Bioelectrochemical Energy Conversion Technologies

by Ramaraja P. Ramasamy

Biology, despite being the largest field of science, has not attracted much interest or attention from electrochemists for reasons I am yet to find out. However, electrochemistry does not receive the same treatment, as most biologists have a fairly good understanding of the Nernstian potentials and electrochemical gradients across a biological cell membrane and its implications for cellular bioenergetics. Biologists recognize that "electron transport" is the universal mechanism of energy conversion. When we eat our food, we extract the energy in the food through a series of biological oxidation reactions, each transferring electrons to a corresponding biological reduction reaction. These biological redox reactions are catalyzed by a set of fuel oxidizing enzymes on one end and a set of oxidant reducing enzymes on the other end, by utilizing the driving force created by the proton transport gradient across the biological membranes, be it mitochondria or chloroplast. If we take a closer look at these biological electron transport processes, we would quickly realize that this scenario is identical to a fuel cell, where the fuel oxidation and oxidant reductions are carried out on two different electrodes separated by an ion-exchange membrane. The principles are the same, regardless of whether it is nature or humans who execute the above described energy capture and conversion.

The field of bioelectrochemistry has been in existence for nearly a century, yet the term "bioelectrochemistry" is rarely used without a hyphen between the words "bio" and "electrochemistry." While I was writing this article, Microsoft Word tried to autocorrect me by splitting the two words. This led me to wonder when was the last time the term "electrochemistry" was used with a hyphen between the words "electro" and "chemistry." (Certainly not in the recent decades.) Perhaps this is one indication that the field of bioelectrochemistry has been overlooked by vast majority of electrochemists. Or perhaps I am exaggerating based on my intrinsic viewpoints on this issue. My point however is that bioelectrochemistry offers unique solutions to many of the important problems we face in the areas of corrosion, electrochemical sensing, chemical production, energy storage and conversion, CO_2 capture, and even electronics, and that the field deserves more than a cursory glance by the majority of electrochemists. While reading this issue, I encourage you to look past the "main stream" electrochemical energy technologies, by which I mean conventional fuel cells, batteries, etc., and explore how nature-inspired bioelectrochemistry could address ongoing challenges in energy storage and conversion.

There are three modes of bioelectrochemical energy conversion — microbial-based, enzyme-based, and photosynthesis-based — each of which operate under similar principles. Microorganisms of a certain type can transfer the excess electrons from their metabolic pathways to a metallic surface via exocellular respiration. This interesting physiological property of electrogenic microorganisms has been utilized to generate electricity in "microbial fuel cells." A microbial fuel cell uses microorganisms as biological electrocatalysts that oxidize any organic matter on the anode and reduce oxygen or a suitable electron acceptor compound on the cathode, resulting in a net voltage under load. The most interesting feature of the microbial catalyst is its ability to grow nanowire appendages for the sole purpose of electron conduction. As the father of aquatic chemistry Werner Stumm pointed out, "Microbes are the best chemists in the world."

The biological process is scaled down in enzymatic fuel cells, where individual enzymes or a group of enzymes replace the whole cell microorganisms as electrocatalysts. Due to the high specificity of enzymes, only the desired "fuel" is oxidized from a complex substrate, resulting in the generation of electrons that can be reduced at the cathode. The concept of enzymatic fuel cells was derived from glucose biosensors, one of the highly successful electrochemical innovations in the past century. Unlike glucose biosensors, in which the generated electrons are processed as an analytical signal, these electrons are transported in an enzymatic fuel cell to a terminal electron acceptor (usually O_2) at a second electrode (cathode) resulting in power generation.

The third mode of bioelectrochemical energy conversion, namely photosynthesis-based bioelectrochemical energy conversion, offers prospects for clean, renewable production of electricity and fuels using sunlight. Here, the native reactions occurring during photosynthesis are manipulated or modified to harvest electrons for electrochemical reactions occurring at electrode surfaces. The catalysts are either individual photosynthetic reaction centers, or thylakoids or whole cells of photosynthetic algae.

These three seemingly unrelated technologies have one thing in common — they all work on the same familiar fundamental electrochemical principles that govern the operation of a conventional fuel cell or electrolyzer.

This issue of *Interface* features three articles on the topic of bioelectrochemical energy conversion based on the three different modes described above. The intent of this issue is to introduce the principles of biology behind these energy conversion technologies to the electrochemical community. The first article focuses on microbial fuel cells and electrolyzers and is written by Abhijeet Borole. The second article, written by Scott-Calabrese Barton, is on the theory and modeling of enzymatic fuel cells. The third article is on electrochemical energy conversion based on natural photosynthesis to generate electricity or chemical fuels written by Narendran Sekar, a PhD student from our group. It is true that the power and energy densities of these bioelectrochemical systems are presently far too low when compared to the established mainstream technologies. But with only a handful of researchers working in the field, breakthroughs do not occur very frequently. It is my hope that the articles in this issue of *Interface* will stimulate new thoughts and gather more interest from the broader electrochemical community to work with biologists and biochemists to further advance the field of bioelectrochemistry.

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About the Issue Guest Editor

Ramaraja Ramasamy received his Bachelor of Technology in chemical and electrochemical engineering from Central Electrochemical Research Institute, India in 2001 and his PhD in chemical engineering from the University of South Carolina in 2004. His PhD research was focused on novel materials for lithium-ion batteries. After serving as a post-doc at the University of South Carolina for a year, Ramasamy joined Penn State University as a Research Associate in 2005 and worked on PEM fuel cells until 2008. Later that year he moved to the Air Force Research Laboratory as Senior Research Scientist to work on bioelectrochemical energy conversion technologies. In 2010, he joined the University of Georgia as an Assistant Professor of Biochemical Engineering, where he founded and directs the Nano Electrochemistry Laboratory. Earlier this year he was promoted to Associate Professor with tenure. His current research focuses on applying nanoscale science and engineering principles to improve the performance of electrochemical and bioelectrochemical systems including fuel cells, batteries and biosensors. He may be reached at rama@uga.edu.

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