

# **RATIONALE OF ENERGY STORAGE AND SUPPLY/DEMAND MATCHING**

**Bjorn Qvale**

*Department of Energy Engineering, Technical University of Denmark, Denmark*

**Keywords:** Availability, Back-Pressure Turbine, Braking energy, CAES, Cogeneration, Compressed Air Energy Storage, Dynamic Programming, Exergy, Extraction Turbine, Garbage Incineration, Geothermal Heat, Hydraulic Accumulator, Mixed stores, Pumped-Hydro, Solar Heat, STES, Stratified stores, Supply and demand matching, TES, Water-Value Method

## **Contents**

1. Introduction
  - 1.1. Background
  - 1.2. Storage Mechanisms and their Physical Realization
  - 1.3. Present Status
    - 1.3.1. Transportation
    - 1.3.2. Comfort Heating and Cooling
    - 1.3.3. Heat Recovery in Industrial Processes
    - 1.3.4. Emergency Power Supply
    - 1.3.5. Power Generation
  2. Thermodynamic Considerations. Energy and Exergy (Availability)
  3. Cases
    - 3.1. Introductory Remarks
    - 3.2. Storage of Mechanical and Electrical Energy
      - 3.2.1. Pumped Hydro (Storage of Potential Energy)
      - 3.2.2. Storage of Braking Energy in Vehicles (Storage of Mechanical Energy)
    - 3.3. Storage of Thermal Energy for Heating
      - 3.3.1. Relationship between Store Losses, Store Efficiencies, and System Efficiency
      - 3.3.2. Solar Heat
      - 3.3.3. Garbage Incineration
      - 3.3.4. Geothermal Heat
    - 3.4. Storage of Thermal Energy for Generation of Electric Power
      - 3.4.1. Introductory Remarks
      - 3.4.2. Back-Pressure Turbine and Seasonal Thermal-Energy Storage
      - 3.4.3. Back-Pressure Turbine and Short-Term Thermal Energy Storage
    - 3.5. Storage of Exergy
      - 3.5.1. Introductory Remarks
      - 3.5.2. Compressed-Air Energy Storage (CAES)
      - 3.5.3. Storage of Heat and Cold in the Groundwater
  4. Computational Tools
    - 4.1. Introductory Remarks
    - 4.2. Evaluations Based on Simple Computations
    - 4.3. Optimization of Operation, Management, and Dimensioning Based on Dynamic Programming
    - 4.4. Study through Simulation

Glossary  
Bibliography  
Biographical Sketch

## **Summary**

A brief introduction is given, sketching the historical background and the conceptual and technical framework for the operation of energy stores and their interactions with the associated energy systems. This is followed by a qualitative discussion of the underlying thermodynamic concepts.

As the number of different types of stores, the number of available working media, and the number of different types of associated energy systems are extremely high, it is not possible to develop a general mathematical framework to cover every possible combination.

The presentation will rather be limited to the most important aspects of the optimization, establishment, and operation of a limited number of energy storage/energy systems constellations and these will be exemplified through illustrations of practical situations. The illustrations have been chosen with the express purpose of introducing the most important ideas that govern the establishment and operation of energy storage systems and their thermodynamic and economic performance. The illustrations demonstrate that very important and often decisive results can be obtained by applying conceptually and computationally simple methods.

The examples will also serve to illustrate the basic ideas that are physical and economic, and thus can also form the basis for the more extensive computerized mathematical models. The results and gains of the application of advanced models are indicated, when known.

The examples will underscore the fact that although the thermodynamic losses of a given store are important, it is the characteristics of the energy system with which it is designed to interact and the price structure of the surrounding society that play the decisive roles in determining whether the introduction of energy storage is an attractive or even acceptable alternative, technically and economically.

## **1. Introduction**

### **1.1. Background**

Passive and active heat storage is as old as the first human settlements. Mechanical energy has been stored in the stresses and strains of the bow or catapult. Kinetic energy has been stored in flywheels for use in the production of yarn and pottery for thousands of years.

However, the identification and designation of the term energy storage is quite recent. The concept of energy storage and its quantification is closely related to a deep understanding of the laws of nature, in particular the first and second laws of

thermodynamic. These were formulated during the nineteenth century, and thus are of fairly recent date.

## **1.2. Storage Mechanisms and their Physical Realization**

As already mentioned, mechanical energy can be stored in the stresses and strains of mechanical springs. But it can also be stored in compressed gas in cavities in the ground or in hydraulic accumulators, which can be regarded as mechanical gas springs (or, from a thermodynamic view point, as exergy stores). Mechanical energy can also be stored in the kinetic energy of a flywheel or in the potential energy when a given mass of water is moved from one reservoir to another at a different altitude.

Electrical energy, that in most respects can be considered to be the equivalent of mechanical energy, can be stored in the form of chemical energy in electrical batteries.

Heat can be stored in the form of internal energy in liquids, for example water, in beds of rocks and in beds of bricks. But it can also be stored in the form of latent heat of liquids, waxes, or metals (alkali). Steam storage, for example, is really the storage of hot, high-pressure water. The store is discharged by steam flashing off from the stored water.

Designations such as storage of heat, storage of electricity, and storage of brake energy are imprecise and some times misleading, and should be used with caution. A few examples will make this clear. The consequence of the storage of heat in connection with a cogeneration plant is that the generation of electricity can be moved to the most favorable time in order to exploit time-dependent pay rates. This is therefore equivalent to the storage of electrical energy. And the consequence of compressed-air energy storage (CAES), is both the transportation of electric energy from one point in time to another and an increase of the production of peaking power. But actually, the compressed-air is stored at environmental temperatures and, therefore, does not represent storage of energy, but as will be explained in a later section, represents the storage of the ability to deliver work. This ability is reflected in the property exergy or (availability).

Finally, a third example is the storage of water at ambient (cold) temperatures from winter to a time when it can be used for cooling, or the storage of water at ambient (warm) temperatures, to a time when it can be used for heating. In both cases the energy invested is zero, but the transportation in time leads to an increase in exergy and hence usefulness.

## **1.3. Present Status**

Today, energy storage is used or considered for use: in transportation in systems for comfort heating and cooling, in continuous and discontinuous industrial processes, in electric emergency supply systems, and in the electric grid (and the associated district heating system).

Specific applications will now be listed:

### **1.3.1. Transportation**

The use of electrically battery-driven vehicles will lead to a substitution of gasoline by electricity thereby reducing the pollution in densely populated areas.

Batteries are used for starting automobile engines, but can also be used to heat the catalyst when starting the automobile, thereby reducing automobile emissions.

Compressed-gas containers, flywheels, or batteries can be used for the recovery of braking energy, thereby reducing energy consumption and automobile emission.

Latent-heat (molten-salt) storage can be used as a heat source for heat engines (Stirling, steam-Rankine) for propulsion of submarines for offshore inspection and repair.

### **1.3.2. Comfort Heating and Cooling**

Warm- or cold-water stores may be used for heating or cooling of apartment buildings, shopping centers, civil-, commercial- and public-office buildings. The source of heat and cold could be solar heat and cool groundwater respectively. The objective is to establish systems that are superior to the conventional systems with respect to energy, environment, and economics.

### **1.3.3. Heat Recovery in Industrial Processes**

In continuous processes such as in electric power plants or in discontinuous process such as in brick factories, the recovery of exhaust gas energy is achieved by the use of regenerators made of iron or rock. This is a common and economically attractive energy-recovery application.

A more challenging application is the use of water tanks for heat recovery when the industrial processes are carried out discontinuously, that is, in batches. But it is difficult to achieve an acceptable economic balance for industrial batch processes.

### **1.3.4. Emergency Power Supply**

Batteries are used for emergency power supply in hospitals and computer centers. In light houses they are recharged by solar cells. These applications are well established. Their roles are so important that investment costs are unimportant.

### **1.3.5. Power Generation**

Compressed-Air-Energy Storage (CAES) uses electric generating capacity that is in excess at night time. By exploiting low night rates for the compression of air, and using the compressed air during peaking periods, very favorable economics may be achieved. CAES could also contribute to a shift of fuel from hydrocarbons to hydro electric or nuclear.

Pumped-hydro storage is very similar to compressed-air storage, except that the possibilities of affecting a fuel shift are limited by economics to a shift between nuclear and hydroelectric power.

The use of warm-water tanks allows back-pressure power plants to operate also when there is no demand for heat. In order to exploit the high rates of electricity during periods of peak demand, the power plant is made to generate electricity when the demand for heat is low, by replacing the missing demand with a charging of a heat store. Then, during periods of low demand, the power plant is closed down, but the heat demand is satisfied by heat from the warm-water tank.

An extraction-turbine power plant is different from the back-pressure turbine mentioned above in that the amount of electricity generated is inversely proportional to the amount of heat demanded. In this case, the warm-water tank is charged by heating the water using extraction steam from the turbine. When the amount of steam extracted is reduced, by closing the bleeds from the turbine, the electric power generation is increased, while the heat to the consumer is satisfied by delivery from the warm-water tank.

## **2. Thermodynamic Considerations. Energy and Exergy (Availability)**

In this section a few concepts and ideas from macroscopic thermodynamics that are central to energy storage will be presented.

To start with, it should be noted that energy has meaning only in the presence of differences. The kinetic energy of an automobile that moves in a specified direction and speed relative to a reference frame can be calculated. If the reference frame moves with the car, this energy is zero. Likewise, it is possible to calculate the thermal internal energy of a system that has a temperature different from a chosen reference temperature. If this reference temperature equals the temperature of the environment and the temperature of the system equals this, the internal energy is zero. However, if this system is insulated and the contents stored until the temperature of the environment has changed, the internal energy relative to the new environmental temperature will take on a value that is different from zero and this difference can be exploited used for either heating or cooling.

It should also be noted here that work is the most easily convertible form of energy in that it can be converted to other forms of energy in full, but the reverse is not always the case. Kinetic and potential energies are equivalent to work, while, for example, thermal internal energy and heat are not. Kinetic and potential energies and work are, therefore, quite a bit simpler to handle than thermal internal energy and heat. Thus the first and second laws of thermodynamics pronounce that a heat engine can only produce work if there are at least one heat source and one heat sink and that these are at different temperatures. Furthermore, from the second law it is possible to prove that if this engine is reversible, the amount of work takes on a unique value, the so-called availability or as it is more commonly called today, exergy, which is the maximum amount of work that can be produced by the given combination of system and environment. The exergy can

also be used as a measure of the value of the energy stored in the thermal energy store, thus serving as some sort of gold standard.

For the specific case of a quantity of heat  $Q$  at a temperature  $T$  with an environment at  $T_0$ , the maximum amount of work  $W$  that can be obtained is given by

$$W = \frac{T - T_0}{T} Q. \quad (1)$$

Likewise, the maximum amount of work that can be produced by a given amount of gas  $M$  interacting with the environment is given by

$$W = MC_p (T - T_0) - T_0 \left[ C_p \ln T / T_0 - R \ln P / P_0 \right] \quad (2)$$

where  $C_p$  is the specific heat at constant pressure,  $R$  is the gas constant,  $P$  is the pressure, and  $P_0$  is the pressure of the surroundings.

If the change takes place at constant temperature, the work reduces to

$$W = MT_0 R \ln P / P_0 \quad (3)$$

Sections 3.2.2 (Hydraulic Accumulator) and 3.5.2 (Compressed-Air Energy Store) are two examples of energy storage in which the energy aspect is unimportant. Rather it is the storage of ability to produce work is the so-called exergy that is important. (It should be noted here, that the Hydraulic Accumulator could also be regarded as a gas spring similar to a mechanical spring). In the case of cooling or heating, the exergy represents the potential reduction of work required to drive an ideal refrigerator or an ideal heat pump. The explanation of the difference of performance of the stratified and of the perfectly-mixed stores of sections 3.3.1.1 and 3.3.1.2 can also be traced back to the concept of exergy.

In fact, the performance of the known energy storage techniques would be easier to describe and explain if exergy were accepted as the common denominator, rather than the energy.

Then the storage of cold from winter to summer, or heat from summer to winter, the usefulness of which depends on the change in the temperature  $T_0$  of the environment, and not of that of the store; and the storage of compressed-air energy, that demonstrably stores no energy, would both be easier to understand.

Research and development in the area of energy storage tend to focus on the conventional losses that represent thermodynamic irreversibilities caused by heat conduction, heat transfer, mixing of fluids with different composition and/or temperature, flow friction, solid friction, inelastic collisions, electric heating etc.

Component efficiencies are usually defined and formulated in terms of these losses. A flywheel may, for example, lose a certain percentage of its stored kinetic energy  $\Delta\eta$  over a certain time period thus offering the possibility of defining an efficiency as  $\eta =$

1.0- $\Delta\eta$ . Such losses and efficiencies quite well express the performance of stores that store mechanical, chemical, or electrical energy or, in other words, that store exergy.

However, in contexts when the storage is based on differences in temperature, such efficiencies may be directly misleading. In such cases a description of the performance of the store is incomplete without considering the characteristics of the system in which the stores are to operate.

Two simple illustrations of the relationship between heat losses, mixing losses, component efficiency and system performance are given in the sections 3.3.1.1 and 3.3.1.2. that address storage of warm water in cogeneration systems.

### **3. Cases**

#### **3.1. Introductory Remarks**

A number of procedures are available for evaluation of the function of energy stores in energy systems, their energy saving potential and losses, and their economics. These range from simple back-of-the envelope calculations, through paper and pencil calculations using dynamic programming, to large computer programs for simulation and optimization.

However, the number of different types of energy stores, both what concerns working principle and technical implementation, is large. Furthermore, the choice of working media, the physical appearance of the store, and the associated energy system can be very different from one site to another.

Therefore, it is not possible to develop a general mathematical description. Rather, it is necessary to approach each new application, site, and operating conditions individually.

In order to give an introduction to the field, a number of cases will be presented. They are expected to cover a reasonable cross-section of the applications to be encountered in today's world.

The examples will serve to illustrate the basic ideas that are physical and economic, and thus can also form the basis for the more extensive computerized mathematical models. The results and gains of the application of advanced models are indicated, when known.

These examples will underscore the fact that although the thermodynamic losses of a given store are important, it is the characteristics of the energy system with which it is designed to interact and the price structure of the surrounding society that play the decisive roles in determining whether the introduction of energy storage is an attractive or even acceptable alternative, technically and economically.

The cases addressed below are introduced in what is believed to be the order of rising conceptual complexity, starting with the simplest, namely the storage of mechanical and electrical energy.

-  
-  
-

TO ACCESS ALL THE 25 PAGES OF THIS CHAPTER,  
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

### **Bibliography**

Bellman R.E. (1957). *Dynamic Programming*. Princeton University Press, Princeton, New Jersey, USA. [Basic text on Dynamic Programming].

Hveding, V. (1970). Digital Simulation Techniques in the Planning of Large Mixed-Supply (Hydro-Thermal) Power Systems. Symposium on Prospects for the Development of Hydro Electric Schemes and for their Incorporation in Future Energy Supply Systems. Economic Commission for Europe Committee on Electric Power, Dubrovnik, Yugoslavia, 19-24 October 1970. [Addresses the value of stored energy. Simple explanation of the “Water-Value Method”].

Stage, Sven and Larsson, Yngve (1961). Incremental Cost of Water Power, AIEE Transactions, (Power Apparatus and System) August 1961. [Addresses the value of stored energy].

Wark, K. (1998). *Thermodynamics*, 6<sup>th</sup> edition, McGraw-Hill Book Company, ISBN 0-07-068305-0. [This is useful for understanding availability (or exergy)].

### **Biographical Sketch**

**Bjørn Qvale** was born in Oslo, Norway, on March 3, 1937. He is now a citizen of Denmark.

He received his S.B. (1963), S.M. (1963), and Ph.D. (1967) degrees in Mechanical Engineering from MIT. The first two degrees in the Gas Turbine Laboratory, the last in the Cryogenic Engineering Laboratory.

For two short periods he also worked in the MIT Heat Transfer Laboratory and in the National Magnet Laboratory. From October 1963 to August 1965 he was employed by Northern Research and Engineering Corporation, Massachusetts. Between 1966 and 1971 he was employed by the School of Mechanical Engineering of Purdue University, as Assistant and Associate Professor.

In 1971 he was appointed professor of Energetics at the Technical University of Denmark, and has served as Director of the Laboratory for Energetics from 1971 until the Institute’s merger with 3 other institutes in 1995 (only interrupted by a one-year sabbatical leave), but continues as Professor.

He has been involved as principal researcher in projects of significant magnitude concerning the utilization of reservoirs for such applications as the extraction of thermal energy from ground water, storage of heat in aquifers, geothermal energy, and oil and gas.

He has also been involved in the study of a number of problems concerning the use of fuels of different types and varying composition in diesel engines, Otto engines and gas turbines. The studies aim specifically at plants with cogeneration of heat and electricity and as a source of power in transportation. He is presently engaged in thermal gasification of biomass.

These R & D projects are typical for the general background that, over the years, have lead him to studies of energy systems based on decentralized production of heat and power, systems for distribution of coal in Denmark, systems for the utilization of geothermal energy, and Industrial Process Integration.

Energy Systems in general and Industrial Process Integration in particular, have been his principal research interest during the last 15 years.