Synthesis Lectures on
Renewable Energy Technologies

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Richard A. Dunlap

Renewable Energy Storage

Mechanical and Thermal Methods

Springer

Synthesis Lectures on Renewable Energy Technologies

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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.

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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

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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

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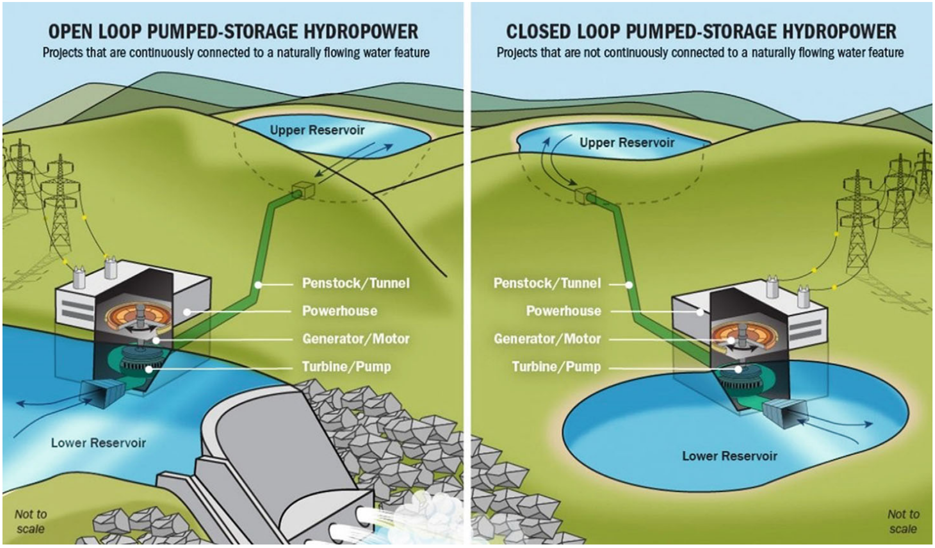

Fig. 1.1 Differences between open-loop (left) and closed-loop (right) pumped hydroelectric storage systems. U. S. Department of Energy (ND) Public domain

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

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

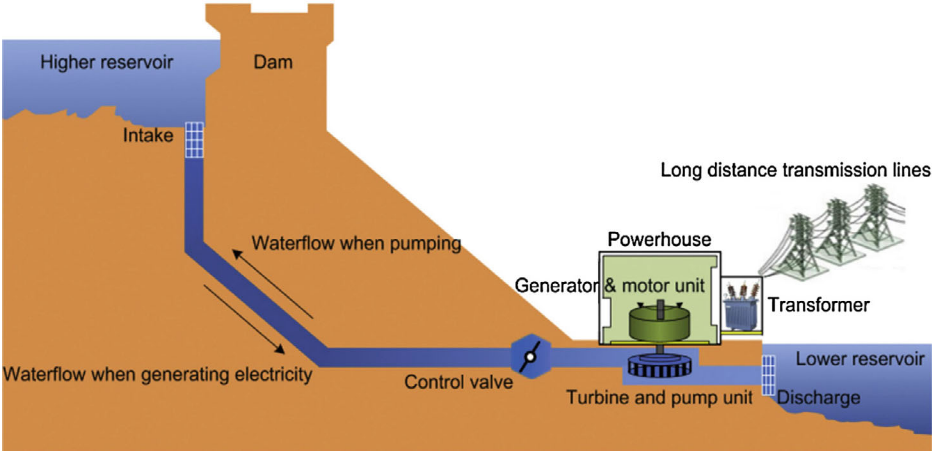

Fig. 1.2 Diagram of a typical pumped hydroelectric storage facility. Figure 4 from Luo et al. (2015) Copyright (2015) the Authors. CC BY 3.0. https://creativecommons.org/licenses/by/3.0/

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

$$E = \eta \rho g h V. \tag{1.2}$$

The power generated by the turbine, in Watts, is

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

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

$$\varphi = vA. \tag{1.4}$$

Thus, Eq. (1.3) may be written as

$$P = \eta \rho g h v A. \tag{1.5}$$

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),

$$t = \frac{V}{vA}, \tag{1.6}$$