Microbial Fuel Cells

Bruce E. Logan
The Pennsylvania State University
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Microbial Fuel Cells

Bruce E. Logan
The Pennsylvania State University
To Maggie, Alex and Angela,
for their love and support
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This book is made possible by work performed in my laboratory as well as experience gained through numerous collaborations that were started only a few years ago, but the roots of my education in the area of exogenous electron transfer go back two decades. I first began to learn about iron reducing bacteria from Bob Arnold and his group in 1986, when Bob and I were both assistant professors at the University of Arizona. Bob was an early pioneer in the area of solid iron oxide reduction by bacteria, and I am grateful to Bob and his students (particularly Flynn Picardal) for sharing their work and thoughts with me over the years about these fascinating bacteria.

In the fall of 2002, I started work on microbial fuel cells (MFCs) and was fortunate to work with Hong Liu, a postdoctoral researcher with my group at that time, as she made essential creative and intellectual contributions to our laboratory’s work on MFCs. Through her efforts and excitement for this topic, work in my laboratory advanced at a rapid pace and we made many interesting discoveries over a short period of time. In the years since I started working on MFCs, I have been privileged to work with a number of talented researchers, but I especially appreciate having worked with the following students and researchers in my laboratory: Shaoan Cheng, Booki Min, JungRae Kim, SangEun Oh, Jenna Heilmann Ditzig, Yi Zuo, Douglas Call, Valerie Watson, Rachel Wagner, Farzaneh Rezaei and Defeng Xing. My own research efforts have always focused on the biophysical interface, and so I have relied on collaborations with others having greater expertise in chemistry, biology, molecular biology techniques. I am grateful to Tom Mallouk at Penn State for all his patient explanations of fuel cells and electrochemistry, and the assistance of his student Ramna Ramnarayanan. I particularly appreciate collaborations with Jay Regan and his group at Penn State, as their expertise and knowledge have been absolutely essential for work that has emerged from Penn State.

Collaborations outside of Penn State have been critical for advancing the field of MFC research. In 2003 I spent a sabbatical at the University of Newcastle upon Tyne, and I benefited from conversations and work with Ian Head, Tom Curtis, Cassandro Murano, and Keith Scott. Collaborations have continued with this group through the efforts of Eileen Wu, who joined my research group for several months. I am continuing to benefit
Preface

from additional collaborations with Yuri Gorby (J. Craig Venter Institute), Ken Nealson and Orianna Bretschger (University of Southern California), Tim Vogel, Jean-Michel Monier (Ecole Centrale de Lyon, France), Yujie Feng and Aijie Wang (Harbin Institute of Technology, China), Kazuya Watanabe and Shunichi Iichi (Marine Biology Institute, Japan), Kyeong-Ho Lim (Kongju National University, Korea), and many others.

This book really represents the next stage of evolution of a paper written in 2006, with co-authors Peter Aelterman, Bert Hamelers, René Rozendal, Uwe Schröder, Jurg Keller, Stefano Freguia, Willy Verstraete, and Korneel Rabaey. The chapters of this book on voltages and power are based on a section of that paper originally crafted by René and Bert, with additional contributions from Uwe and Korneel. I especially appreciate the extra effort and continued discussions with René on thermodynamics, power calculations, and MECs, and with Kornell on MFCs. Each of the chapters in the book has been improved by comments provided by a number of different colleagues, and I thank especially: René Rozendal, Ian Head, Nathan Lewis, Annemiek ter Heijne, Korneel Rabaey, Ken Nealson, Uwe Schröder, Song Jin, Jurg Keller, Lenny Tender, and Denny Parker.

I thank collectively everyone I mentioned above for their help in making a book like this possible. I look forward to continued rapid developments in the exciting areas of MFCs, MECs/BEAMRs, and bioenergy production.

BRUCE E. LOGAN

State College, Pennsylvania
September 2007
CHAPTER 1

Introduction

1.1 Energy needs

There are over six billion people on the planet with 9.4 billion projected for 2050 (Lewis and Nocera 2006). Fossil fuels have supported the industrialization and economic growth of countries during the past century, but it is clear that they cannot indefinitely sustain a global economy. Oil will not appreciably run out for at least 100 years or more, but demand for oil is expected to exceed production from known and anticipated oil reserves ten or twenty years from now, or within the 2015 to 2025 time frame (Rifkin 2002). This may seem distant to many consumers and businesses that rarely plan for more than three to five years in the future, but this is a very short time frame for society as a whole. Planning a single section of an interstate highway in a city, for example, can take ten years or more. The infrastructure changes needed to address our global energy needs will be far more extensive and will likely require changes not only to our infrastructure but also to our lifestyle. Changes will affect everything from home heating and lighting, to where we prefer to live and work and how we get there. The costs of energy and how much energy we use will come to dominate our economy and our lifestyle in the coming decades.

The total annual energy consumption in the US is ~100 quads of energy (100 quadrillion BTU = 10^{15} BTU), or 1.1 × 10^{15} J, which is a continuous consumption rate of 3.34 TW (1 TW = 10^{12} W). On a global scale, energy use is 13.5 TW (Lewis and Nocera 2006). Thus, the US uses about 25% of the world’s energy despite having only 5% of the world’s population. Energy in the US is derived from a number of sources, but most are fossil fuels (Fig. 1.1). Approximately 18% of this energy (600 GW) is generated as electricity at power plants that vary greatly in size, with a typical large power plant producing ~1 GW. Power plants are 33% efficient, so energy used to make this electricity is larger by a factor of three.

If we assume a base of 300 million people in the US, each person in the US consumes on average 11.1 kW, or 97 MWh per year. This is not a level of energy utilization that we see in our daily life as much of this energy is used for manufacturing and transportation or is lost as heat in various energy conversion and utilization cycles. At a more local level, an average US house uses 1.22 kW while a home in British...