Microbial fuel cells (MFCs) are an emerging clean energy technology that use bacteria to digest anything from brewery runoff to human waste, cleaning water and generating electrical power at the same time. Though comparatively in its infancy, microbial fuel cell technology already shows great promise as a novel source of clean energy, with peak power densities approaching 1kW/m^3 in some experiments, while modular and scalable fuel cell geometries allow for high energy production per acre of land used and suitable substrates and feed stocks are plentiful.1 Competition is fierce in this age of abundant natural gas and trans-continental pipelines however, and while MFCs are cheap, and getting cheaper every day, the efficiencies and power densities of even the most cutting edge microbial fuel cells are currently below what would make the technology economically viable in nations like the United States. However, in developing countries where infrastructure is less expensive, MFCs represent a striking opportunity to provide two of the most important resources such regions lack: electricity and clean water.

Using a “design for everyone” philosophy, this project aims to address both the developed and resource deficient sides of this coin simultaneously, to the mutual benefit of both parties. To this end, we hope to tackle the first-world problem of competition with established, optimized energy infrastructure by increasing MFC efficiency through directed evolution of the electricity-producing bacteria in MFCs, while using a graphene-based catalyst to confront the third-world problems of cost, ruggedness, and ease of deployment. By the end of this project, we hope to produce a prototype micro-scale kilowatt+ MFC suitable for deployment in both the US and underdeveloped areas of the globe as a distributed, in situ power source and water treatment system, capable of bringing clean energy and clean water to many in need both at home and abroad.

Microbial fuel cells use a peculiar subset of bacteria, known as electrogenic bacteria, to simultaneously generate
power and digest a feedstock, in effect, cleaning it. This feedstock can take many forms, including a variety of unsavory mixtures like brewery, winery, or yogurt production waste, animal farm and agricultural effluent and waste, raw sewage, or other organic waste products. Bacteria (in general) generate energy for themselves in much the same way as humans—they take a source of carbon, including many compounds found in wastewater, and break it down, plucking electrons from chemical bonds in the process. These electrons are shuttled down a series of chemical pathways, driving cellular production of ATP, the cell’s “energy molecule.” At the end of this electron transport chain the electrons recombine with oxygen from the air and are excreted (or exhaled, in the case of humans) as water vapor. This process is called aerobic respiration. Some organisms, however, possess the unique ability to generate energy in the absence of oxygen, the usual final electron acceptor. Some bacteria do this via fermentation, in a manner similar to how human muscle tissue generates energy (and painful lactic acid) after prolonged physical exertion. Others perform true anaerobic respiration with the same general process as aerobic respiration, but using a different final electron acceptor as the endpoint of the ATP-generating electron transport chain. Some bacteria, in fact, can even transfer electrons directly to a solid piece of conductive materiel, thus forming an electrobiochemical anode, the first half of a power-producing MFC anode-cathode pair. In an MFC, anaerobic electrogenic bacteria grow at this deliberately oxygen-deprived anode, and “eat” a substrate, like the carbon-rich compounds in a waste feedstock, producing electrons and hydrogen ions. The electrons are shuttled down the energy-producing respiration pathways and into the anode structure itself, while the hydrogen ions diffuse into the liquid surrounding the bacteria. The anode is connected via an external circuit to a catalyst-coated cathode exposed on one side to the liquid media and on the other to the air. At the cathode, electrons flowing through the circuit from the anode recombine with the hydrogen ions in media from the anode and oxygen gas from the air to form pure water. The flow of electrons from the anode to the cathode represents a usable electric current.

In the US, this technology theoretically lends itself to being easily socketed into existing water and waste treatment facilities and regimes, thereby recovering otherwise lost power from the chemical energy of the waste itself and simultaneously easing (or supplanting) the process of suitably treating such waste products. Unfortunately at nationwide scales, this technology is, at the moment, simply not economically viable: energy in the US is too cheap, and MFC technology too young, for any significant portion of the energy grid to be served by MFCs. In other areas of the globe, however, such is not the case.

MFCs provide two of the most powerfully transformative, and powerfully absent, resources on the planet today: clean water and electrical power. While the power densities of even the most promising MFC designs diminish their usefulness in many power-guzzling developed-nation contexts, even middling-efficiency designs could be of significant help in resource-poor areas of the globe where power and clean water are scarce. The modularity and scalability of MFCs lends itself to decentralized, in situ power generation, which is particularly useful in areas without established energy grids. Also holding the capacity to run

\[ \text{Wastewater} + \text{Bacteria} = \text{Electricity} \]
on many different feedstocks, MFCs are sustainable in an immediate, day-to-day sense often taken for granted in the gasoline-saturated United States. MFCs are also poised to improve access to clean water – though by the often-overlooked route of improved sanitation, rather than through purification of water for consumption. In many underdeveloped nations, improper sanitation leads to the contamination of water supplies, and latrines and toilets can be significant vector points for direct contraction of disease.3 MFC-based sanitation systems, essentially power generating septic tanks, could serve two simultaneous purposes and provide significant aid to areas of the globe in great need.

Unfortunately, a young, unestablished technology like the MFC, while potentially powerful, can quickly become unviable when confronted with the unique challenges of designing for underdeveloped areas of the globe, and magic bullet solutions are often those that go most wrong. The privileged perspective of the developed-nation designer is often plagued when it comes to designing for the underdeveloped-nation user. Without the feedback loop of client and market forces or direct proximity to the consumer, it’s easy to create a product or distribute aid that, while well intentioned, is poorly executed.

The history of aid given to underdeveloped nations is littered with good willed but ultimately misguided or poorly implemented projects. One such example is the PlayPump, a combination water pump and “roundabout” playground toy designed to leverage children’s playtime activities to pump water. The PlayPump garnered widespread acclaim and support on the crowdfunding platform, Kickstarter, for its innovative design and approach to problem solving. It was received with less acclaim in Africa where it was used. Children are rarely playing at the times when water is most needed, such as at the start or very end of the day. Recognizing this, the creators of the PlayPump designed the tool with an attached water storage system as a buffer supply for peak water demand. Unfortunately, to make the PlayPump function effectively as a roundabout toy, pump efficiency was compromised to the point that the water storage tank was rarely usefully filled. This meant that adults were often forced to use the embarrassingly childish and inefficient pump, a design that would never pass market muster in the United States, but was forgiven or overlooked, because of the trendy nature of the admittedly creative design.4

One way to combat these poisoning factors is by adopting a “design for everyone” philosophy when approaching humanitarian projects.5 The design for everyone philosophy posits that designing a single product for multiple, disparate markets or uses can force a better overall product by not allowing the designer to compromise usability, cost, or other design pillars through misunderstanding or privileged viewpoints. The beauty of this philosophy is that it benefits all parties. Developed-nation users get a product that is designed from the ground up to be affordable and easy to use, but perhaps rugged, while underdeveloped-nation users get a product that can

help provide a much needed service without having to submit themselves to embarrassing designs. Good design is universal. A paragon of this philosophy is the LifeStraw, a self-contained straw-cum-water filtration system designed for both developed-nation backpackers, hikers, and campers, and underdeveloped-nation users for safe, convenient, cheap, and portable water purification.

While traditionally consigned to consumer or humanitarian products and projects, the principles of the design for everyone philosophy can also inform research. Most MFC designs, for instance, use a platinum-based catalyst in their cathode. In US markets, there is little pressure to develop alternative cathode catalysts. Platinum is expensive, but not prohibitively so, and the technology is so young that most research efforts are focused on other low-hanging fruit. Designing an MFC for use in underdeveloped nations reorients those fruit, and platinum becomes an exorbitant. To this end we hope to evaluate a novel graphene-based catalyst for use in MFCs.

Graphene is a single-atom-thick layer of pure carbon. Graphene is, at the moment, a bit of a chemical wunderkind in the science world, exhibiting remarkable electronic, chemical, and physical properties; the 2010 Nobel Prize for physics went to researchers working with graphene. Graphene is also almost shockingly easy to produce. In fact, minute quantities are created every time you use a pencil by mechanical shearing forces in the graphite-based pencil “lead.” This process scales well, and large quantities of small pieces of graphene can be produced by the simple act of ball milling bulk graphite. If one performs this ball milling in the presence of a reactive halogen like iodine, the iodine will “quench” the edges of the graphene as they flake from the bulk graphite. This forms “edge-halogenated graphene” which has catalytic properties approaching that of platinum for the oxygen reduction reactions needed for MFC cathodes – all by, essentially, violently shaking pencil lead in the presence of iodine. Such a catalyst, if it proves effective, is an excellent candidate for a “designed for everyone” MFC - cheap, easy to manufacture, and easy to deploy in existing or new MFC geometries.

Power density is the primary condition to be considered for the effectiveness of these processes in the United States, and edge functionalized graphene almost certainly won’t beat platinum, but will mostly likely end up being markedly less effective. To appeal to a developed-nation market, the power production envelope must be pushed along with the cost envelope, but without incurring added design complications that would render the technology useless in underdeveloped regions. Unfortunately, the exact mechanisms of MFC biology remain a black box. For example, there is still debate within the scientific community, about how, biochemically, electrons are shuttled from the electrogenic bacteria into the anode itself. Likewise, the exact function of the bacterial biofilms that often form on MFC anodes is poorly understood. We understand that they increase current production and that there are layers within them with different functions, but the details of MFC biofilm stratification and precise function are ongoing areas of research. Without a more complete understanding of the processes that govern MFC power production, engineering of better MFC geometries or genetic engineering of MFC bacteria themselves is difficult.

Fortunately, we now know enough about biology to use some of the same principles that led to the evolution of electrogenic bacteria to improve those same bacteria, though much faster. Using directed evolution we hope to create a set of evolutionary pressures that selects for those bacteria that produce the most power, in effect engineering by evolution new bacteria that will be more efficient and more powerful. To do this we hope to build a collection of micro-MFCs that we can batch run for high-throughput screening. Each micro-MFC will be monitored for current production and after a time, the top producers will be selected and the rest discarded.
“unnatural selection” should result in more and more “powerful” electrogenic bacterial cultures, as those bacteria less capable of producing power are discarded and those more capable are allowed to mutate, grow, and be further selected upon. The conclusion of this experiment should produce a bacterial culture with increased current-production capabilities, which could be used both in MFCs as well as for further scientific analysis, hopefully by elucidating, through comparison with non-evolved bacteria, what makes the new strain better at producing current.13 14

In the end, we hope to fuse these two projects into a single prototype MFC suitable in both developed and underdeveloped markets. The system will be designed as a standalone water treatment product, capable of supplementing existing septic systems here in the United States and performing much-needed sewage treatment in underdeveloped nations. The product will use both the graphene catalyst and the newly evolved strain of bacteria in an effort to provide a single, efficient, and powerful design suitable for both markets simultaneously, without creating a need for inefficient redesigns for each market. The design for everyone philosophy will provide ruggedness, affordability, and power, (that is to say: “good design”) in a single package.

There are no short cuts to finding this answer as we work towards building a sustainable future. However, if approached with a philosophy of good will and the right technology, human ingenuity and empathy can come together to do great things. MFCs are a new and promising concept — one that will hopefully improve the lives of people, rich and poor, across the globe.

References


6. Ibid.


8. Ibid.


