1
Introduction

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The widespread use of portable electric and electronic devices increases the need for efficient autonomous man-portable power supplies, of the order of 0.1 W to about 50 W. The predominant technology for portable power generation is the battery. However, the energy density of batteries is of the order of only a few hundred $\mathrm{Wh\,l^{-1}}$ and $\mathrm{Wh\,kg^{-1}}$. Battery performance has significantly improved over the last decades, but it is believed that the upper limit on performance is being approached, because the list of potential materials is being depleted. Additionally, batteries have high cost and life cycle environmental impact.

This book focuses on alternatives to batteries based on microchemical systems, that is, miniaturized devices that use chemical fuels as the primary source of energy. Energy conversion technologies considered include electrochemical reactions in fuel cells, combustion in connection with heat-engines and combustion combined with thermo-photovoltaic elements. The promise of these systems is that significant increments in energy density can be made compared to state-of-the-art batteries. Suppose, for the sake of argument, that it would be practical to operate a fuel cell reversibly at ambient conditions. Then, common chemicals would outperform state-of-the-art batteries by orders of magnitude, as shown in Figure 1.1 [1]. As a consequence, relatively inefficient microchemical systems can significantly outperform batteries. Miniaturization has the advantage of smaller systems as well as potential process intensification. Such considerations have sparked great military [2] and civilian interest in developing these alternatives to batteries.

1.1
Alternatives to Microchemical Systems

The focus of this book is on microfabricated devices that transform chemical energy to power, either directly (fuel cells) or indirectly (micro-engine, photovoltaics). This section briefly describes some other potential alternatives.

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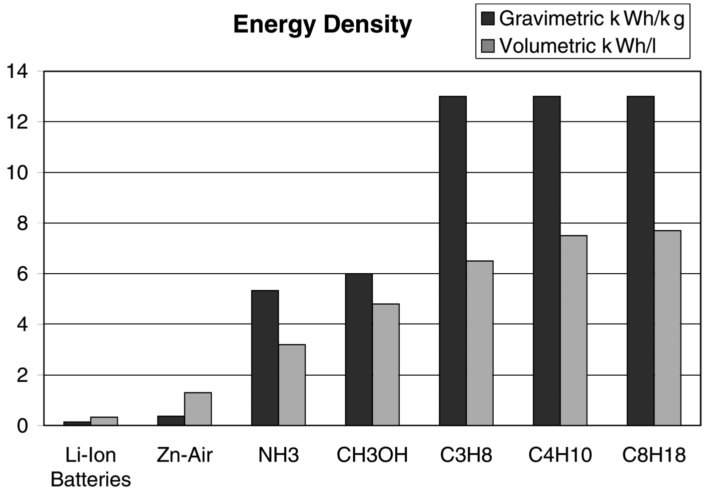

Figure 1.1 Comparison of state-of-the-art batteries with theoretical energy density of fuels in a reversible fuel cell at ambient temperature, in which all the Gibbs free energy of oxidation is converted to power.

1.1.1
Using Manpower

Arguably the most readily available and simplest to use energy form is the mechanical work that the human body can generate. Two main alternatives exist, namely the transformation of active work (e.g. turning a foot pedal), and the capture of passive work (e.g. energy dissipated while running). The human body transforms chemical energy at a rate of the order of a few hundred Watts and therefore capturing a small fraction of this energy could power some man-portable electronic devices. It is interesting to note that some energy-dense food has energy densities comparable to the chemicals considered in the following chapters. Moreover, the body's energy conversion efficiency is approximately 25% [3, 4], which makes it competitive with some of the technologies considered in this book. However, using the body's energy is not as comfortable as using a micro-chemical system and is therefore expected to find use only in niche applications. Various technologies have been proposed in the past to capture and transform this energy:

1. Dynamos which convert mechanical rotation into a direct electric current. Dynamos use the electromagnetic principle: when an electrical conductor moves in a magnetic field, a potential difference is generated.
2. Mechanical systems, for example, by storing the kinetic energy in a spring. The stored mechanical energy is then used for electricity production.
3. Piezoelectric systems which rely on the ability of certain materials to generate an electric potential in response to applied mechanical stress.

Some researchers also consider the possibility of using the heat released by the body (thermoelectric conversion). Since body heat is available at very low temperatures, the efficiency would be very low, even if the Carnot limit was reached. For instance, at an ambient temperature of $T = 298\,\mathrm{K}$ the maximal efficiency would be $\frac{310-298}{310} = 4\%$.

Well-known applications include low-tech devices such as bicycle lights and rechargeable flash lights. In the "One laptop per child" initiative [5] a foot pedal is considered as an alternative for the powering of laptops. People have also envisioned high-tech devices such as shoe generators; while running, significant amounts of energy are dissipated in the human tissue as well as in the middle sole of modern running shoes; therefore, a long term goal of ingenious inventors has been capturing part of this dissipated energy and several patents have been granted [6]. A similar idea is the suspended-load backpack [3, 4] and the knee brace [7].

1.1.2
Harvesting Environmental Energy

An appealing alternative for some applications is harvesting energy from the environment. The most common option is using photovoltaics, which are very practical for powering low power consuming devices such as pocket calculators. However, current technologies do not seem promising for power-intense man-portable devices such as laptops, because the required surface area would be very big (of the order of few m^2).

Recently, the concept of wireless power transfer has been revisited. For instance, a research group at MIT has demonstrated the transfer of 60 W over 2 m with 40% efficiency [8]. The promise of wireless power transfer is to eliminate the need for cables, transformers and so on, and, therefore, it is not truly an alternative to man-portable power generation, but rather to the recharging of batteries. A similar concept is collecting vibrational energy, for example [9].

1.2
Book Outline

The remainder of the book is organized around two main themes. In Part One the various technologies are discussed by experts in the respective fields. First, an introduction to microfabrication is given, focusing on functionalization such as catalyst coating. Then, the various potential components of microchemical systems for portable power generation are discussed, namely fuel processing, fuel cells, micro heat engines and thermo-photovoltaics. Part One concludes with a discussion of system integration from the technology point of view, covering issues such as thermal and material management.

Part Two discusses the state-of-the-art in system design using computational methods. First the selection of alternatives is discussed based on simple algebraic models. Then material and structural considerations are covered. In Chapter 10 methodologies for reactor and reaction engineering are presented based on multiscale modeling. In Chapter 11 the optimal design and operation of fixed alternatives are discussed based on models of intermediate fidelity. Chapter 12 discusses challenges in hybrid electrochemical systems, for example, the combination of a fuel cell with a battery. The book concludes with a discussion of process control issues.

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