

Richard A. Dunlap

Renewable Energy Storage

Mechanical and Thermal Methods

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.

Richard A. Dunlap

Renewable Energy Storage

Mechanical and Thermal Methods

Richard A. Dunlap
Department of Physics
and Atmospheric Science
Dalhousie University
Halifax, NS, Canada

ISSN 2690-5000 ISSN 2690-5019 (electronic)
Synthesis Lectures on Renewable Energy Technologies
ISBN 978-3-031-88941-7 ISBN 978-3-031-88942-4 (eBook)
<https://doi.org/10.1007/978-3-031-88942-4>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer
Nature Switzerland AG 2026

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

Preface

At present approximately 80% of our energy worldwide comes from the combustion of fossil fuels. This approach to energy is not sustainable because of the limited fossil fuel resources available. As well, the need to change to non-fossil fuel energy sources is accentuated by the adverse environmental effects of continued fossil fuel use. Most notable of the environmental consequences of fossil fuel use is global climate change. Although the transition to renewable carbon-free energy sources is essential, it is not easy. A significant aspect of the use of renewable energy sources is the need for energy storage. Most renewable energy sources are neither constant in time, nor are they readily portable. These two features are a requirement for much of our energy use. Specifically, a reliable supply of heat and electricity is needed for residential, as well as commercial and industrial needs, and a portable source of energy is essential for most transportation applications.

The present book considers some of the important technologies for energy storage that utilize mechanical methods and thermal methods to store energy. Chapter 1 considers pumped hydroelectric energy storage and Chap. 2 considers compressed air energy storage. The use of gravitational potential of solid masses and flywheels to store energy is presented in Chap. 3. Chapter 4 reviews the use of sensible heat to store thermal energy. These concepts are expanded upon in Chap. 5, where solar ponds, which act as both solar collectors and thermal energy storage devices, are considered. Finally, Chap. 6 discusses the use of the latent heat of materials as an energy storage mechanism.

Halifax, Canada

Richard A. Dunlap

Contents

1	Pumped Hydroelectric Energy Storage	1
1.1	Introduction	1
1.2	Conventional Pumped Hydroelectric Storage	1
1.3	Pump-Back Hydroelectric Storage	6
1.4	Seawater-Based Pumped Hydroelectric Storage	8
1.5	Sub-surface Pumped Hydroelectric Storage	12
1.6	Underwater Reservoirs	13
1.7	World Use of Pumped Hydroelectric Storage	15
	References	20
2	Compressed Air Energy Storage	23
2.1	Introduction	23
2.2	Physics of Compressed Air Energy Storage	23
2.3	Locations for Grid Scale Compressed Air Energy Storage	26
2.4	Use of Compressed Air Grid Storage	30
2.5	Other Applications of Compressed Air Energy Storage	32
2.6	Combined Pumped Hydroelectric-Compressed Air Energy Storage	36
	References	39
3	Energy Storage Using Solid Masses	43
3.1	Introduction	43
3.2	Gravitational Potential of Solid Masses	43
3.2.1	Advanced Rail Energy Storage	44
3.2.2	Gravity Power Module	45
3.2.3	GraviStore	46
3.2.4	Energy Vault	47
3.3	Flywheels	49
3.3.1	The Physics of Flywheels	50
3.3.2	Flywheel Design Criteria	54

3.3.3 Applications of Flywheels for Energy Storage	57
References	63
4 Sensible Heat Energy Storage	67
4.1 Introduction	67
4.2 Basics of Sensible Heat Energy Storage	67
4.3 Sensible Heat Energy Storage Materials	68
4.4 Residential Heat Storage	69
4.5 District Heating Systems	74
4.5.1 Reykjavik District Heating System	75
4.5.2 Drake Landing Solar Community	77
4.5.3 Brødstrup Fjernvarme	80
4.6 Grid Integrated Systems	84
References	88
5 Solar Ponds	91
5.1 Introduction	91
5.2 Basic Principles of Solar Ponds	91
5.3 Applications of Solar Ponds	93
5.3.1 Solar Pond Heat Removal	93
5.3.2 Industrial Heat	94
5.3.3 Space Heating	96
5.3.4 Desalination	96
5.3.5 Electricity Generation	98
5.4 History of Solar Ponds	99
5.4.1 Beit HaArava Solar Pond, West Bank	99
5.4.2 El Paso Solar Pond, Texas	100
5.4.3 Bhuj Solar Pond, Gujarat, India	100
5.4.4 Pyramid Hill, Victoria, Australia	101
5.4.5 Granada Solar Pond, Spain	101
References	102
6 Latent Heat and Thermochemical Energy Storage	105
6.1 Introduction	105
6.2 Basics of Latent Heat Energy Storage	105
6.3 Solid–Liquid Systems	108
6.3.1 Latent Heat Energy Storage in Ice	108
6.3.2 Other Solid–Liquid Phase Change Materials	109
6.4 Latent Heat Energy Storage in Liquid Air	111
6.5 Thermochemical Energy Storage	112
6.5.1 Reactions	115
6.5.2 Adsorption	116
References	120

About the Author



Richard A. Dunlap received a B.S. in Physics (Worcester Polytechnic Institute 1974), an A.M. in Physics (Dartmouth College 1976) and a Ph.D. in Physics (Clark University 1981). Since receiving his Ph.D., he has been on the Faculty at Dalhousie University where he currently holds an appointment as Research Professor in the Department of Physics and Atmospheric Science. Prof. Dunlap has more than 300 refereed research publications in fields that include critical phenomena, magnetic materials, amorphous alloys, quasicrystals, hydrogen storage and advanced battery materials. His previously published books include *Experimental Physics: Modern Methods* (Oxford 1988), *The Golden Ratio and Fibonacci Numbers* (World Scientific 1997), *Novel Microstructures for Solids* (IOP/Morgan & Claypool 2018), *Particle Physics* (IOP/Morgan & Claypool 2018), *Sustainable Energy—2nd ed.* (Cengage 2019), *Energy from Nuclear Fusion* (IOP Publishing 2021), *Transportation Technologies for a Sustainable Future* (IOP Publishing 2023), *Lasers and their Application in the Cooling and Trapping of Atoms—2nd ed.* (IOP Publishing 2023), *An Introduction to the Physics of Nuclei and Particles—2nd ed.* (IOP Publishing 2023), *The Mössbauer Effect—2nd ed.* (IOP Publishing 2024), *Generation IV Nuclear Reactors: Design, Operation and Prospects for Future Energy Production* (IOP Publishing 2024) and *Renewable Energy—Requirements and Sources* (Springer Nature 2025).



Pumped Hydroelectric Energy Storage

1

1.1 Introduction

Mechanical energy storage methods include several diverse techniques. These are used primarily for the grid-scale storage of electrical energy but applications to transportation have also been considered. The most common grid storage technology is pumped hydroelectric storage. Here electricity is used to pump water to a higher gravitational potential in order to store energy. This energy can be recovered by allowing the water to run back to a lower elevation through a turbine. The present chapter reviews the physics of pumped hydroelectric energy storage and discusses the development and growth of this technology.

1.2 Conventional Pumped Hydroelectric Storage

In a conventional pumped hydroelectric storage facility, water flows between an upper reservoir and a lower water supply (reservoir, river, lake or ocean) where the upper reservoir is supplied only by water pumped from the lower reservoir. The reservoirs may be natural or artificial. The most common configuration uses an artificial upper reservoir and a natural water source (e.g., river) as the lower reservoir. If the lower reservoir is connected to a natural water source, then the system is referred to as an open-loop system. If neither reservoir has a source of water other than that which is cycled through the pumps/turbines, then the system is referred to as a closed-loop system. These types of systems are illustrated in Fig. 1.1.

Overall storage efficiency is limited by the motor/pump efficiency, turbine/generator efficiency and water loss in the upper reservoir due to evaporation. Net efficiencies are typically in the 70–80% range (compared to conventional hydroelectric generating facilities which operate in the 85–90% efficiency range). Since the storage and recovery of

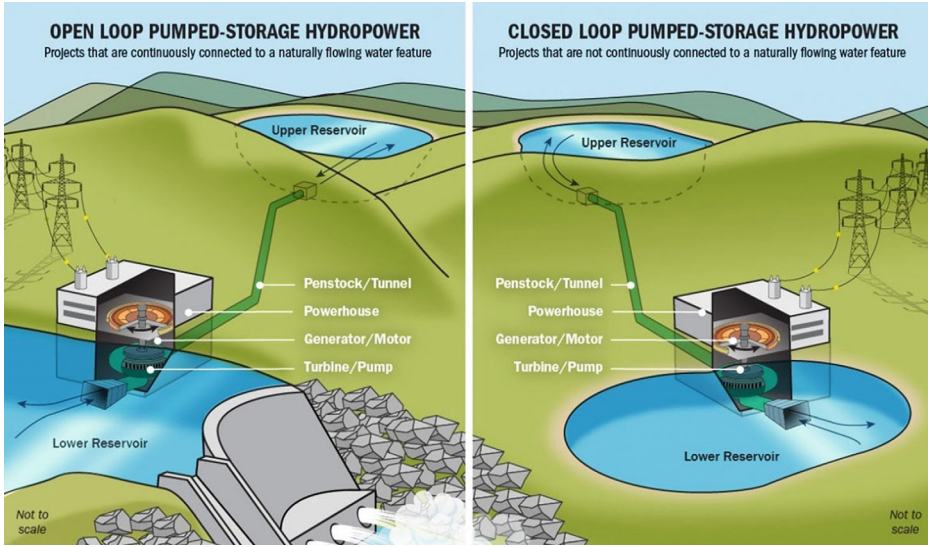


Fig. 1.1 Differences between open-loop (left) and closed-loop (right) pumped hydroelectric storage systems. U. S. Department of Energy (ND) Public domain

electrical energy requires both pumping (to store the energy) and generation (to recover the energy) the overall efficiency is the result of these combined processes.

Pumped hydroelectric storage is a commonly used method of topping up grid electricity during times of higher demand. It is a common method of load leveling or peak shaving, that is storing energy during periods of low demand and recovering this energy during periods of high demand (see Dunlap 2025). Pumped hydroelectric storage is used to store electricity which has been generated by any method, not just hydroelectricity or other renewable methods. It is a convenient means of grid storage as facilities have substantial generating capacity (power), as well as considerable total energy storage capacity. In addition, this power can be brought on-line quickly to satisfy demand.

The typical design of a pumped hydroelectric facility is illustrated in Fig. 1.2. Water is pumped from the lower reservoir through a penstock to the upper reservoir using the motor/pump in order to store energy. Electrical energy is recovered when water from the upper reservoir flows through the penstock to the turbine/generator near the lower reservoir. If the average head between the upper reservoir and the generator is h , then the total energy available from the gravitational potential of the water in the upper reservoir is

$$E = mgh = \rho ghV. \quad (1.1)$$

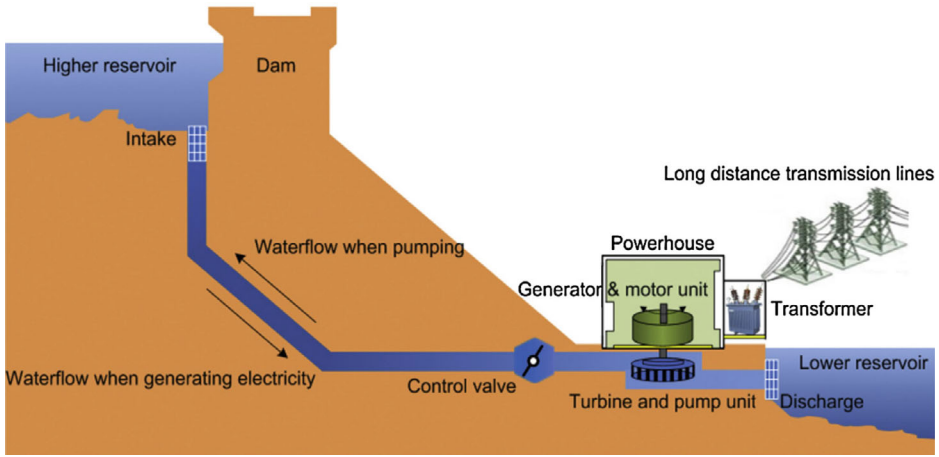


Fig. 1.2 Diagram of a typical pumped hydroelectric storage facility. Figure 4 from Luo et al. (2015) Copyright (2015) the Authors. CC BY 3.0. <https://creativecommons.org/licenses/by/3.0/>

Here m is the total mass of water in the upper reservoir, g is the gravitational acceleration, ρ is the density of the water (kg/m^3) and V is the total volume of the upper reservoir (m^3). When h is in meters then the energy is in Joules. Including the net system efficiency, η , this may be written as

$$E = \eta \rho g h V. \quad (1.2)$$

The power generated by the turbine, in Watts, is

$$P = \frac{dE}{dt} = \eta \rho g h \frac{dV}{dt} = \eta \rho g h \varphi, \quad (1.3)$$

where φ is the flow rate in m^3/s . If the total penstock cross sectional area is A , in m^2 , then the flow rate is given in terms of the water velocity in the penstock, v , as

$$\varphi = vA. \quad (1.4)$$

Thus, Eq. (1.3) may be written as

$$P = \eta \rho g h v A. \quad (1.5)$$

The above equations can also be used to estimate the total time, t , the facility can provide maximum power. Since $P = E/t$ then $t = E/P$ or from Eqs. (1.2) and (1.5),

$$t = \frac{V}{vA}, \quad (1.6)$$