

ENGINEERING ENERGY STORAGE

ODNE STOKKE BURHEIM

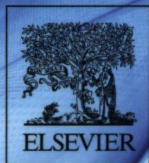


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Traditionally energy has been engineered with respect to harvesting, distributing and consumption. As more energy is harvested from renewable sources, of which the majority is intermittent, the need for energy storage grows. As the front cover indicates; energy storage is a field that covers the nexus between the three traditional energy fields of harvesting, distributing and consumption.

This book covers storage of thermal, mechanical, electrical and chemical energy and this is intended to demonstrate an engineering approach in converting between these energy forms and how to store the energy. To illustrate how technological solutions and dimensions come together, the book contains many useful and illustrative numerical examples, problems and solutions. The book is intended for final year bachelor students, master students, engineers that seek and update on technology, and also PhD students with a background in science who would like to get closer to the engineering approach.



ACADEMIC PRESS

An imprint of Elsevier
elsevier.com/books-and-journals

ISBN 978-0-12-814100-7



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ODNE STOKKE BURHEIM



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An imprint of Elsevier

Academic Press is an imprint of Elsevier
125 London Wall, London EC2Y 5AS, United Kingdom
525 B Street, Suite 1800, San Diego, CA 92101-4495, United States
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom

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Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

ISBN: 978-0-12-814100-7

For information on all Academic Press publications
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Publisher: Joe Hayton
Acquisition Editor: Lisa Reading
Editorial Project Manager: Charlotte Rowley
Production Project Manager: Paul Prasad Chandramohan
Designer: Mark Rogers

Typeset by VTeX

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PREFACE

The front cover of this book illustrates the three branches of energy production, distribution, and consumption. These areas are overlapping by the field of energy storage. By the introduction of renewable energy technologies these three areas will become closer and more interconnected. This is so because most renewables are electric, intermittent, and often out of phase with the demand in energy consumption. It is energy storage that can balance this. Thus energy storage is a growing field for engineering and research. Understanding the elements of engineering energy storage is needed now and ever more in the future.

Energy is the backbone of our society. Today, we have a fossil-based economy. More than eighty percent of the energy consumption today is coal, oil, and gas. This is what drives our economy. It is fundamental in providing our society with the services needed, whether it is transportation, food production, health care, entertainment, or any other. However, the threat from climate changes from the emissions from our economy backbone, coal oil, and gas, means that we need to make changes. Fortunately, the usage of fossil energy is so inefficient that we only need to replace a third of this energy if a renewable energy technology is chosen. That is, it takes at least 3 MWh annually of mixed coal, oil, and gas to make a MWh of electricity each year, though a MWh of renewable energy annually is a MWh annually exactly—and once installed it is without marginal costs.

Renewable, carbon neutral, and sustainable are keywords essential for the energy economy and energy technology of the future.

Inevitably, the energy supply must come from renewable sources, and this change has started.

Regardless of chosen technology, the technology itself must be carbon neutral. This means that if carbon is needed for the technology process or manufacturing, then it must be taken from the air, not the ground. For example, carbon is needed for producing metals like silicon, aluminum, and steel or for components in Li-ion batteries, fuel cells, or supercapacitors. Solutions of extraction from plants and trees exist and relies more, in my opinion, on political will than technological barriers.

Finally, the installed solutions must be sustainable, both with respect to the environment footprint and for the growth of the economy of our society. Currently, we can find examples all over the world where the fear of

climatic unsustainable use of fossil energy has led to much needed incentives for renewable energy by wind and solar. Installing vast amounts of such intermittent energy technologies needs to be accompanied by buffering solutions, not only fiscal incentives to adjust consumption patterns. We need vast amounts of energy storage solutions on the one hand and energy storage solutions of many different types for many different purposes on the other.

This book is intended to help engineering students before moving to a master thesis level, already trained engineers, and interested scientists, with understanding the engineering concepts behind the most relevant energy storage technologies.

Several people deserve a big thank you for supporting me, believing in me, and taking me in on a professional side: Signe, Preben, Jon, Bert, Frode, and, for the longest period, Håvard. You have all been great role models for me in your own very different ways. Ms. K. Taksdal is acknowledged for help with proof reading and with a critical eye from a students perspective.

On a personal side, a big thank you to all members of the family I grew up with, especially to my parents.

A very special thank you goes to my wife for her patience with me in writing this book, of which most of the writing took place during the first seven months after receiving our first child.

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CHAPTER 1

Energy Storage

Energy in the right form, at the right place, and at the right time is the key essence here. Energy drives our economy and is founded on engineering these three aspects. Thus, when installing more electric renewable energy, energy storage technologies that conserve this energy into an adequate form with adequate distribution properties for use whenever needed is what it is all about.

There are many different energy storage technologies that in their own different ways facilitate the trinity of properties: formate, distribution, and timing. As a part of the transition to a renewable energy economy, a great variety of energy storage technologies must be taken into use. This book explains the theory behind the different technologies and why this gives the different technologies different advantages and markets.

As a renewable energy-based economy is inevitable, engineering energy storage is inevitably needed too. This is now.

1.1 A BRIEF HISTORY OF ENERGY

All animals look for energy that they eat. This energy is stored either in vegetables nearby or in animals that live nearby the predators. Almost all of this energy comes from sunlight, that is, in combination with water and chlorophyll, converted to hydrogen via the photosynthesis. In turn, when combined with CO_2 , hydrocarbons of various kinds are produced to store this energy. In this sense, carbon is a hydrogen carrier, and hydrogen is an energy carrier.

An important part of the evolution of not only *homo sapiens* but of our entire society is our ability to stack up energy for later. Storing food is a first example of energy storage, but the humans are not alone in this context. Several animals store food for later. The other very important development in the history of humans was the ability to make and control fire. This is the first example of controlled energy conversion that we know about in nature. It was important for human evolution since it allowed us to digest meat much more efficiently and grow larger brains and next start with houses and agriculture. One key element here is storing energy in the form of food and dry wood. These two forms of energy are chemical energy. Whereas

the first was used for nutrition, the latter was used for heat generation, both whenever needed. The advantage of chemical energy is that it is extremely easy to store. One can keep it in a bunker or a tank. Other forms of energy are less convenient to store, and the quality is sometimes degraded.

Society developed further as villages and cities emerged. Mechanical energy in the form of mills deploying water to rotate a grain mill is a first example. During the first industrial revolution, coal started to be used in steam engines, converting heat into work. At the end of this era, electrical energy started to be developed too. We can already now address four important forms of energy: chemical, mechanical, electrical, and thermal. Chemical energy can be stored on tanks. Mechanical energy can be stored at elevation, rotation or pressure. Thermal energy can be stored by insulation. Electrical energy cannot be stored without being converted into one of the other forms. Over the last centuries, our society has been organized in such a way that mechanical and chemical energy is supplied when needed. This pattern, in particular for the electrical energy, is now about to change.

Over the last few decades, with the introduction of wind and photovoltaic (PV) energy conversion, our society has changed from supplying energy on demand to supplying energy when energy is present, that is, when the sun shines and the wind blows, electric energy is generated and supplied regardless of demand. Also, this energy production does not have much of a cost margin, meaning that once the machines are there, they generate electric energy almost for free. Traditional energy production requires coal, oil, natural gas, uranium, and, to some extent, manpower. Wind and PV hardly do. When energy is supplied beyond the demand, it needs to be stored for later. It is the impact of the intermittent, no-cost-margin, large-scale, and world-wide energy production that will drive the need for energy storage.

Another very interesting change presently occurring is the localization of the energy production and its connection to the Internet. Energy consumers can install a PV on their roof (or in their garden) and thus become energy suppliers, at least for certain hours of the day. This energy production changes over the year in addition to the hours of the day. The energy unit (as the house now becomes) sometimes produces electric energy and sometimes consumes electric energy. This needs to be handled one way or another. Locally, the electricity is distributed on the grid, for instance, to the neighbors or nearby supermarket. It is the transition

Table 1.1 A brief historical over view of development in the modern industrialized society

Ind. Rev. Field and characteristics			
When	Energy:	Transport:	Telecommunication:
1st: 1750–1950	1750–: Digging coal from the ground to run steam engines and later oil and gas for electrical power plants. The energy passes through big hubs and is subsequently redistributed.	1800–: Trains and ships carry people and freight over large distances. For transport, one relies on going via large stations.	1890–: Telephone allowed for direct communication over large distances. This happened via central hubs that connected you via regional and local centrals.
2nd: 1950–	2010–: Everyone can produce electricity and sell it to their energy enterprise, but the energy is delivered locally. Peer-to-peer energy distribution.	1950–: The common man can buy a car and drive from door to door or further. Localized and customized transportation.	1990–: Internet and smart phones. People communicate directly over the Internet. Peer-to-peer.

from having electricity generated at large-power plants into a localized energy market that represents the big change. The change from having a commodity distributed from the big banks, centrals, and hubs to a more localized market is often acknowledged as a second industrial revolution.¹ We have in the past seen this for the transport and telecommunication sectors as common people got cars and tools to communicate peer-to-peer online via chat rooms. This is illustrated in Table 1.1. The impact of the second industrial revolution in the energy sector is not yet quite understood. It will, however, require more storage of electric energy for days, weeks, and months. Moreover, the energy infrastructure already developed will not become redundant. From the so-called second industrial revolution in the transportation sector and the telecommunication sector we can see that this second industrial revolution only contributes to the infrastructure that was already there. In less developed parts of the world, however, this new infrastructure of local electric energy becomes the only one.

¹ Historians consider several industrial revolutions, while here it is simplified to two.

1.2 RENEWABLE ENERGY AND ENERGY STORAGE

Renewable energy and power sources are getting cheaper and competitive with existing ones (coal, oil, gas, and nuclear). Once installed, these power sources have hardly no operational costs. This has led to a growing share of the renewable energy sources. Because the renewables currently growing in market share (wind and PV) have intermittent nature and represent the cheapest alternative when available, the established power sources are seeing significant changes in the need for them. That is, they must deliver more power for some hours during a day and hardly none for other hours of the day. These changes are demanding because the existing power plants were built for stationary power production and with a perspective of 30–40 years. The introduction of renewable energy is not only lowering CO₂ emissions; it has in two to five years changed the electric energy market that we have known for decades. The characteristics of these changes continue to grow in strength. The most sensible ways to ensure that the electric energy market remains sustainable is by ensuring hourly power rates, appropriate political solutions, and including a lot of different energy storage solutions.

The final impact and politics for implementation of renewable energy in the form of wind and PV are difficult to predict. However, there are a few indications already revealing themselves. One is the introduction of electricity meters that allows for price timed with the hours of the day, as an economic political mean to curb the consumption peak, particularly in evening hours. However, this can be seen as late coming in regions where PV are installed and continue to be installed at the consumers location. This creates a deficit in the demand for electric power from the grid when the sun shines. In many regions, the consumers have a legal right to become suppliers to the grid too. With consumers becoming suppliers that force energy with no marginal (operational) cost into the grid or just not demanding any, new market scenarios emerge. Some trends remain as expected; however, the impacts are different. In Fig. 1.1, we can see some of these impacts from continuously adding PV at the power grid end point. Some changes are as expected and others are not.

Traditionally, two trends are generally accepted as a nature of the electric power market, a market that will be strongly affected by the implementation of renewable energy sources. One is that the energy consumption has always been increasing. The other is that there are peaks in the power consumption in the morning and in the evening. When we evaluate these statement in the light of Fig. 1.1, we can see that the power demand from the grid,