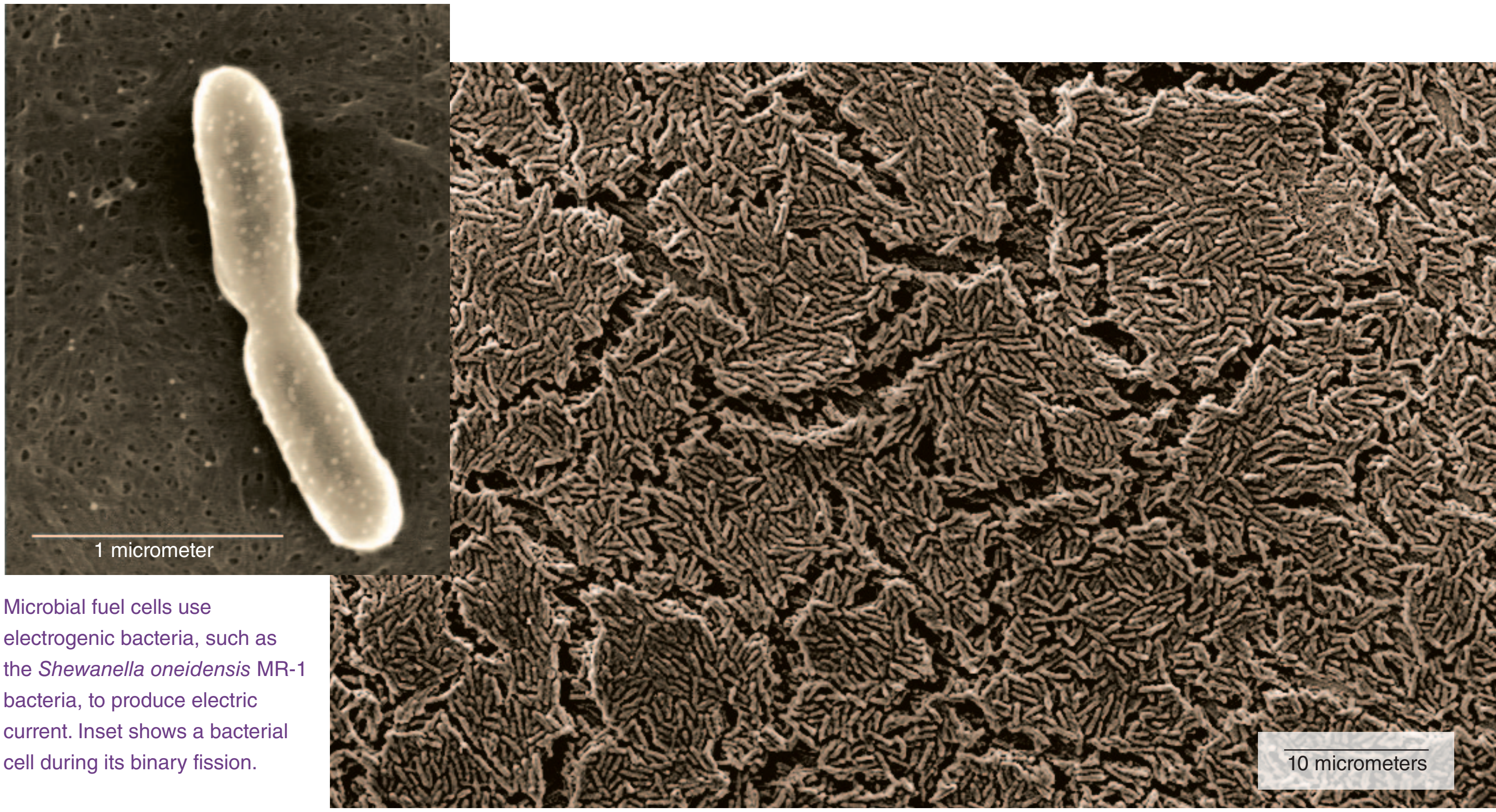
Friendly Microbes Power Energy-Producing Devices

Livermore researchers Fang Qian (left) and Michael Thelen display a canister of wastewater sludge, which contains plenty of organic nutrients and microorganisms. The team's solar–microbial energy device is designed to use this sludge to purify water.

THE tiniest living organisms on Earth could become key to addressing some of the world's biggest energy challenges. For decades, researchers have pursued energy generation by bacterial processes, most recently through the development and wider application of microbial fuel cells (MFCs), devices that convert biomass directly into electricity. These bioreactors are powered by select strains of bacteria capable of oxidizing organic matter and transferring electrons from their outer cell surface to an external electrode, thereby producing electrical current. But for all the ingenuity behind this technology, practical applications for MFCs have been limited because of the low efficiency of the bacterial energy conversion.

Livermore scientists are currently seeking ways to maximize microbial-based energy generation and develop novel applications for MFC technologies and the special bacteria that power them. Fang Qian, a scientist in the Physical and Life Sciences Directorate, is leading a study to demonstrate enhanced MFC performance using the *Shewanella oneidensis* MR-1 bacteria and a unique bioreactor design that incorporates carbon cloth electrodes with micro-size chambers. In experiments, the device yielded a power output of 250 nanowatts (billionths of a watt)—an order of magnitude increase in performance compared to most previously reported MFCs of similar dimensions.

Qian views this accomplishment as a first step toward developing new MFC technologies that integrate improved microbial metabolism with advances in materials science and fuel cells. Qian's goal is to design and build novel bioelectrical systems that combine a variety of renewable energy sources, including solar power. Ultimately, she aims to couple MFCs and solar cells to produce hydrogen, creating a hybrid system that supports more efficient and environmentally friendly energy production.



Microbial fuel cells use electrogenic bacteria, such as the *Shewanella oneidensis* MR-1 bacteria, to produce electric current. Inset shows a bacterial cell during its binary fission.

Electrogenic Bacteria Fuel Bioreactors

MFC technologies use a relatively rare type of bacteria known as electrogenic bacteria, which transfer excess electrons produced by their central metabolism to the cell surface. “Most bacteria use organic compounds as nutrients, oxidizing the carbon source and generating electrons,” Qian says. “But most of these bacteria are insulators—they generate electrons but do not release them. They are needed in biosynthetic processes to produce biomass. Electrogenic bacteria have developed unique types of transmembrane proteins that deliver unused electrons to the outside, one by one.”

This characteristic makes electrogenic bacteria excellent candidates for use in electricity-generating devices. MFCs use a pair of battery-like terminals (anode and cathode electrodes) connected to an external circuit and an electrolyte solution to conduct electricity. When bacteria physically attach to the anode, electrons generated in the interior of the cell are transferred to an external electrode, producing electrical current.

“Because bacteria are some of the oldest living systems on the planet, they have invented ways to interact with the environment very efficiently,” explains microbiologist Michael Thelen, Qian’s mentor at the Laboratory. “As an example, they are able to gain energy from minerals. We can exploit this process by isolating the bacteria and then examining their genes and the encoded proteins that are actively involved in the electron transfer.”

Most of Qian’s research into electron transfer pathways has focused on *Shewanella*, a dissimilatory metal-reducing bacteria considered a model microbe for fundamental research. The bacterium, which she used in the optimized micro-MFC study, is well understood and easy to identify, culture, and manipulate. But for all its great qualities, *Shewanella* is inefficient at generating power because it cannot completely oxidize organic compounds to maximize the energy extraction process. Moreover, a pure culture such as *Shewanella* always generates less power than do mixed cultures that contain a rich variety of microorganisms, including perhaps yet-unidentified electrogenic bacteria. Such microbial assemblies, or communities, can be found in natural environments or in municipal wastewater—a potential gold mine for bacterial prospectors like Qian and Thelen, who seek to improve MFCs.

Turning Wastewater into Drinking Water

Electrogenic bacteria exist in sludge, the by-product of wastewater treatment, which contains rich organic nutrients and diverse microbes that feed on them. While studying wastewater as a potential energy generator, the scientists realized that these clever microbes could do even more: They can purify water. To this end, Qian devised a method to inoculate MFCs with bacteria-filled sludge collected from a local water reclamation plant. The bacteria attached to the MFC anode, coating it with a biofilm that converts organic waste into carbon dioxide, producing electrical current while also reducing organic matter in the water. "We can consider this microbial fuel cell a multifunctional device," Qian says. "It produces energy and also treats wastewater. We hope to develop this technology and scale it up for broader use."

The research, funded by the Laboratory Directed Research and Development Program, is a collaboration with the University of California at Santa Cruz and the Livermore Water Reclamation Plant. During the first year of the project, Qian and her colleagues have designed different devices that can generate electricity from wastewater. Once they achieve a self-sustaining, continuous-flow system in a laboratory setting, they plan to scale up the device to operate continuously in the water plant. By the end of this year, the team wants to produce hydrogen from wastewater as well, which would add value to the water reclamation process.

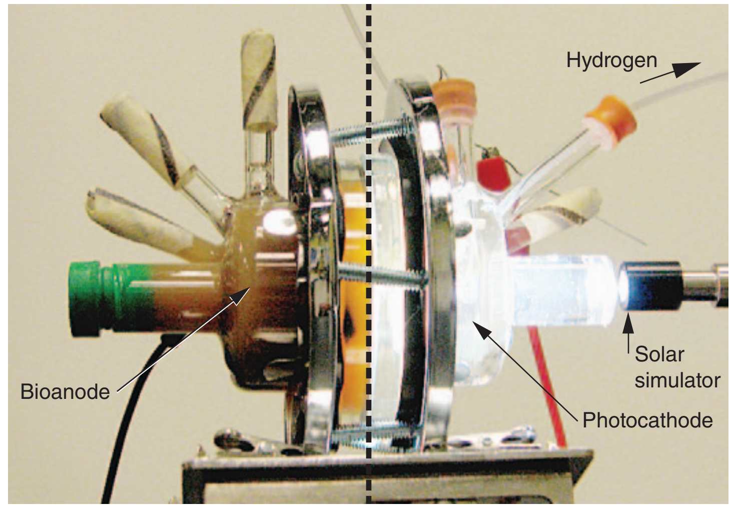
More importantly, Qian's research with bacterial communities could lead to the discovery of new, more efficient strains of electrogenic bacteria. Scientists are constantly searching for microbes with performance characteristics that will improve the bacterial-colonizing anode. As microbes are found, their genomes can be sequenced for optimizing future microbial technologies. "Our research could open up a whole new world for bioenergy applications," says Thelen.

Adding a Solar Device

While working on the wastewater purification project, Qian devised another ingenious application for MFCs. The system uses bacteria, wastewater, and sunlight to produce clean, renewable energy. The hybrid device integrates an optimized MFC with a photon-absorbing semiconductor to convert light to electrical current. The result is a solar-driven microbial photoelectrochemical cell that Qian anticipates will harvest solar light and recycle biomass, generating hydrogen in a self-sustained way while simultaneously purifying water. "No one has developed a way to couple a semiconductor photocathode and a microbial anode and have them work together synergistically," Qian says. "This innovation is really exciting in terms of fundamental science."

The hybrid system takes advantage of the best features of both technologies. Semiconductors transfer electrons at a much faster rate than microbial systems do, but most semiconductors need additional external electrical input to work as photoelectrodes. "Fang's idea was to couple the two systems so that the bacteria will provide that extra energy," says Thelen.

For now, the solar-driven microbial reactor is not envisioned as a competitor to solar cells because microbial systems are intrinsically slower than semiconductors. Instead, the team would like to use this device to enhance the capabilities of water reclamation plants and to sow the seeds of future research. "Microbes are easy to work with and they reproduce," says Thelen. "Just give them a little food, which we can get from sludge, and we have an infinite supply."



Livermore's hybrid solar–microbial energy device is designed to recover energy from the Sun and wastewater. The microbial fuel cell chamber (left) contains a bioanode, where electrogenic bacteria thrive and extract electrons from organic nutrients in wastewater. A cuprous oxide photocathode in the photoelectrochemical chamber (right) works with the anode to produce hydrogen. In this laboratory setup, the device is mounted to a solar simulator to mimic energy from the Sun.

While applications for MFC technologies are still in their infancy, Qian's creative uses of electrogenic bacteria for energy harvest and environmental applications are providing a glimpse into their future potential. One day, solar-driven devices that incorporate microbial photoelectrochemical cells may be useful on military bases or in other operations that necessitate the transport of water to remote facilities. Having the capability to treat and purify water locally in such environments could prove extremely valuable. In the meantime, the research conducted at Livermore is improving our fundamental understanding of key processes at the interface of biology, environmental science, nanotechnology, genetics, and other disciplines that will define science in this century.

—Monica Friedlander

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