MECHANICAL ENERGY STORAGE

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Summary

To store the excess mechanical or electrical energy as kinetic energy in flywheels, potential energy in water or compression energy in air, to use it at high demand time as mechanical or electrical energy has great importance for the civilized world mainly because of irregularities of demand or supply.

Today mostly used and largest capacity systems are for storage of electricity in pumped hydro power plants. Water of a lower reservoir is pumped up to a reservoir hundreds meter higher and next day during the peak demand electrical power is produced by letting the water flow down through the hydraulic turbines. With high efficiency and very high reliability they have served more than a century and further plants will be built in future even at places with less suitable geological conditions.

Compressed air energy storage (CAES) systems are essentially gas turbine power plants with an additional cavern to store the compressed air. By the cheap night electricity air is compressed into this cavern at a pressure 40 to 80 bar and used next day to run the gas turbine. They have the advantage to increase total installed power by less investment in comparison to pumped hydro power plants. However they depend on liquid or gas fossil fuel. Furthermore geological conditions to create a cavern are not satisfied at most places.

For medium and small-scale mechanical energy storage flywheels are very suitable, e.g. in the reciprocating engines and rolling mills. By recent research on materials and design their energy density has been increased considerably, so that they are applied as spinning reserve at a power rate 1.6 MW and 5 kWh energy capacity. Research efforts for improving applicability of flywheels and compressed air to recover braking energy of road vehicles are continuing.

The most important characteristics of mechanical energy storage systems are their capacity [kWh; MWh or MJ, GJ] and their delivery power [kW; MW]. In comparing different types of storage methods the energy storage density is an important parameter.

1. Introduction

Valuable items will be stored if they are easily available but not needed at the moment. Mechanical energy is such a valuable item and should be stored whenever it is available but not consumed.

Figure 1 shows different types of energy stored in matter with emphasis on the mechanical stored energy and its applications. The figure distinguishes firstly the stored energy from the modes of energy transfer, namely work, heat and convection of matter. The common aspect of the means for mechanical energy storage is that they deliver the energy whenever required as mechanical work. However, only for the flywheel the supplied and the consumed energies are in mechanical form; the other two important applications, namely pumped hydro energy storage and compressed air energy storage, are for electrical power production at peak demand.

Figure 1 indicates the mechanical energy storage types of smaller capacity also, like moving bullet. It delivers its stored kinetic energy as deformation work at the target. Most of the springs and lifting weight to drive clocks are now replaced by electrical drives, wherever needed with a battery. Compressed air energy storage in fluid power applications and water delivery systems and deformation energy storage in springs of machinery still have importance. The external energy of a collection of matter, or system, is related to the relative condition of the matter with respect to its environment. Transfer of work to a matter resulting in a change in its linear velocity, causes increase of the kinetic energy of the matter:

$$\dot{W} = F \cdot v = m \cdot \frac{dv}{dt} \cdot v = \frac{d}{dt}(m \cdot \frac{v^2}{2}) = \frac{dE_{k,v}}{dt} \qquad (1.1)$$

In this equation $\dot{W}$ is the rate of work supplied to the matter, i.e. power, *F* is the force, *v* is the velocity, *dv*/*dt* is the acceleration and $E_{k.v}$ is the linear kinetic energy. If written independent of the rate of change, Eq. (1.1) becomes:

$$W = \Delta E_{k,v} = m \cdot \frac{v_2^2}{2} - m \cdot \frac{v_1^2}{2} \qquad (1.2)$$

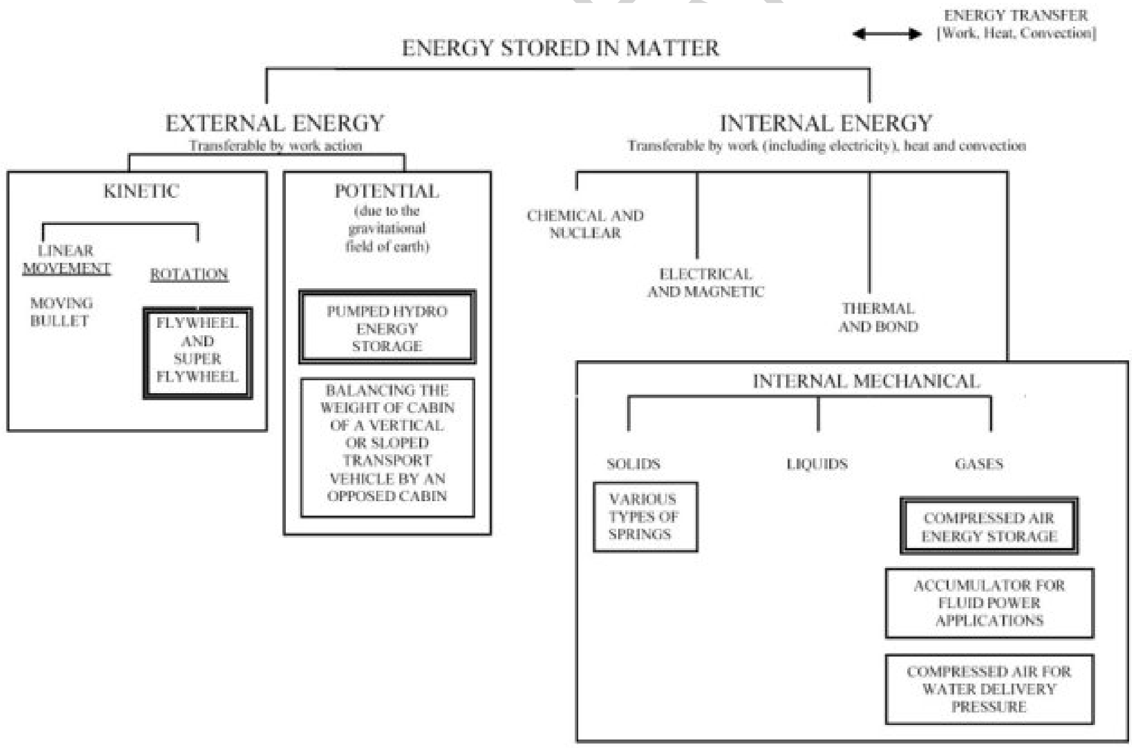

Figure 1: Three Main Types of Mechanical Energy Storage: Kinetic Potential and Internal Mechanical

Similarly for a rotational acceleration caused by torque *T*, and at rotational speed *w*, one can write

$$\dot{W} = T \cdot w = (m \cdot \frac{d(r\dot{w})}{dt}) \cdot rw = \frac{d}{dt}\left[(m \cdot r^2) \cdot \frac{w^2}{2}\right] \qquad (1.3)$$

$$= \frac{d}{dt} \cdot (I \frac{w^2}{2}) = \frac{dE_{k,r}}{dt}$$

$$I = m \cdot r^2 = \sum m_i \cdot r_i^2 = \int_m r^2 dm \qquad (1.4)$$

$$W = \Delta E_{k,r} = I \cdot \frac{w_2^2}{2} - I \cdot \frac{w_1^2}{2} \qquad (1.5)$$

In these equations *r* is the distance of the matter element from the axis of rotation. $E_{k,r}$ is the rotational kinetic energy of the matter and I is the moment of inertia of the matter with respect to the axis of rotation.

A rotating wheel that is used for storage of mechanical energy is called a flywheel. Flywheel applications in machinery have short period of charging-discharging cycle. In these applications either power supply is interrupted but power demand is continuous like in case of a reciprocating engine and pottery wheel, or the power supply is continuous but sudden large forces, bursts perform the desired work that is of interrupted nature. In both cases the rotational kinetic energy helps the supply to match demand. Flywheels are explained below in Section 4 and more detailed in *Flywheels and super-flywheels*.

The change of the elevation of a matter in a gravitational field, e.g. vertical movement of an object on earth due to a work transfer to it, results a change of the potential energy of that object.

$$W = m \cdot g \cdot \Delta h = m \cdot g \cdot h_2 - m \cdot g \cdot h_1 = \Delta E_p \qquad (1.6)$$

For a fluid being pumped:

$$\dot{W} = \dot{m} \cdot g \cdot (h_2 - h_1) = \frac{dE_p}{dt}$$

Here *g* is the gravitational acceleration, 9.81 m s^{-2}.

It is the rate of energy transfer in pumped water energy storage system. This type of mechanical energy storage is explained in Section 3 and more detailed in *Pumped water energy storage*.

Another important type of mechanical energy storage is internal mechanical energy increase of compressible or deformable substances, as shown in Fig.1. Gases are highly compressible and air is an abundant suitable substance. An example of its judicious application is combination of compressed air storage with gas turbine power production. During the process of discharging, the internal energy of the previously compressed gas, combined with combustion and turbine expansion, produces power to cover peak demand of utility power systems. Compressed air energy storage of this type is explained below in Section 4 and more detailed in *Compressed air energy storage*.

Figure 2 shows the daily variation of demand on utility power systems (curve 6) and power production of base load power plants (curve 1). Because the investment costs of nuclear, wind and large-scale coal power plants are high and their operation costs including fuel cost are low, these base load power plants run day and night continuously. At night, 1 a.m. to 6 a.m. the demand is low, it is called trough. The excess power produced at night (the lower shaded area) is stored as the potential energy of the pumped up water of pumped hydro power plants. During the daytime when the power demand is highest the gas turbine power plants (curve 2) and the industrial cogeneration systems (curve 3) are run. These are not enough, the pumped hydro power plants, the compressed air energy storage and in special small systems electrical, flywheel energy storage systems produce the additional power to satisfy the demand their stored energies (the upper shaded area).

Since conversion of energy from mechanical to electrical and vice versa is carried out with only small losses, pumped water energy storage and compressed air energy storage are used in large-scale for satisfying the peak demand of the utility power systems. Diurnal fluctuations of demand in utility power systems and the solutions to these fluctuations are explained in *Compressed air energy storage.*

In the fallowing sections, after a survey of the common aspects of mechanical energy storage systems, namely their characteristics, control and economics, the above mentioned three most important applications will be explained. The less widespread applications of storing smaller energy amounts form the subject of Section 6.

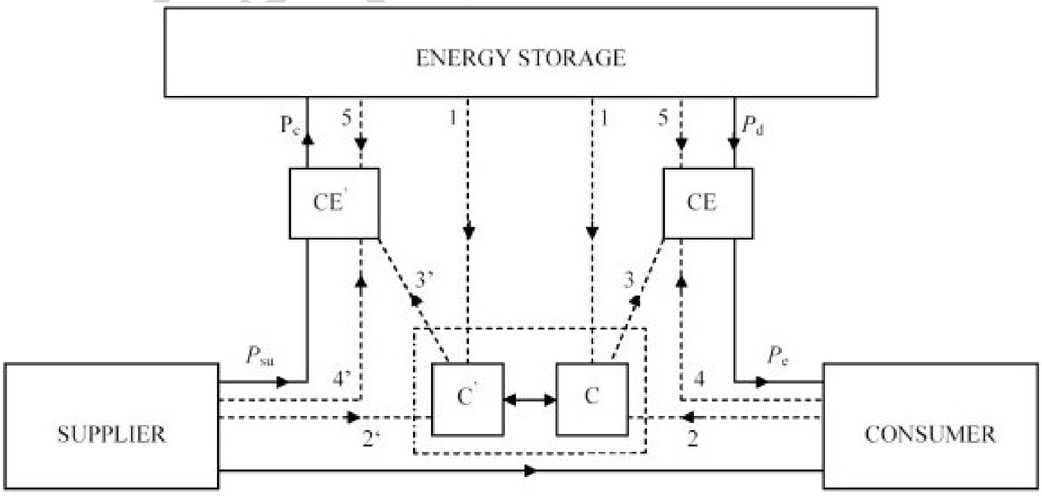

Figure 2: Control of Energy Flow to and from a Mechanical Energy Storage System CE, CE’: Conversion Equipment; C, C’: Control System; Full lines indicate flow of energy or energy carrier and dashed lines indicate signal transfer

2. Characteristics, Efficiencies, Control and Economic Evaluation of Mechanical Energy Storage Systems

2.1. Characteristics of Mechanical Energy Storage Systems

Like of other energy storage types, the most important characteristics of mechanical energy systems are the capacity [kWh; MWh or MJ, GJ] and delivery power [kW; MW]. The capacity is that part of the stored energy which is deployable, i.e. discharged during the normal operation conditions. E.g. the kinetic energy of a rotating ring is used between its highest and lowest speeds. Table 1 gives the applied capacity of various mechanical energy storage methods. Capacity is expressed frequently not in energy units but in time units (s or h) i.e. the duration of uniform delivery of the useful stored energy at the design rate of discharge. It is the ratio of the stored energy to the discharge power.

In comparing different types of storage methods the energy storage density is an important parameter. The mass specific and the volume specific energy storage densities of the five types of mechanical energy storage systems are given in Table 1. One sees on the Table the order of magnitude difference between the capacity of pumped hydro energy storage and the others. For medium-scale energy storage the flywheel has the advantage of occupying smaller volume.

	Applied Capacity [kJ]	Mass Specific Energy Density [kJ/kg]	Volume Specific Energy Density [kJ/m^3]
Pumped Hydro Power Plant (100m)	10^{10}	$9.8 \cdot 10^2$	10^3
Flywheel	10^6	~ 60	10^5
Compressed Air (50 bar)	10^9	~ 60	10^2
Organic Elastomer	-	~ 20	-
Torsion or Plate Spring	10	~ 0.20	-

Table1: Applied Capacity, Mass Specific and Volume Specific Energy Densities of Mechanical Energy Storage Systems

Today mostly used systems out of these are pumped hydro power plants for large-scale, flywheels for medium-scale and springs for small-scale energy storage applications.

2.2. Efficiencies

Other important characteristics are related to performance. They are expressed as various efficiencies of the partial processes and of the complete energy storage process.

Overall or (total) efficiency (η_0) of a mechanical energy storage process is defined as the ratio of the output (exit or delivered) energy (E_e) to feed or (supplied) energy (E_{su}). All energies are for one period .The overall efficiency depends on the efficiencies of conversion equipment and that of the storage. One can easily establish the fallowing relations on rate bases:

$$\eta_0 = \frac{E_e}{E_{su}} = \frac{E_e}{E_d} \cdot \frac{E_d}{E_c} \cdot \frac{E_c}{E_{su}} = \eta_d \cdot \eta_{st} \cdot \eta_c \qquad (2.1)$$

$$\eta_d = \frac{E_e}{E_d}; \eta_{st} = \frac{E_d}{E_c}; \eta_c = \frac{E_c}{E_{su}} \qquad (2.2)$$

Here η_c, η_{st} and η_d mean charging (and related conversion) efficiency, storage efficiency and discharging (and related conversion) efficiency respectively.

To respond to the demand of the consumer in a short time, the storage is located in general as close as possible to the consumer.

Nevertheless there are also losses during the transfer between main supply and storage and between storage and consumer. These losses are taken into consideration in the expressions for efficiency of charging and discharging respectively.

An important characteristic of mechanical energy storage systems is that their storage efficiency is higher than those of thermal and also higher than some electrical and some chemical storage systems. Table 2 shows the overall efficiency of three types of mechanical storage systems.

Storage Systems	Efficiency
Pumped Hydro Power Plant	75 - 80
Compressed Air (average of with and without heat addition)	50 - 55
Flywheels	70 - 85

Table 2: Overall Efficiencies of Main Types of Mechanical Energy Storage Systems

2.3. Control of Mechanical Energy Storage Process

In all applications storage can be considered as a buffer between supply and consumption. However, for most applications there are control elements to regulate energy flows as shown on Figure 3.

Control of a mechanical energy storage system bases on information flows that are shown on the Figure by dashed lines. In the fallowing the control of discharge from the storage will be discussed; control of charging is similar. (see *Pumped water energy storage*)

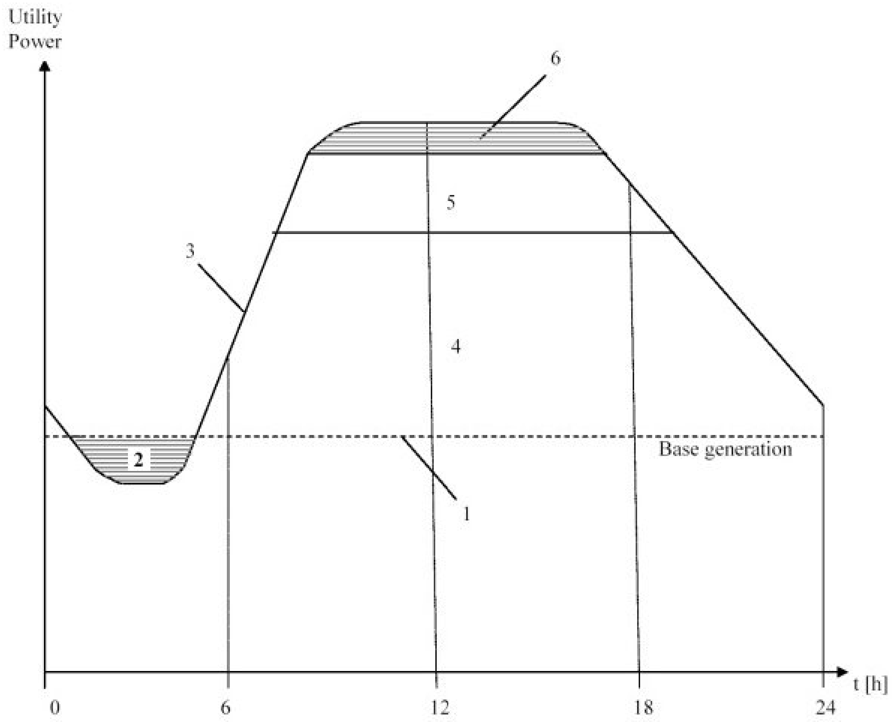

Figure 3: Approximate Variation of Utility Power Demand and Satisfying it by Various Power Sources: i) Base load power plants together (nuclear, hydraulic, wind), ii) Surplus electrical power absorbed by utility energy storage plants, iii) Demand variation of utility grid, iv) Gas turbines and other smaller power plants, v) Power produced by cogeneration and independent private power plants, vi) Power delivered by utility energy storage plants

The controller C is a microcomputer with special software and input-output interfaces. It receives the signals for the variable parameters of the consumer and supplier (shown as 2 and 2’ on Figure 3) and determines the desired additional power (P_{des}). Furthermore receiving the signals (1) for the variable parameters of the store the controller calculates and transmits the signals for the regulating parameters needed by the energy converter CE (3). This input to CE is combined (via digital-analog converters) with the characteristics of the storage and the consumer to activate the rate of conversion or the rate of flow. The charging controller C’ and charging converter CE’ work similarly. Although on Figure 3 the control functions of C and C’ are shown separately, they are one and same computer. In modern pumped hydro power plants the converters CE and CE’ are one and same unit.

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WEB-Sites

Argon National Laboratory: *www.ipd.anl.gov/energy_partners/advanced.html* Advanced concepts in energy storage. [State of the art explanations of recent research on flywheels and electrical systems like ultra capacitors, batteries and SMES are given and further links are offered.]

US Department of Energy (DOE) / Energy Efficiency and Renewable Energy: *www.eere.energy.gov/EE/power_energy_storage.html* [Results of research supported by DOE on flywheels, pumped hydropower, CAES, SMES and lead acid battery are explained and for most recent reports links offered.]

Rochester University: *www.energy.rochester.edu/storage/* [Energy storage systems mainly for building HVAC systems are explained. It is given through a link to District Energy Virtual Library. There is reference to other types of energy storage also.]

Biographical Sketch

Yalçın Göğüş received his high school training in Ankara, his B.S. degree in 1958 and his PhD degree in 1964 at the Faculty of Mechanical Engineering of Technical University of Munich. He was Alexander von Humboldt Fellow in the years 1959 to 1961. He joined METU (the Middle East Technical University, Ankara) in 1961 and was Professor of Mechanical Engineering in the years 1976 to 1982. After working for UNESCO as a specialist and Project Director at Makarere University, Uganda 1980 to 1986 he returned to the Department of Aerospace Engineering of METU. He was as NATO-Fellow at Brown University (1970) and as Visiting Professor at University of Gaziantep (1975), Technical University Munich (1979) and Technical University Istanbul (1999). He has written, translated or edited ten books and more than one hundred journal or conference papers and research reports. He was founding Chairman of Turkish Society for Thermal Sciences and Engineering and Editor-in-Chief of its scientific journal Isı (1976), Founding Vice-Chairman of International Centre for Applied Thermodynamics (1997) and Associate Editor-in-Chief of its *Int. J. of Thermodynamics* (1998-2004) He received academic awards. Since 2001 he is working as Emeritus Professor at METU in the fields applied thermodynamics and propulsion engineering.