ENERGY STORAGE (SPECIFIC ENERGY)

Energy is always stored in matter (e.g. in the water dams, chemical fuels, and nuclear fuel that feed our power stations; the amount of energy stored in empty space is very small), although it often appears naturally flowing from one store to another (e.g. a water stream, wind, and solar radiation). People need energy services (heating, illumination, transportation...) widely varying with time; and societies have developed public utilities to supply energy in the most convenient form (electricity, and refined fuels). But, when the energy supplier (the public utility or the Sun) is not under direct command of the end-user, it is a difficult problem to match energy demand and available energy in both time and space. The only solution is to provide some intermediate energy storage (the Neolithic Revolution can be explained as the ability to store food energy in livestock and storage pits).

Ever-increasing demand of portable energy (from peacemakers to deep-space probes), sensitivity to energy cut-offs and energy surges of modern equipment and services (e.g. dependence on electrical elevators, electronic transactions, intensive care units...), the growing share of variable renewable energy sources in the electrical grid (solar and wind), and rational energy use in general (e.g. load levelling), are pressing on the need of energy buffering in different amounts and time-scales (from below-microsecond power spikes, to seasonal national energy reserves). Most of the times, energy storage is synonymous of electricity storage (or power storage), since the other end-user energy-carrier (fuels) is already stored. Storage of solar or wing energy implies intermediate conversion to electricity or a fuel-type store, since neither radiation nor wind can be directly stored in sizeable amounts. That is why an electricity cut-off holds up most human activities in developed countries (not elevators, not lighting, not computers, not shopping or banking... and not even fuel-powered heating or hot-water if the boiler is electronically controlled); on the contrary, a cut-off in fuel supply usually has no incidence in the short time.

Specific energy storage data

Since energy is stored in matter (electromagnetic storage under vacuum is too small), a most important parameter is specific energy storage, i.e. energy per unit mass.

Table 1. Specific energy storage in different systems (maximum value without regard of energy spent in manufacturing, or heat-to-work conversion efficiency and auxiliary systems needed).

System	J/kg
DT (pure deuterium-tritium mix for thermonuclear fusion, $E=\Delta mc^2$ [1]	$340\cdot10^{12}$
UO_2 (enriched to 3 %, pellets ready for use in nuclear power stations), $E=\Delta mc^2$ [2]	$2\cdot10^{12}$
PuO_2 (pure plutoniun-238 dioxide; natural radioactive decay, heat), $E=\Delta mc^2$ [3]	$2\cdot10^{12}$
UO_2 ore (as found in uranium mines, with some 10 % mineral and 90 % gangue) [4]	$0.05\cdot10^{12}$
H_2O (150 ppm of deuterium hydrogen in natural water) for thermonuclear fusion [5]	$5700\cdot10^6$

H_2 (hydrogen higher heating value, HHV)	$142\cdot10^{6}$
CH_4 (methane, approximately natural gas, HHV)	$55\cdot10^{6}$
LPG (liquefied petroleum gas, propane C_3H_8, butane C_4H_{10}, HHV)	$50\cdot10^{6}$
Diesel, kerosene, gasoline (HHV)	$47\cdot10^{6}$
Fat (edible lipids HHV)	$38\cdot10^{6}$
Coal (dry), aluminium (heating value), kinetic energy in low Earth orbit ($E=½mv^2$)	$30\cdot10^{6}$
CH_3OH (methanol), hydrazine, average proteins (HHV)	$23\cdot10^{6}$
Wood (dry, HHV)	$20\cdot10^{6}$
Carbohydrates (sugars, starch, cellulose), lignite coal, biomass (HHV)	$16\cdot10^{6}$
H_2 produced by methanol or fossil-fuel reforming (HHV per mass of raw stuff)	$16\cdot10^{6}$
USW (urban solid waste, HHV)	$10\cdot10^{6}$
PEFC (low temperature fuel cell, complete with liq-H_2 or compr-H_2 at 30 MPa tank)	$8\cdot10^{6}$
TNT (lower heating value, LHV)	$4.2\cdot10^{6}$
Ammonium perchlorate composite propellant (APCP, used in solid rockets, LHV)	$4\cdot10^{6}$
H_2 contained in $LaNi_5H_6$ metal hydride (HHV per total mass)	$2\cdot10^{6}$
Li-battery (non-rechargeable Li/Cl_2OS battery, electrochemical energy)	$2\cdot10^{6}$
Ammonium perchlorate (AP, pure, LHV)	$1.4\cdot10^{6}$
Hydroelectric dam 100 m high (potential energy, $E=mg\Delta z$)	$1\cdot10^{6}$
Li-ion battery (rechargeable) and Mg/AgCl,Zn/AgO battery (non-rechargeable)	$0.8\cdot10^{6}$
Ni-Cd and Pb-acid rechargeable batteries	$0.2\cdot10^{6}$
Compressed air at 30 MPa (thermo-mechanical energy)	$0.1\cdot10^{6}$
Flywheel (kinetic energy, $E=½I\omega^2$)	$0.1\cdot10^{6}$
Electric supercapacitor (electric energy, $E=½CV^2$)	$0.03\cdot10^{6}$
Spring (elastic energy, $E=½kx^2$)	200

[1] Based on ${}^{2}_{1}H+{}^{3}_{1}H\rightarrow{}^{4}_{2}He+{}^{1}_{0}n$ +17.6 MeV (or $1.7\cdot10^{12}$ J/mol, or $340\cdot10^{12}$ J/kg of DT).

[2] Based on ${}^{235}_{92}U+{}^{1}_{0}n\rightarrow{}^{95}_{42}Mo+{}^{139}_{50}La+2{}^{1}_{0}n$ +200 MeV (or $19.3\cdot10^{12}$ J/mol or $82.1\cdot10^{12}$ J/kg of ${}^{235}U$), 88 % U in UO_2, and 3 % ${}^{235}U$.

[3] Based on ${}^{238}_{94}Pu\rightarrow{}^{234}_{92}U+{}^{4}_{2}He+5.6$ MeV (or $0.54\cdot10^{12}$ J/mol or $2.27\cdot10^{12}$ J/kg of ${}^{238}Pu$), and 88 % Pu in PuO_2.

[4] Based on ${}^{235}_{92}U+{}^{1}_{0}n\rightarrow{}^{95}_{42}Mo+{}^{139}_{50}La+2{}^{1}_{0}n$ +200 MeV (or $19.3\cdot10^{12}$ J/mol or $82.1\cdot10^{12}$ J/kg of ${}^{235}U$), 88 % U in UO_2, 0.7 % ${}^{235}U$, and 10 % mineral in the ore.

[5] Based on ${}^{2}_{1}H+{}^{3}_{1}H\rightarrow{}^{4}_{2}He+{}^{1}_{0}n$ +17.6 MeV (or $1.7\cdot10^{12}$ J/mol, or $340\cdot10^{12}$ J/kg of DT), 150 ppm D of all H-atoms, and 11 % of hydrogen mass in H_2O.

Energy storage technologies

There are many energy-storage systems, but none as handy as chemical fuels (if oxidiser are available); the only more-powerful option, nuclear systems, have shown too much harmful to life (accidents and deadly residuals in nuclear fission), or are not jet mastered (nuclear fusion). At present, fuels are so convenient to mankind that, if natural fuels were depleted, we had but to synthesise artificial fuels to store solar, wind, water, nuclear or any other kind of energy (consider how to safely carry several megajoules in one's pocket, but in a few grams of liquid fuel, in a simple plastic container as in a typical lighter). Additional properties of fuels can be found aside.

Energy storage technologies may be grouped according to the type of energy as:

- Mechanical energy
    - Kinetic energy, in flywheels. Energy stored is $E=½I\omega^2$, where I is the moment of inertia, dependent on size and material density, and ω the angular speed of the spinning body,

limited by size and material strength to some 2000 m/s of rim speed; best with magnetic bearings and under vacuum.

  - Potential energy
    - Gravitational, in water dams. Energy stored is $E=mg\Delta z$, where m is the mass stored at height Δz over the hydraulic wheels, in the gravity field g.
    - Elastic, in springs. Energy stored is $E=\frac{1}{2}kx^2$, where k is the spring constant, dependent on material and size, and x is the displacement relative to the unstressed state. Most springs are of compression-tension type (coiled metal wire), but there are torsion springs and flexural springs too (e.g. spirals and bows).
    - Pressure, in compressed gases. Energy stored is $E=mRT_0\ln\pi_0$, where m is the mass of gas stored, R=287 J/(kg·K) for air, T_0 ambient temperature, and π_0 the pressure ratio between the reservoir and the environment. Notice that this is the thermodynamic limit; only about a half of it might be recovered in practice. Instead of using just the stored air in the output turbines, best results are obtained by using the compressed air to feed a combustion chamber (with fuel addition) before entering the turbines. The largest such a store, the Huntorf plant in Germany, can provide 290 MW during 4 hours, taking 400 kg/s of compressed air and some 9 kg/s of natural gas, both from separate 310 000 m^3 old-salt-caverns about 600 m underground, while stored air pressure decreases from 7 MPa to 5 MPa (the plant may deliver additional energy at an exponentially-declining power level for over 10 more hours).
- Chemical energy
  - Thermochemical, in fuels (fuel and oxidiser really). Energy stored is $E=mh_{\mathrm{HHV}}$, where m is the fuel mass, and h_{HHV} the fuel higher heating value (really a fuel and an oxidiser react, but all the effect is ascribed to the fuel because the oxidiser is usually free-available as air. Notice that this is the thermal energy that would be released (e.g. in a combustion process), but the useful work storage (exergy) is smaller, typically curtailed by thermodynamic conversion efficiencies to a half or a third of the HHV.
  - Electrochemical, in batteries. Energy stored is commonly stated indirectly in Amper·hour [Ah], which multiplied by the nominal voltage, gives an approximation of the energy storage (1 V·Ah=1 Wh=3600 J). Theoretically, electrical energy stored would be $E=mg_{\mathrm{r}}$, where m is the mass of reactives, and g_{r} the reaction free enthalpy (Gibbs potential of reaction), but in practice the reaction cannot be completed in either way, charging or discharging. Notice that, contrary to fuel storage, both a reducer and an oxidiser are stored in a battery, what, in addition to non-reacting items in the latter, means that for the same exergy storage a battery-pack weights about 20 times more than a fuel-filled tank (e.g. a 100 kWh battery pack in an electric car weights about 500 kg (e=0.7 MJ/kg=0.2 kWh/kg), whereas the same work can be delivered from a 23 kg gasoline tank with a heat engine of 30 % efficiency).
- Nuclear energy, the most condensed form of energy (see footnotes in Table 1); it is presently only a primary storage (i.e. found in nature), since we do not master yet the synthesis of nuclear fuels (particle accelerator colliders are extremely inefficient in energy terms).

- Electrical energy
  - Electrostatic, in capacitors. Energy stored, in the electric field, is $E=\frac{1}{2}CV^2$, where C is the capacitance, dependent on size and material, and V the electrical potential difference, limited by dielectric breakdown. Supercapacitors are a variety of electrochemical capacitors.
  - Electromagnetic, in superconducting coils. Energy stored, in the magnetic field, is $E=\frac{1}{2}LI^2$, where L is the inductance of the coil, dependent on coil size, and I the electrical current, limited by conductor size, material, and temperature, which must be cryogenic. A voltage applied across the coil serves to add or remove energy in it.
- Thermal energy (conversion of thermal energy to mechanical or electrical energy may have efficiencies of much less than 50 %, compared most others with about 90 %):
  - Temperature, in heated or cooled media (or both, as on pumped heat electricity storage systems). Energy stored is $E=mc\Delta T$, where m is the mass heated or cooled a ΔT relative to the environment, and c the thermal capacity, only dependent on the storing material.
  - Phase change, in molten salts, ice slurries, etc. Energy stored is $E=mh_{\mathrm{PC}}$, where m is the mass that transforms, and h_{PC} the enthalpy for the phase change. Energy storage in phase change materials (latent heat) is more efficient than on simple temperature change (sensible heat).

Other features in energy storage

There are several different time and size scales important in matching energy demand:

- Specific energy storage, i.e. energy per unit mass [J/kg], may rank differently than energy density (i.e. energy per unit volume [J/m^3]); e.g. H_2 has the most HHV per mass, but the less HHV per volume.
- Specific power, i.e. [W/kg] instead of [J/kg], measure energy rate, and is limited by discharge rate of reservoir (e.g. an electrical battery or a water dam), by burning rate in fuel combustion, by heat-transfer rate in nuclear power, and so on; e.g. electrical capacitors have very high specific power, but very low specific energy. Specific power is often assigned to engines with no energy-store inside, in the understanding that a suitable energy source is available, as when saying that car engines have some 1 kW/kg and jet engines 5 kW/kg. When specific energy is ascribed to such an engine, some additional energy amount is assumed (e.g. a car engine with its fuel tank).
- Operation time, ranging from very short laser pulses to several-years heating or cooling capacity of spacecraft-embarked systems. A concise way to present energy-storage technologies is by plotting specific-energy values versus specific-power values, as in Fig. 1 (known as Ragone plots, 1968), so that diagonals (of unitary slope) correspond to constant operation periods. Sometimes only the region of optimum use of a technology is depicted in such plots (i.e. when both specific-power and specific-energy are high), as when saying that rechargeable Li-ion batteries are best used for applications running in the hour-range, with specific power around 100 W/kg and specific energy around 100 kJ/kg, in spite of the fact that they can be used for shorter times with higher powers, and for longer periods with smaller power, as indicated in Fig. 1. It can be appreciated that internal combustion engines (ICE) are often the best power-source solution.
- Recharging efficiency, i.e. useful energy output divided by useful energy input in a cycle. Most energy stores must be regenerated for sustainability (to avoid squandering of means in single-shot

and expandable systems). For instance, modern Li-ion rechargeable batteries hold 0.7 MJ/kg and deliver 97 % of the energy expended in recharging, whereas envisaged regenerative fuel cells (PEM-type fuel cell electrolyser) are expected to hold 2 MJ/kg but to deliver only 50 % of the energy required to recharge them.

- Energy capacity [J], or power capacity [W], often not directly scalable because of logistic constraints; e.g. huge amounts of energy, besides natural fuel reserves, are only practical at present by means of pumped hydraulic reservoirs, or compressed air in caves; on the other end of sizes, the only suitable power source at present for portable electronic devices, demanding less than few watts during several hours, is the electrochemical battery. We are far from the mastery of minute power sources (e.g. like those we can see on insects).
- Other logistic performances of energy storage and power generation must be considered, like weight and volume (particularly in vehicles), modularity, response time, recharging time, storage life, operating life, whole-life pollution, safety, and, of course, price. For instance, great savings, in both energy and pollution, are obtained with hybrid-engine cars, working on electrical batteries when speed is lower than say 50 km/h (city traffic) and on internal combustion engine (ICE) at higher speeds or during rapid acceleration, because not only idle ICE running is avoided, but most of the start-stop transients; however, logistic problems are widely different on full electric cars. It is worth comparing the price of energy, about 10^{-1} €/kWh (for grid electricity or gasoline), with the price of the energy-storage system; e.g. about 10^{2} €/kWh for a 80 Ah car-battery or a similar uninterruptible power supply for the PC.

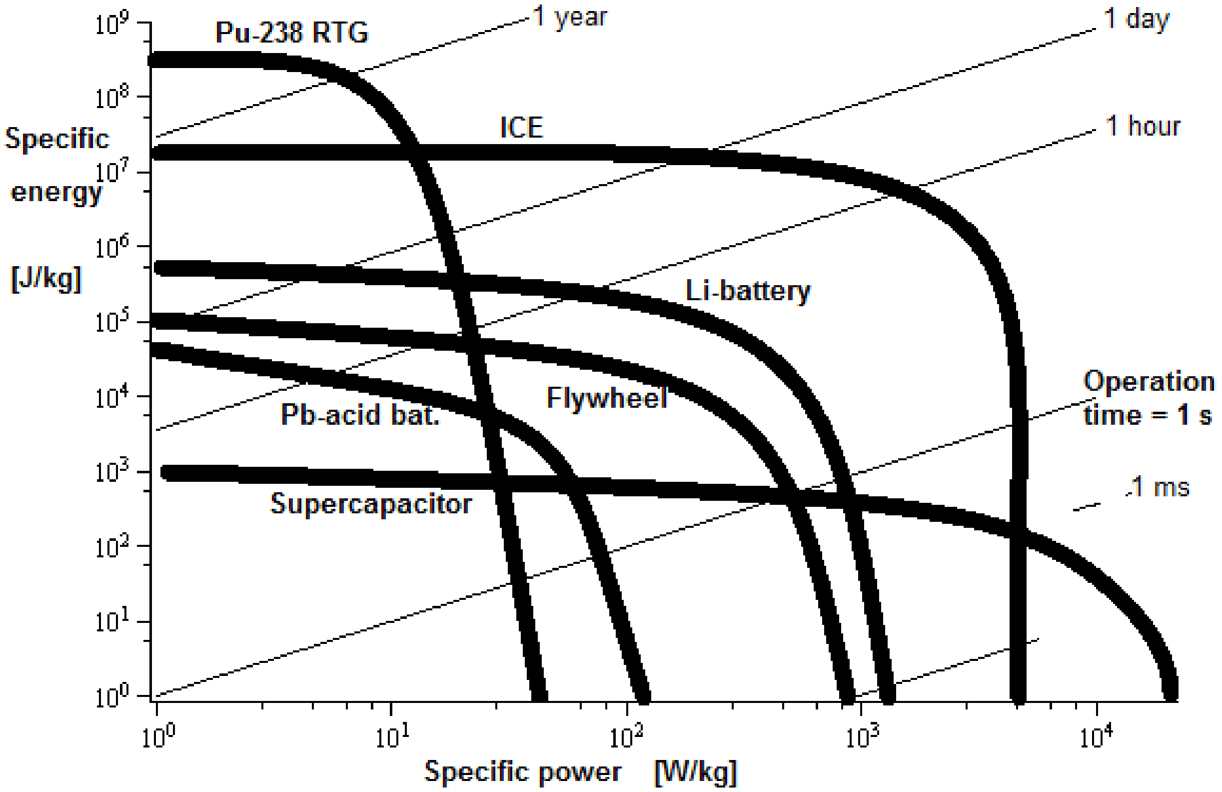

Fig. 1. Specific energy versus power density for several power-generation devices (Ragone chart). The size of the system may not be scalable to low-mass or high-mass systems (e.g. the flywheel curve applies to large advance systems; conventional flywheels may have a tenth of those values). Fuel cells can match ICE in specific energy, but are less efficient in specific power. Thermal energy systems are not shown because of the large variety of configuration and efficiencies involved, but specific energy is limited to some 10^{5} J/kg in the best phase-change systems (e.g. molten salts used in solar towers), and specific power is limited by heat-exchanger design to some 10^{2} W/kg.

As a rule of thumb to compare specific energy (or energy density) of different propulsion systems, Table 2 may be a first approximation.

Table 2. Specific energy storage in typical propulsion systems.

System	MJ/kg	kWh/kg
Compressed air system	0.1	0.03
Limit of modern carbon-fibre flywheels	0.3	0.1
Li-ion batteries (excluding electric motor)	1	0.3
Fuel cells (including fuel, and reformer if needed)	3	1
Heat engine for city car (including fuel system)	10	3
Heat engine in airliner (including fuel system)	30	10
Pu-238 with thermoelectric generator (without motor)	10^5	$30\cdot10^3$

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