Foreword

Sources of energy: density of stored energy

Energy sources are all stored, whether on a geological scale or greater (the sun), and the stores are used up according to need (the idea of “renewables” therefore is only meaningful when considering human timescales). We can distinguish the primary source of fossil fuels that exist “naturally” and for which we only pay the cost of extraction, from secondary sources, which are man-made, and for which we must pay for both storage and extraction.

Sources	Unit of time
Biomass	Years
Oceanic thermal gradients	Hundreds of years
Fossil fuels	Millions of years
Tides/waves	Hours
Geothermal	Days - years
Thermal mass	Hours
Batteries	Minutes
SMES	Seconds
Capacities	Seconds
Hyraulic pumping	Hours

Table 1. *Time required to replenish sources (source: W.A. Hermann, Quantifying Global Energy Resources, Science direct, Elsevier 2005)*

Foreword written by Yves BRUNET.
We may also refer to the chapter “Energy storage: applications related to the electricity vector” by the same author, in *Low Emission Power Generation Technologies and Energy Management*, ISTE / John Wiley, 2009.

In this work we will primarily be interested in these secondary forms of storage.

The energy that can be exploited is not only stored in nature under various forms, but is also stored with very different densities (Figure 1).

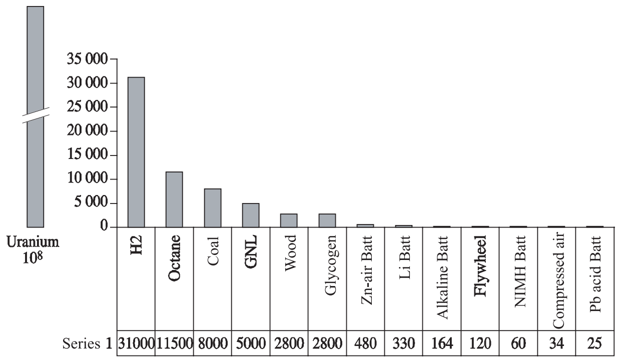


Figure 1. *The density of energy stored in materials or storage components varies greatly. The figure above shows the great advantage of fossil fuel sources over secondary storage sources. Nuclear sources are even more concentrated as we can obtain 10^8 Wh/kg from fission of natural uranium*

The range in the amounts of energy usage is such that it is good to consider a few simple applications: what can be done with 1 kWh?

We can:

– drive 1 km with a car that consumes 8 liters per 100 km;

– run a refrigerator for a day;

– light a house for an evening;

– make 200 g of steel or 100 g of plastic.

On average, the total amount of energy consumed in France, for each inhabitant, comes to 40 MWh/year, which is 4.5 kWh/hour per person.

Conversion of stored energy

Stored energy is released, according to target applications, either in the form of power (W), or in the form of energy[1] (J or Wh), which is sustained power over a

[1] 3,600 J = 1Wh, 1 MWh = 0.0857 toe (ton of oil equivalent), 1 tep = 11.7 MWh.

certain amount of time. Storage sources, which combine a quantity of stored energy with power that is instantaneously available, are often useful.

The storage strategy may lead to a range of different solutions (Figure 2).

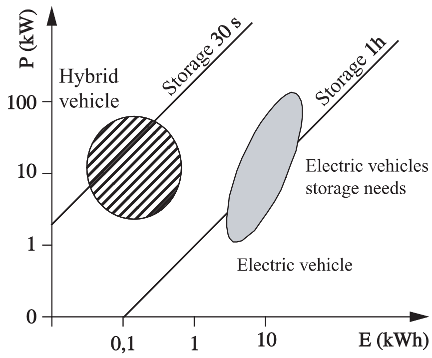


Figure 2. *The requirements of an electric vehicle. A hybrid vehicle essentially needs stored power, whereas an electric vehicle will need both power and energy. For a hybrid vehicle, the amounts required are of the order of 12 Wh/kg and 500 W/kg, with available energy of 300 Wh and available power of 10 kW over 2 seconds and a lifetime of 15 years*

Energy is brought to the user by an energy carrier, after transformation and conversion to the most suitable form possible for the target application. Electricity is one of these forms, without doubt the most flexible form known to this day (Figure 3).

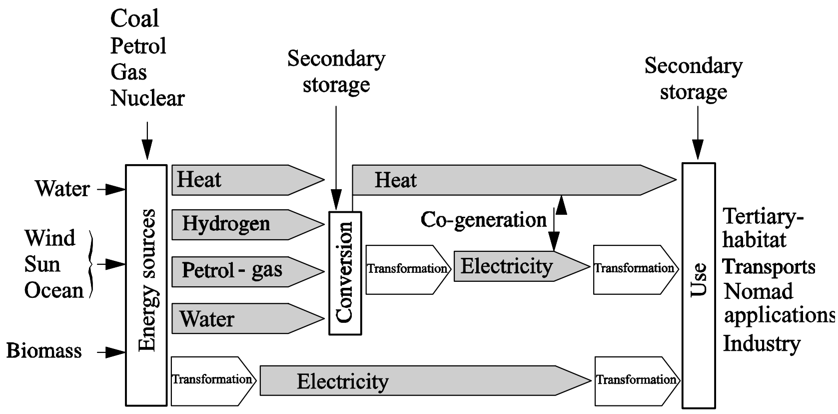


Figure 3. *Principal energy carriers*

The problem of energy storage is both technical and economic, and the solutions depend very much on the target applications (see Chapters 1-5). Regarding energy storage for technologies linked to the electricity carrier, this is not of immediate interest, particularly in the case of networks, and at least two opposing situations can be distinguished:

− onboard systems (mobile or portable applications, etc.), which carry their energy with them in order to ensure autonomous functioning, or pulsing systems for which storage acts as a "buffer" that releases the necessary high power;

− coupled systems (networks), which put into play high energy and high power.

The special case of pulsing systems[2]

A pulsing system stores energy and releases it in a very short time. In general, the energy is stored in electromagnetic form (an electric or magnetic field) and delivered in a very brief time (several milliseconds) as a result of a rapid switch. Therefore, for an amount of stored energy W, the power, P=W/t, can be very large.

In the case where energy is stored by a series of capacitors (Marx generators), several parameters are involved in the release of energy:

− the electrical characteristics of the storage circuit (R, L, C);

− the electrical characteristics of the charge impedance (R, L, C);

− the initial conditions;

− the characteristics of the switching system (R, L, t).

The voltage can reach several megavolts, for currents of several mega-amperes. Pulsing systems can be single shot or can go up to several kilohertz.

A capacitive system includes capacitances and a closing switch (V). An inductive system includes inductances and both closing (I) and opening (V) switches.

Switching devices can be of the following types:

− gaseous: pressurized spark gaps, ignitrons, thyratrons, etc.;

− semi-conductor: thyristor, GTO, IGBT, MOSFET, SRD diodes, etc.;

− solid: fuse.

2 I would like to thank Jean-Claude BRION (Europulse) for help with the editing of this section.

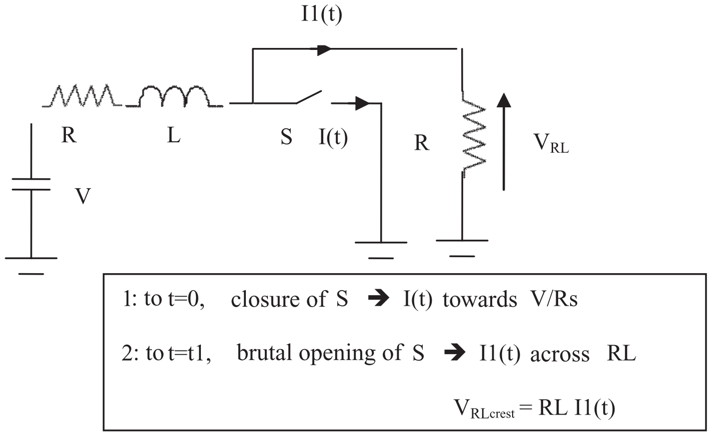


Figure 4. *Inductive storage for a voltage generator: the principle is to generate current in an inductance, and then to force the current to cross an impedance in a given instant. This technology requires a sharp opening switch*

In the case of capacitive storage, Marx generators enable a high voltage to be generated by charging capacitors in parallel and discharging them in series.

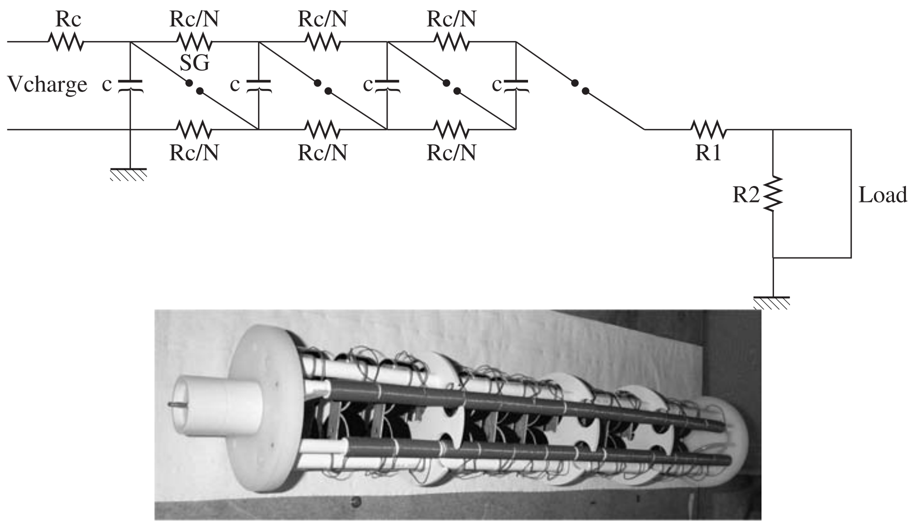


Figure 5. *Marx generator: diagram and photograph of a compact generator with 13 stages of 5.2 nF. 40 kV, 6 kJ/s. Vmax = 350 kV, mounting time = 15 ns, width of pulse = 50 ns, rate of repetition = 115 Hz*

Pulsed energy is used in several domains, industrial as well as research based. Among the applications using pulsed power-based systems, we can cite radar, particle accelerators, creation of very high magnetic fields, lasers, electric cannons (railgun) etc.

The special case of electrical networks

This case will be detailed in Chapter 1. Here, we outline the principal characteristics of storage in electrical networks. The storage problem takes on a greater level of seriousness when looking at electrical networks. As electricity is not readily stored in an efficient manner and in useful quantities, it is necessary to constantly adapt the power supplied to the power demanded, whilst recognizing that this fluctuates according to the time of day and season (Figure 6). Storage technologies break this link by allowing production and storage of electricity for later use.

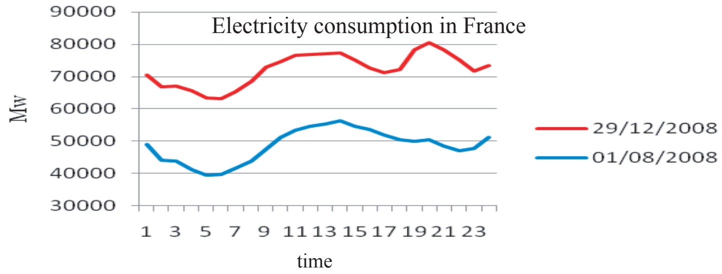


Figure 6. *Electricity consumption in France (source: RTE)*

It is therefore necessary to store energy in an intermediary physical form (mechanical, thermal, chemical, etc.) and to convert this stored energy into electricity (battery, generator, etc.) by incorporating energy converters, based on power electronics, whose efficiency (of the order of 80% to 90%) nevertheless has energy and financial costs.

In the energy chain, storage can be used in every one of these steps (Figure 7).

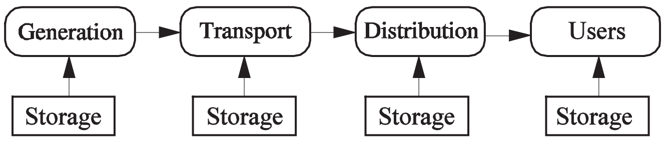


Figure 7. *Points where storage can be inserted within a network*

Storage technologies must demonstrate technical viability and economic interest. The cost of energy, linked to its variability according to time of day and of year (due to the supply and demand law in a market, which is increasingly open) and the difference between this cost at peak and off-peak times, are parameters that determine the degree of interest in adding storage. Storage is a means of adding flexibility competing with other factors:

– the value of the storage depends very much on the technology used and on its sizing compared to the predicted usage;

– the same type of storage can have a different value on different markets and for different agents;

– several factors have a strong influence on the value that agents can give to storage, such as the energy mix, the level of congestion on the network, etc.

A storage system can play different roles and can be, for example:

– a peak-time electric power station;

– a source of charge smoothing (harnessing transits over targeted work);

– a way to maintain the quality of the current, voltage, and frequency;

– a support to the network during downgraded function;

– a promotion permitting investment;

– a stabilizing function in a context where renewables have properly penetrated the market.

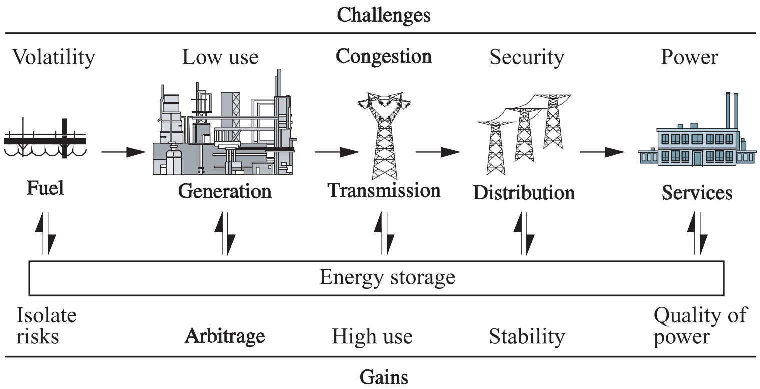


Figure 8. *Storage brings answers to problems in electrical networks (source Energy Storage, The Missing Link in the Electricity Value Chain: An ESC White Paper, Published by the Energy Storage Council, May, 2002)*

There are also intermediary situations (micro-networks, isolated systems, etc.), which often use intermittent energies (wind power, solar energy, etc.) for which the storage solutions must be studied according to technical and economic criteria. Storage, therefore, enables us to resolve the problem of intermittence of renewables by allowing us to:

– maximize the use of photovoltaic electricity;

– consume energy at the place of production and increase energy efficiency;

– increase the flexibility and efficiency of energy management;

– ensure safety of the user in the case of network outage.

Following the target applications, several technical and economic parameters (investment costs, energy or power densities, cyclability, impact on the environment, etc.) influence the choice of storage technologies (Figure 9). These different technologies will be detailed in Chapter 6 and later chapters.

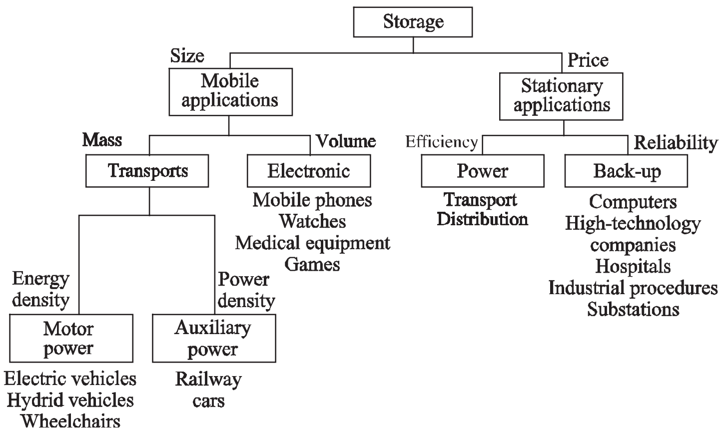


Figure 9. *Constraints and criteria for choosing storage technology based on applications*

If we look again at Figure 6, we see that using storage to account for increases beyond the average daily consumption of electricity leads to a requirement to store several tens of gigawatt hours. At the user level, the problems are different as the quantities of power are much lower, and it might be interesting to consider storage solutions closer to where they are needed[3] (Figure 10). Storage is a way to

3 EPRI 2.4 kW, 15 kWh Salt River Residential Photovoltaic-Battery Energy Storage System Project 1997.

guarantee the quality of the energy at user level (UPS, Uninterruptible Power System).

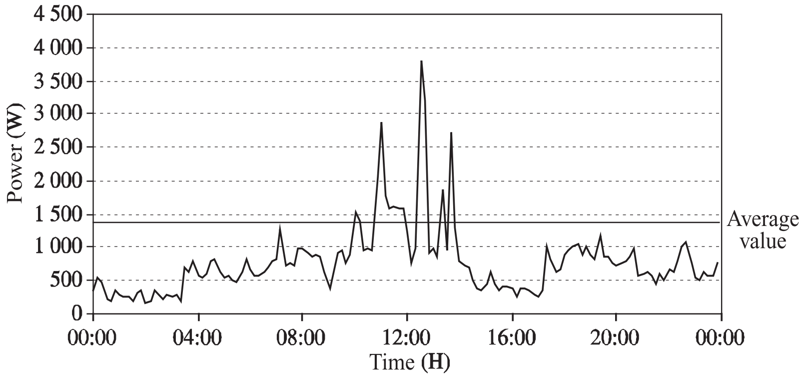


Figure 10. *Daily consumption for a house (November 2005[4]). Instead of installing 6 kW of power, corresponding to a standard power that is already higher than the maximum necessary, we could install 1 kW of power connecting to the network (average value = 780 kW) and linked to storage system of 4 kW,4 kWh, which would be able to deal with peak times*

However, the financial cost resulting from instantaneous interruptions or from prolonged interruptions (blackouts) of the electrical network is very important as the network today touches all sectors of the economy (it is calculated to be several tens of billions of dollars per year in the USA)[5] and this cost must be compared to that of the storage systems that could reduce the risks of interruption.

Power and energy must be globally managed using network management systems that use ICT (Information and Communication Technology) at the network-operator level, even more in the presence of distributed production. In addition to their traditional function of control-command, these systems are also capable of managing the entire production, storage, and charge using virtual power stations.

Storage technologies

The two tables below summarize the different storage technologies alongside their domains of application.

4 Doc GIE IDEA (Tuan Tran Quoc).
5 Communication J ETO EESAT 2004.

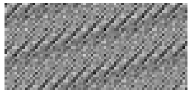
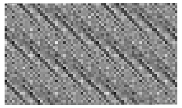
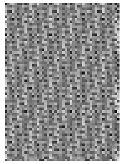
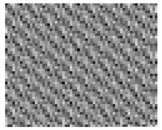
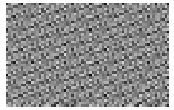
Technology	Gravity hydraulics	Underground compressed air	Electrochemical batteries	Circulation batteries	Heat and turbine
					
Energy density	1 kWh/m³ for a drop of 360 m	12 kWh pr m³ of underground space at 100 bars	Lead battery: 33 kWh/t Li-ion battery: 100 kWh/t	**33 kWh/m³**	**200 kWh/m³**
Achievable capacity	**1000 - 100000 MWh**	**100 - 10000 MWh**	**0.1 - 40 MWh**	**10 - qq 100 MWh**	**1000 - 100000 MWh**
Achievable power	100 - 1000 MW	100 - 1000 MW	0.1 - 10 MW	1 - qq 10 MW	10 - 100 MW
Electricity Efficiency	**65%-80%**	50% (with the support of natural gas)	70% per month in rapid discharge	**70%**	**60%**
Installations existing	**100 000 MWh 1000 MW**	**600 MWh 290 MW**	**40 MWh 10 MW**	**120 MWh 15 MW**	–
Cost E/kWh E/kW	70 to 150 600 to 1500	50 to 80 400 to 1200	200 (Pb) to 2000 (Li) 300 (Pb) to 3000 (Li)	100 to 300 1000 to 2000	50 350 to 1000
Maturity	Very good	Several examples throughout the world	Several examples throughout the world	Working prototypes in development	Planning stage
Notes	Site with altitude difference and water reserves	Underground site	Heavy metals	Chemical products	Independent of geographical constraints

Table 2. *Storage technologies of high capacity (source CEA)*

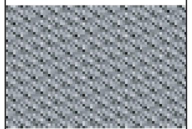
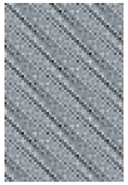
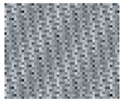
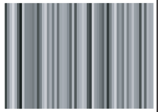
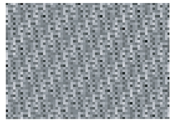
Technology	Inductive superconductor	Supercapacitor	Electrochemical	Flywheel	Bottled compressed air	Reversible PAC hydrogen
						
Energy form	Magnetic	Electrostatic	Chemical	Mechanical	Compressed air	Fuel
Energy density (only accumulator, without attached equipment)	1 to 5 Wh/kg	**10 Wh/kg → 60Wh/kg**	20 to 120 Wh/kg	1 to 5 Wh/kg	**8 Wh/kg (200 bars)**	300 to 600 Wh/g (200 to 350 bars) without PAC
Achievable or achieved capacity	several kWh	several kWh	several Wh to several MWh	several kWh to several 10 kWh	several kWh to several 10 kWh	N/A
Time constant	several seconds to 1 mn	several seconds to several minutes	several 10 minutes (NiCd) to several 10 hours (Pb)	several minutes to 1 hour	1 hour to several days (little autodischarge)	1 hour to several days (little autodischarge)

Table 3. *Storage technologies of average and low capacity (source CEA)*