will place great strains on our planet and lifestyles. The release of large amounts of carbon dioxide and other greenhouse gases into the atmosphere is causing changes in our climate that are altering global patterns of temperature, rainfall, and runoff, ultimately affecting water availability. These changes are occurring along with an increasing global demand for energy and water.

The challenge to the water community is how to achieve energy sustainability of our water infrastructure while relying only on methods of energy production that are carbon neutral. We can do this partly by exploiting an unused energy resource: the organic matter present in various domestic and industrial wastewaters.

Rather than expend energy to remove organic matter in wastewater, we should be improving on existing methods and developing new methods for energy recovery from wastewater, effectively converting our wastewater treatment plants into power plants.

New methods for obtaining energy from wastewater being investigated in my laboratory, and in many other locations around the world, are based on microbial fuel cells (MFCs). These devices use

bacteria to directly produce an electrical current that can be used to power the wastewater treatment plant and, additionally, to provide electricity for potable water treatment. Alternatively, the current produced in this bioelectrochemical system can be converted directly into gaseous fuels, such as hydrogen and methane gas. Further modification of these devices allows direct water desalination, coupled to wastewater treatment and electrical energy production, providing for the first time a biomass-based process for water desalination that does not require an external electrical energy input.

While MFC technologies are still at an early stage of development, they show great promise as one approach for ensuring the energy sustainability of the water infrastructure.

Introduction

The energy demand for maintaining our water infrastructure in the United States is already large and, with increasing challenges posed by climate change and the adoption of more energy demanding treatment systems, this situation will not improve without changes in the way that we use energy. The amount of energy needed for our water infrastructure has been estimated to

consume 4 to 5 percent of the electricity produced in this country, with about 1.5 percent of this used for wastewater treatment alone. In California, it was recently estimated that 19 percent of the electricity used in the state was for water-related services (including agricultural operations) (Stokes and Horvath, 2009).

This high energy demand poses a problem for the United States in the future, and it particularly affects developing countries if they try to use the same technologies for meeting their own water needs. Over 1-billion people lack reliable supplies of potable water, and 2.4-billion people lack adequate sanitation. Not only would the cost of this energy be prohibitive for developing countries, but producing this much electricity from fossil fuels for the water infrastructure would add considerably to the release of carbon dioxide and other greenhouse gases to the atmosphere.

Climate change and the large amount of energy needed for the water infrastructure together create a large obstacle for providing water and adequate sanitation to the global population of over 6-billion people. The average temperatures around the world are changing, with projected increases of 3 to 5°Celsius (C) for Southern California (Figure 1).

With these temperature changes, it is expected that there will be a decrease in water runoff and, thus, a reduction in needed

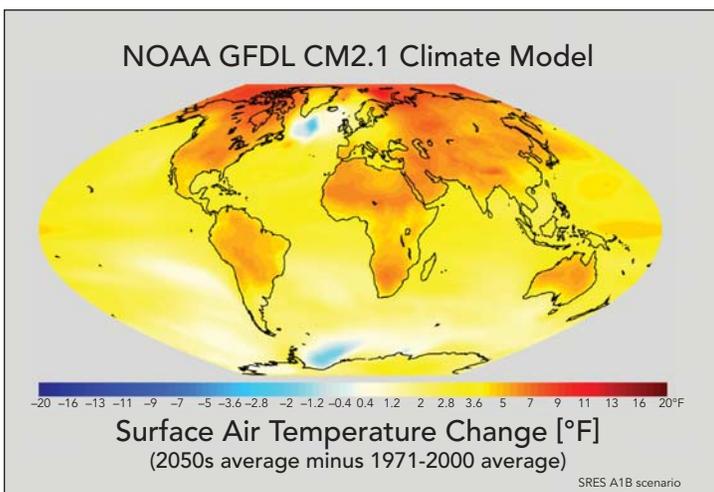


Figure 1. Predicted changes in surface air temperatures by middle of the 21st century by a National Oceanic and Atmospheric Administration (NOAA) climate model (NOAA, 2007).



Figure 2. Decrease in water storage in Lake Mead is evidenced by the change in the coloring of the rocks.

water flow into rivers and critical water storage systems. These changes in runoff will be in addition to natural variations and cycles in rainfall that already are challenging water supplies in some areas of the nation. For example, Lake Mead in Arizona – a major reservoir of water for many southwestern cities – is exhibiting critical decreases in water levels as a result of reduced flow (Figure 2). Water conservation and changes in water uses will allow us to respond to some of these changing patterns, but energy costs for pumping and moving water remain a challenge.

Energy used for producing potable water is increasing as more advanced treatment technologies are used, such as membrane-based reverse osmosis (RO), compared to conventional coagulation and flocculation systems. Decreases in freshwater availability could also result in an increased reliance on water desalination. Various desalination technologies are being used, and energy requirements for these methods vary substantially, although overall energy requirements have decreased in recent years with the development of RO systems. Desalination techniques and their associated energy requirements normalized to a cubic meter of water produced (Semiat, 2008) include:

- Single stage evaporation (650 kilowatts hour per cubic meter [kWh/m³]).

- ▶ Multistage flash (55-80 kWh/m³).
- ▶ Multi-effect distillation (40 to 65 kWh/m³).
- ▶ RO (3.7 kWh/m³ with seawater).

If all the water used in California were to be provided by water desalination, however, 52 percent of the electricity used in the state would be needed to meet water demands (Stokes and Horvath, 2009).

The amount of energy used for wastewater treatment varies by over a factor of 10, depending on the technology used (Table 1). For example, trickling filters use 0.12 kWh/m³ of wastewater treated, but they do not meet advanced treatment requirements without the addition of other processes, such as solids contact. This energy demand for activated sludge (0.28 to 0.71 kWh/m³) is actually decreased with more advanced treatment through biological nutrient removal to 0.23 kWh/m³. However, the use of membrane biological reactors (MBRs) substantially increases the energy needed for treatment due to wastewater filtration, with an average power use of 2.4 kWh/m³. The MBR is the only treatment technology that uses more energy than that in a typical domestic wastewater in the United States, which is approximately 1.2 kWh/m³ (based on 300 milligrams per liter [mg/L] of chemical oxygen demand [COD]).

The energy used at domestic wastewater treatment plants for treatment is being reduced through online and dynamic control of aeration systems to better match oxygen utilization, through energy recovery processes and the replacement of energy utilizing processes,

such as aerated sludge thickeners with stirred systems, and other processes. The largest gains in energy recovery are being made by recovering natural gas from anaerobic digesters. This gas can be used to generate electricity to power the plant. Some plants can even become completely self-sufficient in terms of energy needs using the natural gas produced. In cases where the organic matter concentration in industrial wastewaters is on the order of several grams per liter, it is usually feasible to use anaerobic processes to directly treat the wastewater and produce methane. These types of plants are used more frequently in Europe than in the United States.

Since substantial funding is needed for our aging water infrastructure in the United States, now is the time to put in place new technologies that have low energy demands or that can produce net energy. It is estimated that \$2 trillion is needed in the United States over the next 20 years for building, operating, and maintaining wastewater and drinking water facilities (WIN, 2001). About \$45 billion is needed for wastewater alone, in addition to the current annual expenditure estimated at \$25 billion.

The costs for operating these treatment plants, and the energy used by these plants, could be greatly reduced by using the energy in the wastewater. The energy in the organic matter in domestic, animal, and food wastewaters is estimated to be about equal to the electrical energy currently used for our water infrastructure (Logan, 2008). Capturing this energy should be our next main goal in designing new wastewater treatment systems.

New Technologies for Energy Recovery Based on Microbial Fuel Cells

While energy conservation and the advancement of existing technologies can reduce energy consumption at water and wastewater plants, the next generation of treatment systems will require substantially different approaches. One of the newest and most promising approaches is using microbial fuel cells (MFCs) to simultaneously treat wastewater while generating electricity (Liu et al., 2004; Logan et al., 2006). Through modifications of MFCs, it is

Table 1.

Energy Usage for Different Wastewater Treatment Processes

Wastewater Treatment Process	Energy Used (kWh/m ³)
Oxidation Pond	0.047 - 0.12
Trickling Filter (TF)	0.12
Activated Sludge (AS)	0.28 – 0.71
+ Nutrient Control	0.23
Membrane Bioreactor (MBR)	2.4

Adapted from Cooper et al., 2007.

possible to develop systems we call microbial electrolysis cells (MECs) that can be used for other purposes, such as producing gaseous fuels like hydrogen and methane (Logan et al., 2008). The newest type of MFC-based technologies is the microbial desalination cell (MDC) (Cao et al., 2009). In the rest of this presentation, three new promising technologies (MFCs, MECs, and MDCs) are reviewed.

Microbial Fuel Cells for Bioelectricity Generation

The basic concept of energy capture in an MFC is similar to the way that organisms, from bacteria to humans, generate and capture energy: food is consumed and broken down, and energy is captured during respiration. When we eat food, our bodies break complex organic matter into simple molecules that are then oxidized, releasing electrons to an energy carrier in our cells. When these electrons flow through a series of respiratory enzymes, our cells capture and store that energy (in adenosine triphosphate [ATP]), but then the electrons must then be discarded to continue the cycle. We get rid of these electrons by breathing air, so that the electrons combine with oxygen and form water. Thus, we see that production of energy requires two steps:

- Chemical oxidation (removal of electrons from molecules).
- Oxygen reduction (oxygen accepting electrons).

These two oxidation and reduction processes are used to generate electricity in MFCs, but the key to capturing the electrical current from the bacteria is to keep them separated from a source of oxygen.

An MFC consists of two electrodes: an anode and a cathode (Figure 3). Bacteria oxidize the organic matter and release electrons to the anode and protons into the water. Electrons flow through the circuit to the cathode, where they react with protons and oxygen, forming water. It is possible in MFCs to use electron acceptors other than oxygen, but except for nitrate their use so far has not been considered to be practical or sustainable. The maximum amount of energy that can be captured is the chemical potential between the electron carrier in the bacterium and oxygen, which is about 1 Volt (V).

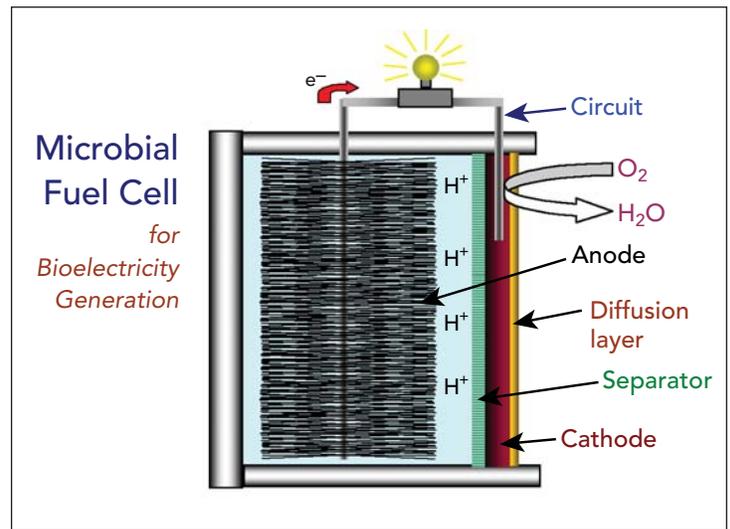


Figure 3. Example of an MFC where the anode is made of an electrically conductive graphite fiber brush and the cathode is a piece of carbon cloth containing a catalyst on the water-facing side to catalyze oxygen reduction (not shown) and a diffusion layer on the air side (to prevent water loss and reduce oxygen diffusion into the chamber). This MFC design contains a separator that is placed between the electrodes to insulate the cathode against touching to anode, while allowing for charge transfer (Modified from Logan, 2009).

In an MFC, the anode potential is less than 1 V (only a few tenths of a volt) so that bacteria capture the part of the energy between that of the carrier and the potential of the anode. The remaining energy (about half a volt) – which is the difference in the anode potential and the cathode potential (based on the chemical reduction of oxygen) – is captured in the MFC, with the remaining electrical energy lost as heat.

The outcome of organic matter degradation in an MFC that is fueled by wastewater is that the organic matter in the wastewater is removed, so the wastewater is cleaned, and useful power is produced. This process requires no net energy input as these reactions are thermodynamically favorable. As long as oxygen reacts at the cathode in a passive manner, which is typical of “air-cathode” MFCs, there is no need to aerate the wastewater. Because the bacteria derive much less energy than they would if they directly used oxygen, there is less biomass produced in an MFC than in an aerobic treatment

process, such as activated sludge. As a result, there are three advantages of MFCs compared to conventional aerobic treatment:

- (1) A useful product (electricity) is produced.
- (2) No aeration is used, so electricity for that is not needed.
- (3) Bacterial solids (sludge) production is greatly reduced compared to an aerobic process.

The lack of a need for aeration is the most significant contribution to the savings of the process as wastewater aeration can consume 30 to 50 percent of the electricity used at a wastewater treatment plant. Solids reduction is another saving, as solids handling can account for 20 to 50 percent of operating costs at a treatment plant.

The power densities produced in MFCs have substantially increased in the past decade. Systems initially developed by Kim and coworkers produced only 0.001 to 0.01 milliwatts per square meter (mW/m^2) of surface area of the anode (projected) (Kim et al., 1999; Logan and Regan, 2006). These levels were rapidly increased to about $50 \text{ mW}/\text{m}^2$ in 2002 to levels of $2,770 \text{ mW}/\text{m}^2$ ($2.77 \text{ watt per square meter } [\text{W}/\text{m}^2]$) in recent years when both the anode and the cathode have the same size (Figure 4) (Logan, 2009; Xing et al., 2008).

It is possible to increase this power density further to $\sim 7 \text{ W}/\text{m}^2$

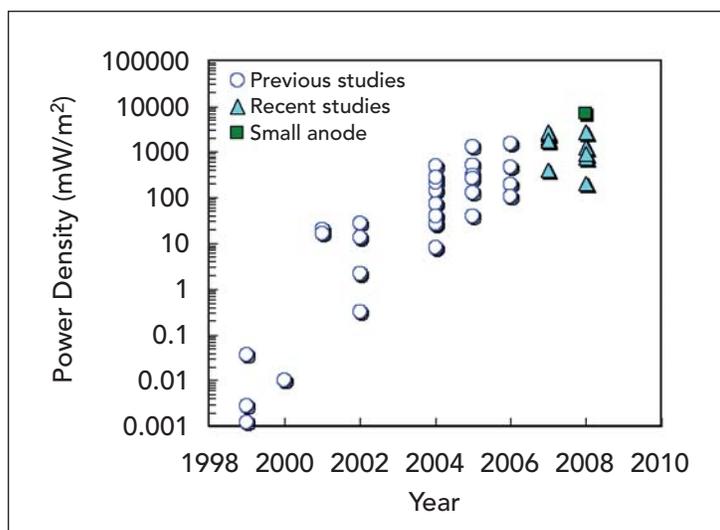


Figure 4. Increases in power production in MFC studies, emphasizing higher power densities and considering only systems using oxygen-based cathodes (adapted from Logan, 2009).

by using much larger anodes than cathodes, but systems with these very large cathodes are unlikely to be practical (Fan et al., 2008).

It is estimated that substrate diffusion to biofilms of bacteria would not limit power generation until ~ 15 to $17 \text{ W}/\text{m}^2$ (Logan, 2008; Logan, 2009). Thus, it is currently thought that the MFC architecture is limiting power generation, not the bacteria.

Work today continues to focus on increasing power densities based on the volume of the reactor (volumetric power densities) and reducing the cost of the materials. Typical MFC designs with an air cathode produce ~ 10 to $100 \text{ watt per cubic meter } (\text{W}/\text{m}^3)$. Decreasing the spaced between the electrodes can increase power, but if the electrodes get too close to each other, then oxygen contaminates the anode and power decreases (Cheng et al., 2006a). In one recent design, where a cloth separator was placed between the anode and cathode to reduce oxygen intrusion and the electrodes were closely spaced, power reached $2.7 \text{ kW}/\text{m}^3$ (Fan et al., 2007). Such designs may not be practical, however, due to the high cost of the materials in this particular system. High performance anodes and cathodes can cost $\$1,000$ per cubic meter (m^3); with only 100 square meters per cubic meters (m^2/m^3), this would result in costs of $\$100,000/\text{m}^3$. Obviously, these are too high to make systems with these materials practical.

New MFC designs are being developed that use much less expensive electrodes and materials. Graphite fiber brush anodes, which consist of electrically-conductive graphite fibers held in a twisted non-corrosive metal core (this looks like a common bottle brush), can have very high surface areas ($10,000$ to $15,000 \text{ m}^2/\text{m}^3$) and low costs ($\0.58 per square meter [m^2]) (Logan et al., 2007; Zuo et al., 2008). In tests with these electrodes, power densities of $73 \text{ W}/\text{m}^3$ were achieved.

It is essential that we reduce the cost of the cathode – and develop cathodes that do not use precious metals – to produce MFC designs that are practical and economical for scale up. The cathode in an MFC typically contains a platinum catalyst for oxygen reduction. Alternative catalysts that use non-precious metals, such

as cobalt and iron, have been tested (Cheng et al., 2006b; Zhao et al., 2005), and bacteria alone may even be able to catalyze oxygen reduction on cathodes lacking metals (Clauwaert et al., 2007). Providing a catalytic surface that allows oxygen to diffuse from air to the catalyst, but also allows for protons in water to reach the catalyst, has proven to be quite challenging. Tubular cathodes, which resemble cassettes of tubes used in membrane bioreactors, have shown promise as a new type of cathode architecture. The catalyst can be applied to the water surface of the tube with a conductive paint, and oxygen can diffuse from the inner (air) side of the tube to the water interface (Zuo et al., 2007). Such designs have produced low power in early studies, but power levels are increasing through the use of higher performance ion exchange materials (Zuo et al., 2008).

Microbial Electrolysis Cells for Hydrogen or Methane Production

With modification of the MFC to exclude oxygen, it is possible to create a system that produces hydrogen or methane gas based on the same principal used to produce hydrogen gas in a water electrolysis system. A hydrogen fuel cell captures the chemical energy from hydrogen gas oxidation and oxygen reduction as electrical energy. A water electrolyzer is essentially the opposite of a fuel cell: electrical energy is put into the system and water is electrolyzed at the anode to produce oxygen gas, and electrons that go into the circuit and protons that go into the water. When two electrons and two protons combine at the cathode, they form hydrogen gas, which then bubbles out of the water. Thus, electrical energy is converted to hydrogen gas and oxygen gas at an applied voltage of about 1.8 V. It is important to keep these two gases separated (by a membrane) so that they do not (explosively!) re-combine.

Bacteria on the anode of an MFC are breaking down organic matter to produce electrons and protons, effectively “electrolyzing” organic matter into electrons, protons, and carbon dioxide. However, the voltage produced by the anode is insufficient to allow these

electrons and protons recombine at the cathode to form hydrogen gas. By adding a small voltage to that produced by the bacteria of about 0.2 V or more, however, it is possible to produce hydrogen gas at the cathode in a microbial electrolysis cell (MEC) (Figure 5). This voltage is only about one-tenth that needed for water electrolysis; thus, hydrogen can be produced in this MEC using organic matter and much less electrical energy than that needed for water electrolysis.

The development of MECs to produce hydrogen gas has followed a similar pattern as MFCs. Over time, the current densities and efficiencies have been increasing as we gain a better understanding of the factors that affect current generation. Recent MECs have achieved hydrogen production rates of 3.1 to 6.3 liters of hydrogen per day per liter of reactor volume (L H₂/L-d), using acetic acid (an end product produced by glucose fermentation) and precious metal catalysts such as platinum (Pt) on the cathode (Call and Logan, 2008; Tartakovsky et al., 2008).

While membranes can be placed between the anode and cathode (see Figure 5) to produce a high purity hydrogen gas at the

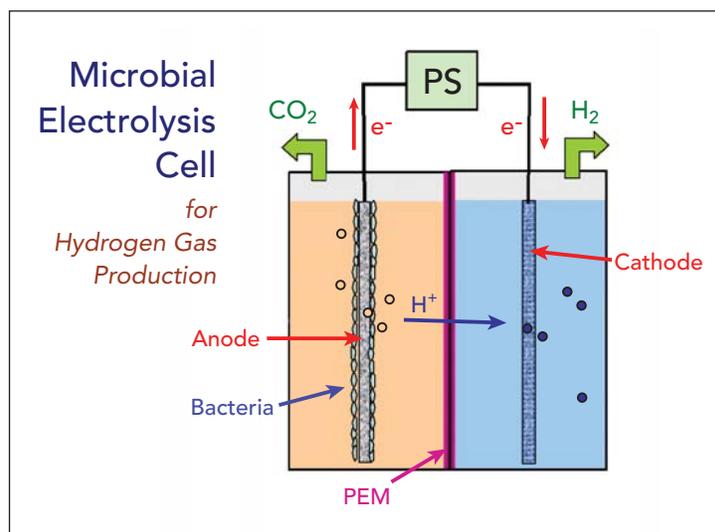


Figure 5. An MEC that produces hydrogen gas. An MFC is modified by removing oxygen from the cathode chamber and adding additional voltage to that produced by bacteria on the anode. The result is that electrons and protons combine on the cathode to form hydrogen gas, which bubbles out of the water (adapted from Liu et al., 2005).

cathode, these membranes are not essential, as the main gases produced (hydrogen and carbon dioxide) do not chemically react with each other. Avoiding the use of precious metals in these systems is important for sustainability of the process. It was recently demonstrated that a non-precious metal cathode made with a high surface area stainless steel brush cathode ($810 \text{ m}^2/\text{m}^3$) could be used with a graphite fiber brush electrode to produce hydrogen at the same rate (based on applied voltages and reactor volume) as that achieved with a similar system that used Pt on the cathode (Call et al., 2009). This finding provides a route for generating hydrogen without the need for precious metal catalysts.

The energy recoveries in MECs can be very high. In the MEC with a stainless steel cathode, for example, the energy efficiency relative to the electrical energy input was 221 percent, with hydrogen produced at a rate of $1.7 \text{ L H}_2/\text{L-d}$ at an applied voltage of 0.6 V. This efficiency is greater than 100 percent because the energy in the substrate (acetic acid) is not included in this calculation. When both the electrical and chemical energy are included, the overall energy efficiency was 78 percent, which is still a very high energy recovery. The electrical energy efficiencies can be even higher, and need to be improved through the use of other cathode catalysts. When Pt is used on the cathode, electrical energy efficiencies have reached 400 percent. In theory, they could exceed 900 percent, making this a very effective method of capturing the energy in organic matter as hydrogen gas (Logan et al., 2008).

The production of methane instead of hydrogen gas in an MEC represents another new opportunity for capturing electrical energy as a gaseous fuel. The conversion of acetate or hydrogen gas into methane is a thermodynamically favorable reaction, although the possible electrical energy gain is low. Both acetate and hydrogen are used by methanogenic microorganisms to make methane. It was recently discovered that methanogens can directly accept electrons from an electrode (and, thus, presumably from other microorganisms), so that an organic fuel (e.g., acetic acid) or hydrogen gas does not need to be produced to make methane. It was shown that a

methanogenic biofilm on a cathode of an MEC could produce methane at much greater rates than could be explained by possible rates of hydrogen formation on the cathode (Cheng et al., 2009). Carbon dioxide is used by methanogens in an MEC to make methane. This ability of methanogens to turn electrical current into methane means that renewable sources of electricity, for example from a windmill or solar panel, could be converted into methane. The fuel could then be used, stored for later use, or transported in trucks or conventional natural gas pipelines. The production of methane using MECs is at a very early stage compared to MFCs for electricity production or MECs for hydrogen production.

Microbial Desalination Cells

While the energy generated by MFCs or MECs can be used for water desalination, modification of these reactor designs allows for a more direct method of water desalination based on the concept of water electro dialysis. In a conventional electro dialysis system, a high voltage is applied to a stack of cells containing both anion and cation exchange membranes. Water is desalinated by the motion of the ions through these membranes in response to the applied charge and current flow. This concept can be modified to achieve water desalination using the voltage produced by bacteria (Cao et al., 2009).

In a microbial desalination cell (MDC), the saline water is placed between an anion (AEM) and cation exchange membrane (CEM) (Figure 6). The AEM is placed next to the anode, and the CEM next to the cathode. Bacteria grow on the anode using organic matter (for example, in a wastewater) and produce electrical current and release protons in to the water. The protons cannot move to the cathode, however, because they cannot diffuse through the AEM as only negatively charge ions can pass through this membrane. In order for charge balance to occur, anions (i.e., chloride ion $[\text{Cl}^-]$) in the middle desalination chamber flow into the anode. At the cathode, protons are removed from water, and so sodium ion (Na^+) ions in the desalination chamber move into the cathode chamber to balance charge. As a result of this process, the sodium chloride

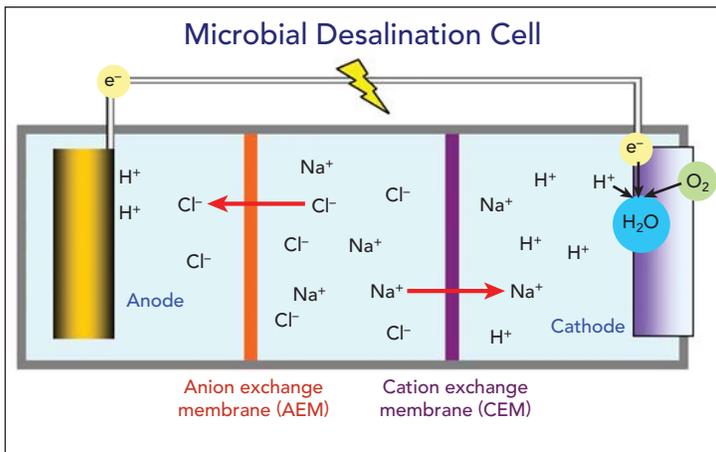


Figure 6. An MDC that produces electricity while desalinating the water in the middle chamber. Bacteria growing on the anode produce electrons and protons, causing a chloride ion to move into the anode chamber to balance charge. The reduction of oxygen at the cathode removes a proton, so a sodium ion moves into the cathode chamber to balance charge. This process results in water desalination in the middle chamber.

(NaCl) salt in the middle chamber between the AEM and CEM electrodes is removed; thus, the water is desalinated.

There are multiple advantages for desalinating water using an MDC. First, water is desalinated without the need for electricity. Second, wastewater or any source of biodegradable organic matter can be used as a source of renewable energy for desalination. Third, electrical energy is generated, which makes it possible to gain additional energy for water pumping and other processes. The fourth advantage of the MDC has to do with improving the treatability of the wastewater. High solution conductivities (i.e., saltier water) can improve power generation in an MFC because it improves charge transfer in the water and reduces the internal resistance of the system. The electrical conductivity of many wastewaters is quite low (1 millisiemens per centimeter [mS/cm] or lower); therefore, power generation is limited using real wastewaters compared to laboratory systems that operate with solutions with much higher conductivity (5 to 20 mS/cm). As the water is desalinated, the solution conductivity of the wastewater increases, allowing higher current densities, which may help more effectively treat the wastewater.

The idea of water desalination using an MDC has only just been discovered (Cao et al., 2009), so it is too early to know how cost effective this approach to water desalination will be compared to others. However, it is another example of how current production by bacteria in different types of fuel cells can be harnessed for useful purposes.

Conclusions and Outlook for Commercialization of MFC-Based Technologies

It is important to continue to look for methods to reduce energy consumption at water and wastewater treatment plants, to conserve water, and to reuse and recycle wastewater for the maximum benefit to society. We must continue to innovate and explore new methods for conservation and treatment, such as using wastewater as a source (and not a loss) of energy. The MFC-based technologies that have been described here are just emerging from the laboratory, but they show tremendous promise as a new approach for wastewater treatment. It is still too early to know when (or if) they will become efficient and economical methods for wastewater treatment and energy production, but it is important that we continue to develop these and other techniques through this new century and beyond, and that we do not solely rely on approaches developed a century ago.

Pilot-scale testing of MFC technologies is needed. There has already been one test of an MFC in Australia. This fall, the first MEC pilot scale test is planned for a site in Napa County in California. We hope that these are just the first of a wave of new tests of these technologies at larger scales that will allow us to gain the engineering experience needed to continue to advance the designs of these systems. There is also promising commercial interest in MFCs, as evidenced by several new start-up companies that are working to design these systems. We need to support additional research and the activities of these companies to ensure that these new technologies succeed and move into the marketplace.

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My research over the years has spanned a great many topics, from studies of particles in lakes and oceans to environmental remediation and bioenergy production. I could not have worked in so many fields had it not been possible to collaborate with many people having expertise in different scientific and engineering areas. I would like to especially thank three colleagues for their wonderfully collaborative and team-based approach to research:

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The 2009 Clarke Prize Honoree

BRUCE E. LOGAN, PH.D.

Environmental biotechnologist Bruce E. Logan, Ph.D., was selected as the sixteenth recipient of the NWRI Athalie Richardson Irvine Clarke Prize because of his innovative efforts to generate clean, renewable forms of energy during the treatment of wastewater.

Logan is the Kappe Professor of Environmental Engineering at The Pennsylvania State University. He also established and directs the Penn State Hydrogen Energy (H₂E) Center, which is dedicated to developing and promoting the use of hydrogen for sustainable energy production.

Logan is best known for his groundbreaking work on microbial fuel cells, which are bioreactors that use natural bacteria to break down organic matter in wastewater, producing both electricity and treated effluent. His 2008 textbook, *Microbial Fuel Cells*, is one of the first books written on this technology. He is also currently working on a newly invented bioreactor, the microbial electrolysis cell, which breaks down organic matter to produce hydrogen as an energy source.

A prolific and internationally renowned researcher, Logan is actively involved in collaborations around the world to promote the development of energy-sustainable water infrastructure.

Among these efforts, he is a Visiting Professor at both Harbin Institute of Technology in China and Newcastle University in the United Kingdom, focusing on renewable bioenergy production, and a collaborator with Tsinghua University in China, where he developing a new zero-electrical energy desalination technology. He is also a Global Research Partner with King Abdullah University of Science and Technology in Saudi Arabia, investigating novel technologies for energy production using wastewaters and agricultural waste.

More information about Logan and his research can be found at www.engr.psu.edu/ce/enve/logan/.



The
ATHALIE RICHARDSON IRVINE
Clarke Prize
*for Outstanding Achievement
in Water Science and Technology*

*The 2008 Clarke Prize Lecture, Energy Sustainability of the Water Infrastructure,
by Bruce E. Logan, Ph.D., was first presented on Thursday, July 9, 2009,
at the Sixteenth Annual Clarke Prize Award Ceremony and Lecture,
held at the Fairmont Newport Beach in Newport Beach, California.*

*The National Water Research Institute (NWRI) of Fountain Valley, California,
established the Clarke Prize in 1993 to recognize outstanding research scientists
who have demonstrated excellence in water-science research and technology.*

*Dr. Logan was the sixteenth recipient of the prize,
which includes a medallion and \$50,000 award.*

*The Clarke Prize was named after NWRI's co-founder,
the late Athalie Richardson Irvine Clarke, who was a dedicated advocate
of the careful stewardship and development of our water resources.
Mrs. Clarke's daughter, Mrs. Joan Irvine Smith (also an NWRI co-founder),
is patron of the award.*

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