

Richard A. Dunlap

# Renewable Energy Storage

Electrical, Magnetic, and Chemical Methods

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# **Synthesis Lectures on Renewable Energy Technologies**

The series, Synthesis Lectures on Renewable Energy Technologies publishes concise books, focused on technologies that harness energy from naturally occurring sources, such as sunlight, wind, water, geothermal heat, and biofuels from organic materials. These renewable energy technologies play a crucial role in transitioning away from fossil fuels, helping to mitigate the effects of climate change, and promoting a sustainable energy supply.

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Electrical, Magnetic, and Chemical  
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## Preface

Due to diminishing fossil fuel resources and the adverse environmental impact of their continued use, it is essential that carbon-free renewable energy sources are developed. Most renewable energy resources, such as solar, wind, hydroelectric and geothermal, are not constant in time and/or are not portable. For this reason, the development of renewable energy must be accompanied with the development of energy storage capabilities in order to provide energy when it is needed and for portable applications.

The present book considers some of the important technologies for energy storage. Chapter 1 deals with batteries, which utilize electrochemical reactions to store electrical energy and are one of the most important energy storage technologies with applications that range from consumer electronics to transportation and grid-scale storage. Chapter 2 considers the storage of energy in electric fields through the use of supercapacitors. Chapter 3 reviews the use of superconducting magnets to store energy in magnetic fields. Chapters 4 and 5 look at some chemical approaches to energy storage. As discussed in Chap. 4, electrical energy may be used to produce hydrogen, and this energy can then be recovered by combustion or through the use of fuel cells. As well, hydrogen may be used to produce methane, methanol or ammonia, and these may be used as fuels in fuel cells or internal combustion engines. These methods are presented in Chap. 5 where the various advantages and disadvantages of these energy carriers are discussed.

Halifax, Canada

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## 1.1 Introduction

Batteries are probably the best-known energy storage device. We encounter them in a wide variety of applications in our daily lives. They power electronic devices such as watches, cell phones and notebook computers and are used to start gasoline and diesel-powered vehicles. Batteries store energy using electrochemical reactions and a large fraction of those that we encounter utilize reactions that are reversible, meaning that the batteries can be recharged. The present chapter gives an overview of the common types of batteries that are in use, as well as some types of batteries that are in the early stages of development and commercialization. It also provides a brief description of the physics and chemistry of how batteries work. Finally, some important battery applications are presented.

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## 1.2 Types of Batteries

The terms “cell” and “battery” are sometimes used ambiguously or interchangeably, but both have well-defined meanings. A cell is an electrochemical unit containing two electrodes and an electrolyte that provides a means of storing energy by electrochemical reactions. A battery is one or more electrochemical cells with appropriate packaging so as to constitute a practical device that is suitable for use in applications. In the present section, batteries are considered in terms of their overall characteristics. In the next section cells, with particular reference on lithium-ion cells, are discussed in terms of the fundamental physics and chemistry of their operation.

Batteries may be categorized in different ways. One approach is to divide batteries into two categories, non-rechargeable and rechargeable. Non-rechargeable batteries are referred to as primary batteries and rechargeable batteries are referred to as secondary

batteries. From an energy storage standpoint, secondary batteries are the most relevant. Another approach to categorizing batteries is on the basis of their chemistry. Different chemistries include, for example, carbon-zinc batteries, lithium-ion batteries and lead-acid batteries.

1.2.1 Battery Chemistry

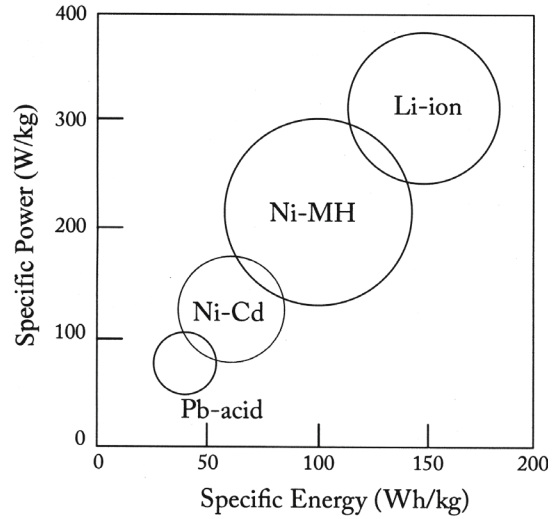
There are numerous different chemistries that can be used to produce batteries. Some of the most common are shown in Table 1.1. Carbon-zinc and alkaline are typically only used as primary batteries, while the other chemistries can be used to produce secondary batteries. The voltages given are for a single cell. More than one cell can be connected in series inside the battery to provide larger voltages. The specific energy refers to the energy produced per unit mass of the battery. This depends mainly on the chemistry, but also on the details of the battery construction. The specific energy is also a function of battery size, as smaller batteries tend to have lower specific energy because the non-active components tend to account for a greater proportion of the mass. The values given in the table are typical of larger size batteries of each particular type.

From the rechargeable batteries shown in Table 1.1, it is clear that Li-ion batteries have the largest specific energy. This feature is also illustrated in Fig. 1.1, which shows a graph of the energy density, that is the energy per unit volume, as a function of the specific energy. The ranges on the graph for the different battery chemistries are shown. It is clear that in many devices where size and weight are important factors, e.g. cell phones, iPads, etc. and in applications where a large energy storage capacity and portability is required, e.g. battery electric vehicles, Li-ion batteries are used almost exclusively. Other battery chemistries may be more cost effective than Li-ion, and in cases where small size and weight and/or large capacity are not critical factors, other battery chemistries are also often used; for example, Pb-acid for starting gasoline engines, Ni-MH for hybrid vehicles and Ni-Cd for power tools.

**Table 1.1** Typical properties of some common battery chemistries (Ni-MH = nickel metal hydride)

Chemistry	Cell voltage (V)	Specific energy (mWh/g)
Carbon-zinc	1.5	55
Alkaline	1.5	160
Pb-acid	2.1	36
Ni-Cd	1.2	56
Ni-MH	1.2	78
Li-ion	3.6	160

**Fig. 1.1** Ranges of energy density as a function of specific energy for some secondary battery chemistries



### 1.2.2 Battery Sizes

Batteries come in a wide variety of sizes. The most common sizes used for primary batteries are shown in Table 1.2. The capacity, shown in mAh in the table, is discussed further below. The same size designations are often used for rechargeable Ni-Cd and Ni-MH batteries.

Other size batteries do not necessarily have a standard numbering scheme. In fact, batteries with the same specifications from different manufactures may have different numbers. Some lithium batteries, which can be primary or secondary batteries, use a reasonably standard method of numbering. Cylindrical lithium batteries are given a 4 or 5 digit number. The number refers to the size of the battery. The first two digits of the number refer to the diameter of the battery in mm. The last two or three digits of the

**Table 1.2** Common sizes of carbon-zinc and alkaline primary batteries showing their dimensions, mass and capacity (in mAh)

Name	Diameter (mm)	Length (mm)	Carbon-zinc		Alkaline	
			Mass (g)	Capacity (mAh)	Mass (g)	Capacity (mAh)
AAAA	8.3	42.5	–	–	6	625
AAA	10.5	44.5	10	540	12	1200
AA	14.5	50.5	19	1100	23	2700
C	26.2	50	48	3800	66	8000
D	34.2	61.5	98	8000	135	12,000