

ENERGY STORAGE

Yalçın Abdullah Göğüş

Department of Aerospace Engineering, METU, Ankara, Turkey

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Summary

Present applications and future developments of energy storage are closely related to the nature of demand, transport, and resources, and economics of these. Energy is stored as internal energy (U) and external energy (E_e) of objects. Internal energy of an object has physical, chemical and nuclear components. Physical internal energy covers compressive, thermal, electrical, magnetic, radiation and other internal energies. Thermal changes, e.g. for water with 10 K, are around 500 times as much as mechanical energy changes, compared on the basis of same mass amount, e.g. acceleration to 50 km.h⁻¹ or lifting to 10 m. Chemical energy changes, e.g. combustion of gasoline, are around 10³ times as much as sensible thermal changes. Nuclear reactions have around 10⁴ times as much energy change as chemical reactions. The external energy is relative to the external objects and consists of kinetic energy and potential energy.

The two often used types of energy, namely heat and electricity, are stored in their original form to avoid conversion losses, if the resources are of the some kind, e.g. solar heat and excess electricity due to short time fluctuations of electricity consumption. In deciding for the suitable type of energy storage one has to consider the conversion losses- heat to work and vice versa. Internal thermal energy and heat are due to random molecular vibrations and only a part of this energy can be converted to work; that part is called *exergy*. The ratio of the discharged energy of a store to the charged energy is the overall storage efficiency. Losses due to leakage, charging and discharging processes and, if there are conversions the losses due to these, result in overall efficiencies less than unity. Another factor in deciding for a suitable type and size of energy storage system is the investment required.

Sensible heat energy storage systems consist of a heat transferring fluid and heat storage elements, which are fluids or solids. Storage elements undergo temperature change (swing) during heat addition and discharging. Such systems with very large thermal capacity are used for seasonal energy storage. Sensible heat storage systems with smaller capacity are used for daily storage of solar energy and for heat recovery systems in industry. Phase change energy storage systems are filled with materials that undergo a phase change solid-to-liquid or liquid-to-vapor during charging and vice versa during discharging of thermal energy. Because of their large energy capacity at constant temperature they are preferred in many applications. However, in comparison to sensible heat energy storage systems with water, they are more expensive. Bond energy is the energy that is released when different molecules are bound to one another as in adsorption, absorption and chemical reactions. Because of higher energy density bond

energy is more cost-effective; however, the reactions require special chemicals. Hence they are not widespread. The energy densities in stores involving phase change and bond energy storage are close to those in chemical energy storage.

Compression internal energy of gases has energy density between sensible thermal energy storage and potential energy storage. Liquids are incompressible, however, in fluid power systems and emergency water supply systems air is compressed in an intermediary container and it allows the system to work flexibly. Solids can store limited useful energy by deformation, e.g. in springs. The stored energy is not large but the force during discharging of energy is great and this force is available at a very high rate. Hence springs are used generally as components of machinery.

To store cheap electricity which is produced by nuclear, wind or large fossil power plants at low demand times, pumping water from a low reservoir or river to a high reservoir is a well established method. These plants are called pumped hydro power plants and have an overall storage efficiency around 0.7.

Fluctuations of power production of heat engines are smoothed by rotating discs which are called flywheels. When the work production is at a rate that is higher than demand, the rotational speed increases slightly and the disc stores energy; at lower rate of work production this stored energy is taken from the flywheel resulting in a slight decrease in its speed. Flywheels are used also to accumulate energy flow to a machine and to put it at disposal in a very short time, as in powered blacksmith hammers. Super flywheels have the highest energy density and high efficiency.

In a gas turbine power plant, around one half of turbine power is consumed by the compressor. Running the compressor at low demand time and storing the compressed air in a cave allows more power to be produced at peak hours using this compressed air. Compressed air energy storage has various applications in smaller scale as in busses and emergency water supply.

Batteries convert chemical energy to direct current electrical energy. They are of three types: Primary batteries, i.e. batteries which are not rechargeable and they will be used only once; secondary batteries, i.e. rechargeable batteries, are reversible and are used many hundreds of cycles of charging and discharging; and lastly fuel cells which produce electricity whenever fuel is supplied into them.

The main storage devices for electrical energy are secondary batteries. Their best known type is the lead-acid battery. Its energy density is typically more than that of a sensible thermal energy store but less than that of a chemical energy store because of the high mass density of lead.

Such batteries can be used together with suitable converters in smaller independent alternating current networks for peak shaving or as spinning reserve. Also, by interconnection of electrical networks smaller peaks are adjusted between regions by load sharing. In future, modern nickel metal hydride and lithium ion batteries may replace lead acid batteries.

Capacitive storage is suitable for direct current and consists of charging an electrical capacitor. It has much smaller energy density than batteries but has the advantage that it does not need maintenance. In alternating current circuits and converters it has found wide applications.

Magnetic energy gives another possibility for storage of electrical energy. Its applicability to special needs with very high discharge rate is demonstrated at pilot plants. Very strong magnetic fields with small joule heating can be created by superconducting coil at low absolute temperature. However, it is not used yet widely because of economic considerations.

Storing and transporting the chemical energy of fossil fuels is the easiest and one of the most economical ways to store and to transport energy. The oxidation loss of coal and the leakage losses of liquid and gaseous hydrocarbons stored underground are small in comparison to the storage losses of thermal and mechanical energy.

For synthetic fuel hydrogen, which can be absorbed by metal hydrates for storage purposes, the development of technology is still continuing. For more extensive usage of nuclear and renewable energies by storage and transport of hydrogen, metal hydride technology is considered as the correct way. Storage energy losses of fissionable materials are, on the other hand, most difficult to avoid.

The main problem of electrical networks is hourly fluctuation of power demand. Hence pumped water storage and compressed air storage are run with the surplus electricity at low demand (night) time in charging mode. They work in discharging mode later to satisfy the peak demand. The support of these energy storage systems during the peak may last up to 6 hours, although the usual discharge period is less than half of that.

Developments of energy storage techniques will continue at macro, medium and micro scales also in future. At macro scale, better utilization of solar, wind, geothermal and ocean energies will be possible by storage. At medium scale, in passive houses around 80 percent of heating energy is already being saved by collection and storage of solar energy and by improved insulation. In micro scale to recharge the batteries of medical implants by electromagnetic waves gives them very long life.

1. Introduction

Diversity of energy demands and resources

Energy is needed at so widely distributed locations and so different occasions that humankind has to find ways to match this diversity of demands with the existing diversity of resources. The solution is to convert the primary energy to more suitable forms and store them to have flexibility of usage in time and in space.

A typical day starts with having bath, cooking for breakfast and traveling to the workplace etc., all of which consume energy. At the same time, electrical power is needed to drive machines at many work places; demand for electrical energy reaches its maximum level, which is called “peak” in electrical power systems.

Illumination of roads at night would not be a load problem for electrical networks, but in winter evenings this demand contributes considerably to the peak in electrical power demand because it coincides with industry and transportation loads.

To match these peak demands, some auxiliary hydraulic power stations are built which have reversible turbine and generator units. At late time when nuclear or thermal power plants continue to run at their lowest level, but still produce more electricity than the demand, the turbines of the auxiliary hydraulic power plants are reversed; they lift the river water up and store this excess electrical energy as potential energy of water.

These power stations, called pumped hydro power stations, have an important role in electrical power systems. Also mechanical energy storage in the form of compressed air in underground cavern is used for matching electrical supply to electrical demand in combination with gas turbine power systems.

Another important example of matching demand and supply of energy is winter heating of buildings by the solar heat which is collected in summer months and stored in large caves filled with water. Some northern countries save considerable fuel amounts in this way.

Considering all types of energy consumed by humankind, each of the following three sectors has roughly equal weight: heating-cooling-illumination, transportation, and industry. Seasonal and daily variations of energy demand for heating and cooling are the greatest.

If the heating energy is produced by combustion process, coincidence of various demands at certain hours of the day or certain weeks of the year is not a problem. However, to conserve the energy, the rejected heat of electrical power plants is used more and more for industrial and domestic heating and even for cooling purposes.

This is called cogeneration. Figure 1 shows such a cogeneration plant. Generally during the operation of a cogeneration plant electrical energy production matches the electrical energy demand. This necessitates storage and shift of the rejected and unused heat to the time of the maximum demand. Also, as mentioned above, the produced excess electricity is stored.

Present applications and future developments of energy storage are closely related to the types of demand, transport, and resources, and economics of these. Even a short explanation of all possible or proposed types of energy storage and their combinations would be very voluminous.

Hence only those alternatives which are viable will be treated here. After having a bird's-eye view of the past and the future of energy storage in this section and classification of its types in the next section, an overview of transportation and conversion techniques will be presented. A section about performance and economic criteria will follow. Finally each of the main types of applied energy storage systems will be explained briefly.

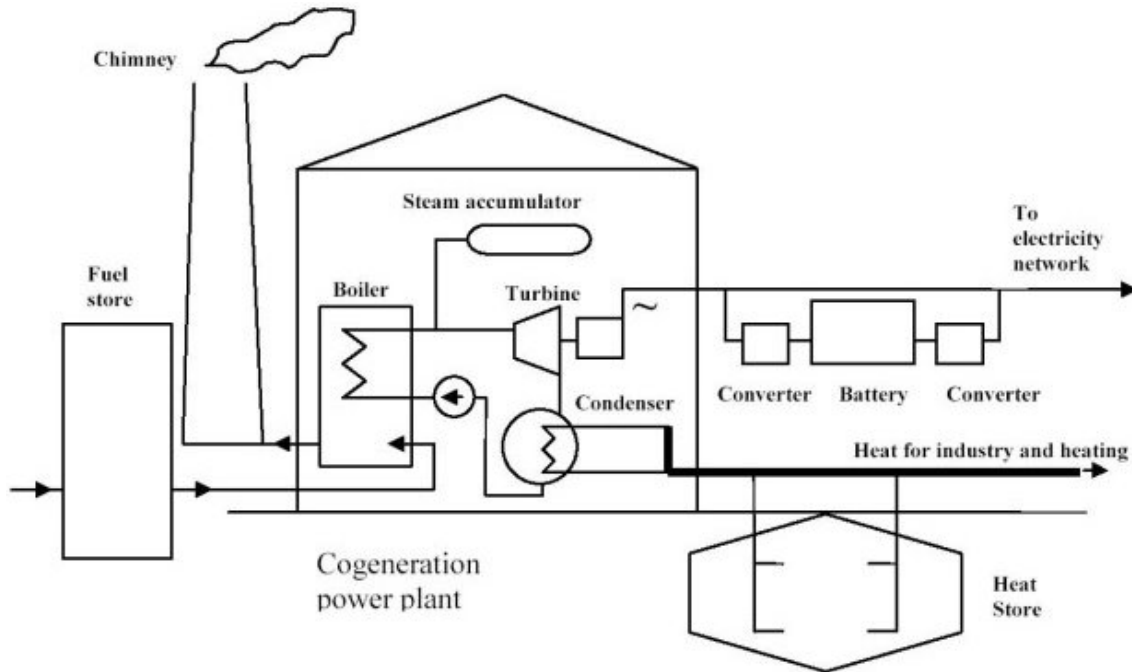


Figure 1: Efficient operation of cogeneration plant by fuel, electricity and heat storage

Historical perspective and future of energy storage

Collecting wood pieces in excess of the momentary need was the storage of chemical energy known for thousands of years. Bending a bow to throw an arrow was accumulating muscle work by storing it in strain energy of the bow. In potteries the discontinuous muscle power was supplied to the turning wheel of the bench, which rotates continuously and functions as flywheel.

By improvement of technology, large clocks at towers were constructed which were driven by gravitational potential energy of a weight moving down. The weight was moved up once a day or once a week.

As another application, especially in mountainous warm countries, snow was stored in caves and was used to cool beverages in summer.

By the beginning of industrial revolution in the eighteenth century large amounts of coal was stored because of its chemical energy. For this purpose special precautions were taken. At the end of the nineteenth century petroleum storage became necessary. At the beginning of the twentieth century electrical power was widely distributed and pumped hydro power plants were built. Also storage of natural gas for future use started around the 1920s. More intensive development work on seasonal storage of thermal energy (heat) was initiated to save fossil fuels, especially after the oil crisis in the last quarter of the twentieth century.

The desire for greater mobility has been the driving force behind research on and development of transportable power sources. Hydrogen fuel cells and electrical batteries have been receiving great attention since the 1980s, because chemical energy storage

per unit mass is three orders of magnitude greater than thermal energy storage per unit mass. For utilization of renewable energy sources, hydrogen is the most efficient energy carrier. However, its storage and transport are important problems. Considerable progress has been achieved on the solution of these problems during the last few decades of the 20th century.

Recent advances in the storage of electrical energy in small scale have changed the capability of many household items from laptop computers to handy vacuum cleaners. Micro scale applications have great impact on medical auxiliary devices like heart pacemaker batteries. Chemical and nuclear energy stored in fuels for outer space propulsion systems enable us to realize missions to far away planets of our solar system.

Developments of energy storage techniques will continue at macro, medium and micro scales also in future. At macro scale better utilization of solar, wind, geothermal and ocean energies will be possible by storage, so far that demand for fossil fuels will reduce considerably. Energy storage is one of the sound solutions to the climate problem of earth and sustainable development.

Improvements of the techniques and economics of energy storage at medium scale will contribute to solving the energy shortage problem. In many passive houses in Europe built for demonstration purpose around 80 percent of heating energy is already being saved by collection and storage of solar energy and by improved insulation. In some batch type processes of industry energy storage techniques are not applied yet because of techno economic reasons; however, efforts are under way to find solutions for these also.

Very surprising innovations are found in micro scale applications. To recharge the batteries of medical implants by electromagnetic waves gives them the desired service life. It will be soon possible to inspect even the regions of the human body which are the most difficult to reach by reducing the size of in-body inspection capsules and their energy carriers.

Storing energy can function like the lever of Archimedes to avoid waste of energy and waste of investment.

2. Types of Energy Storage, En Route from Resources to Utilization

Everything is changing, also energy in our environment, from one form to another. However, between any two changes or transfers energy is contained by, or stored in, a substance. The important factor for humans is to have these with desired effects at desired locations and at desired periods of time and furthermore, to preserve the quality and quantity of the stored energy.

Energy transfer is one of the two types, either it is at macroscopic level, in ordered form, called work; or it is at microscopic level, in disordered form, called heat. Work transfer can be expressed by a change of donor system that is equivalent to or replaceable by mechanical work:

$$W = F \cdot \Delta r ,$$

where F is force and Δr is displacement of the point of action in the direction of the force (or projection of the displacement of that point in the direction of force).

Heat transfer occurs due to the effect of molecules of a warmer object on the molecules of a colder one. The universal measure of intensity of warmth is absolute temperature; its scale starting at absolute zero is called as Kelvin temperature scale. For ambient (environment) temperature the Celsius scale with the same unit size is preferred, which has its starting point at 273.15 K, corresponding to the freezing point of water at atmospheric pressure.

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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 explanation of recent research on ultra capacitors, batteries, flywheels 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 flywheel, 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.]

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Biographical Sketch

Yalçın Göğüş received his B.S. degree in 1958 and his PhD degree in 1964 at the Faculty of Mechanical Engineering of Technical University of Munich. 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 Makerere 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), and Technical University Istanbul (1999) and as Alexander von Humboldt Fellow at Technical University Munich (1979). He has written, translated or edited ten books and more than one hundred journal or conference papers and research reports. He contributed to establishment of Turkish Society for Thermal Sciences and Engineering and its scientific journal *Isı* (1976), International Centre for Applied Thermodynamics (1997) and its *Int. J. of Thermodynamics* (1998) He received academic awards. Since 2001 he is and working in the fields of applied thermodynamics and propulsion engineering as emeritus professor of METU. He is married to Turkan Göğüş (Sorguç) since 1962. They have two grown up boys Akın and Ozerk Gogus