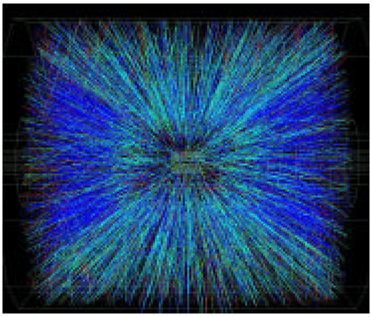
LESSON 6.
ENERGY STORAGE



Contents (I)

- Introduction.
- Choosing an energy storage method.
- Classification of energy storage methods.
- Mechanical energy storage methods.
  - Pumped hydro storage.
  - Compressed air.
  - Flywheels.
- Chemical and electrochemical storage.
  - Hydrogen.
  - Batteries.

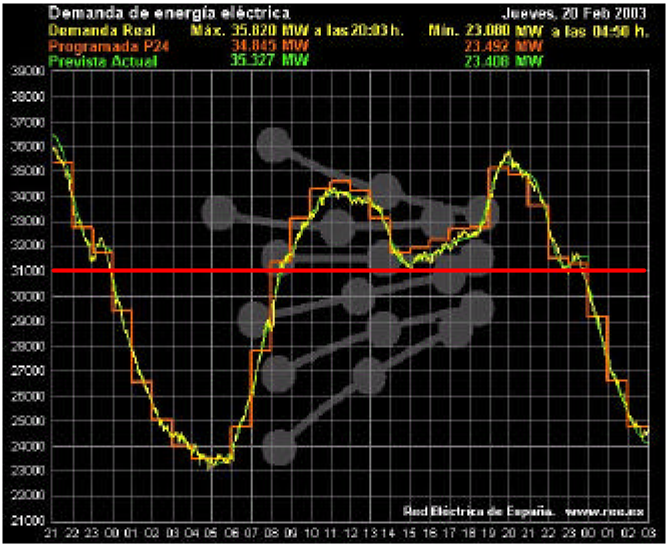
Contents (II)

- Chemical and electrochemical storage.
  - Hybrid electric vehicles.
  - Reaction enthalpies.
- Thermal storage methods.
  - Sensible heat.
  - Latent heat.
- Electric and magnetic storage.
  - Capacitors.
  - Magnetic fields.
- Bibliography.

Introduction (I)

- Main problem of an Energy System: to match supply and demand of energy.
- Transport sector: energy demand is variable over time Þ engine (M.A.C.I.) Þ no storage, the clutch is used to produce or not to produce movement (energy losses).
- Electricity supply: the demand varies along the day Þ power plants not adaptable.
- Electricity: principal application of energy storage.

Introduction (II)



Introduction (III)

- Solution to electricity supply: to generate a mean value between the maximum and the minimum, to store the energy when the demand is lower and to recover it when the demand is greater.
- Storage advantage: fast answer to a change in the demand (relative to the startup of a generation system).
- Why is important the energy storage?:
  - Fuels costs increase.
  - Energy demand increases.
  - Social awareness: saving and pollution.

Introduction (IV)

- Large scale energy storage systems: electricity power plants and large factories.
- Medium and small scale: solar and wind power plants. Variability of the supply due to weather changes.
- The energy storage system means a saving in initial investment (the power system works at a lower level of load) and in fuel. The energy storage system cost must be recouped.
- Disadvantage: energy storage density (J/kg or J/m^3) less than fossil fuels.
- Oil: 40 MJ/kg; coal: 29 MJ/kg; natural gas: 50 MJ/kg.

Choosing the method (I)

- Storage methods work by applying a transformation to spare energy and applying the reverse transformation to recover it.
- The most important parameter is the efficiency of the transformations.
- Economic parameters:
  - Cost per kW of the transforming systems (to store and to recover the energy).
  - Cost per kW of the storage system.

Choosing the method (II)

- Energy Parameters:
  - Efficiency of the storage transformation.
  - Storage capacity of the system:
    - Energy density.
    - Supply time to a steady load.
  - Efficiency of the recovering transformation.
  - System useful life: number of storage/recovering cycles.
  - System use function: storing system output/production system output (relative to storage capacity).

Choosing the method (III)

- Safety: storage system and transformation systems designed to be non-destructive to life and property.
- The choice must be a compromise between the method with the highest storage capacity and the one which is most economically favourable.

Choosing the method (IV)

- Ideal storage system equation:

$$\frac{dE_s}{dt} = \dot{W}_{in}(t) - \dot{W}_{out}(t) - \dot{Q}(t)$$

- E_s is the energy in the storage system.
- $\dot{W}_{in}(t)$ is the input power.
- $\dot{W}_{out}(t)$ is the output power demanded by the user.
- $\dot{Q}(t)$ are the energy losses. Function of:
  - System state properties (temperature, speed,…).
  - Time.

Choosing the method (V)

- Storage system performance condition:
  - The power input must be such as to make up for losses, to ensure that over a cycle time, t_{max}, the change in stored energy is zero:

$$\int_0^{t_{max}} \frac{dE_s}{dt} dt = 0 \Rightarrow \int_0^{t_{max}} \dot{W}_{out}(t)dt = \int_0^{t_{max}} \left(\dot{W}_{in}(t) - \dot{Q}(t)\right)dt$$

- Storage efficiency:

$$\eta_s = \frac{E_{out}}{E_{in}} = \frac{\int_0^{t_{max}} \dot{W}_{out}(t)dt}{\int_0^{t_{max}} \dot{W}_{in}(t)dt}$$

Choosing the method (VI)

- Main parameters:
  - Storage efficiency.
  - Output power and the cycle time: determine the size and the cost of the storage system.

Classification (I)

- By type of energy source:
  - Electrical storage: spare electric energy is stored.
  - Thermal storage:spare thermal energy is stored.
- Electrical storage systems:
  - Most widely used method (power plants).
  - Mechanical storage:
    - Pumped hydro storage: potential energy.
    - Compressed air: potential and thermal energy.
    - Flywheels: kinetic energy.

Classification (II)

- Electrical storage systems:
  - Chemical and electrochemical storage:
    - Hydrogen.
    - Batteries.
  - Electrical and electromagnetic storage:
    - Capacitors and ultracapacitors.
    - Magnetic fields and superconductor rings.

Classification (III)

- Comparing some electrical storage systems:

System	Power Density (kW/kg)	Energy Density (Wh/kg - MJ/kg)	Mean life (No. of cycles)
Compressed air	10	180 - 0.65	10,000,000
Lead-acid battery	0.2	50 - 0.18	1,000
Nickel-cadmium battery	0.2	50 - 0.18	2,000
Steel flywheel	10	55 - 0.20	100,000
Fused silica flywheel	-	870 - 3.13	100,000

Classification (IV)

- Thermal storage systems:
  - Thermal storage:
    - Sensible heat.
    - Latent heat.
  - Chemical storage:
    - Reversible endothermic reactions enthalpy.

Classification (V)

- By type of stored energy:
  - Mechanical storage:
    - Pumped hydro storage: potential energy.
    - Compressed air: potential and thermal energy.
    - Flywheels: kinetic energy.
  - Chemical and electrochemical storage:
    - Hydrogen.
    - Batteries.
    - Reaction enthalpy.
  - Thermal storage:
    - Sensible heat.
    - Latent heat.
  - Electrical and electromagnetic storage.

Classification (VI)

BY TYPE OF ENERGY SOURCE

- ELECTRICAL
  - MECHANICAL
    - PUMPED HYDRO STORAGE
    - COMPRESSED AIR
    - FLYWHEELS
  - CHEMICAL AND ELECTRO-CHEMICAL
    - HYDROGEN
    - BATTERIES
  - ELECTRICAL AND MAGNETIC
    - CAPACITORS
    - MAGNETIC FIELDS
- THERMAL
  - THERMAL
    - SENSIBLE HEAT
    - LATENT HEAT
  - CHEMICAL
    - REACTION ENTHALPY

BY TYPE OF STORED ENERGY

Classification (VII)

POR PROCEDENCIA ENERGÍA

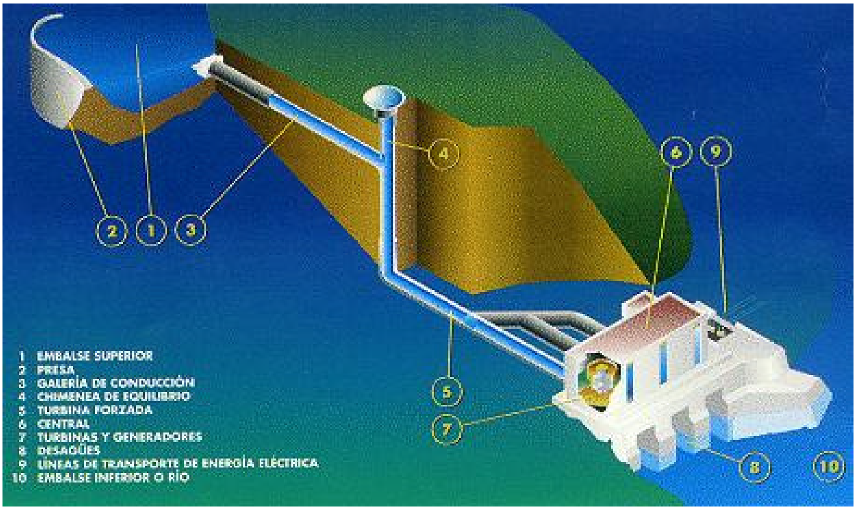
- ELÉCTRICOS
  - MECÁNICO
    - BOMBEO HIDRÁULICO
    - AIRE COMPRIMIDO
    - VOLANTES DE INERCIA
  - QUÍMICO Y ELECTROQUÍMICO
    - HIDRÓGENO
    - BATERÍAS
  - ELÉCTRICO Y MAGNÉTICO
    - CONDENSADORES
    - CAMPOS MAGNÉTICOS
- TÉRMICOS
  - TÉRMICO
    - CALOR SENSIBLE
    - CALOR LATENTE
  - QUÍMICO
    - ENTALPÍA DE REACCIÓN

POR FORMA DE ENERGÍA ALMACENADA

Pumped hydro storage (I)

- Most highly developed and widely used method.
- Storage of a mass of water in form of gravitational potential energy.
- Example: 1,000 kg (= 1 m^3) raised to 100 m Þ $E = m \cdot g \cdot z$ = 9.8·10^5 J » 1 MJ = 0,2725 kWh.
- It is neccesary to store great amounts of water at large height.
- Appropriate topography: two big reservoirs, big height difference and small horizontal distance.
- Elevated reservoir (dam) or natural underground cavity.

Pumped hydro storage (II)

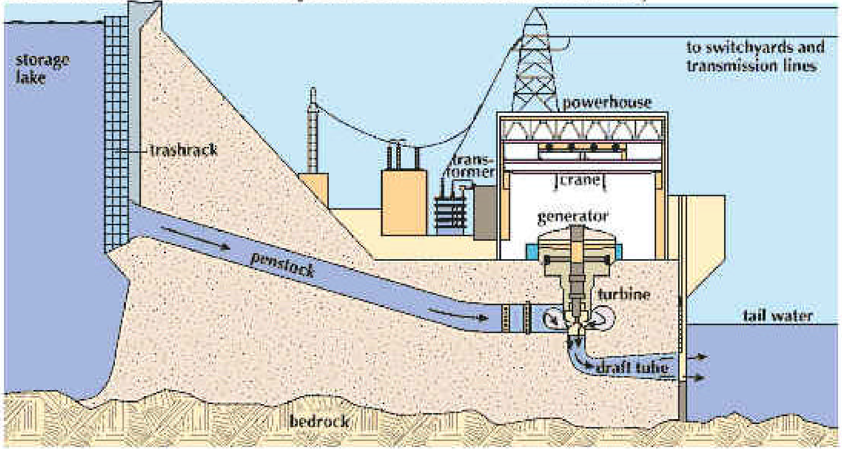


Pumped hydro storage (III)

- Two types:
  - Pure pumping power plant: diversion between two reservoirs or dams without supply of outside water (only for leakages).
  - Mixed power plant with pumping: water provided by river in upper dam (hydroelectric power plant).
- They work with reversible pump-turbine.
- Losses: pump and turbine efficiencies, piping head losses, leakages and evaporation.

Pumped hydro storage (IV)

How a Dam Uses Waterpower to Generate Electricity



Pumped hydro storage (V)

- Global efficiency: » 65-75%.
- Stored energy: between 200 and 2.000 MWh.
- Main Spanish pumping power stations:

Power plant	River	Province	Power (MW)
Villarino	Tormes	Salamanca	810
La Muela (*)	Júcar	Valencia	628
Estany-Gento-Saliente (*)	Flamisell	Lérida	451
Aldeadávila II	Duero	Salamanca	421
Tajo de la Encantada (*)	Guadalhorce	Málaga	360
Aguayo (*)	Torina	Cantabria	339
Conso	Camba-Conso	Orense	228
Valdecañas	Tajo	Cáceres	225
TOTAL			5.120

(*) Pure pumping power plant

Pumped hydro storage (VI)

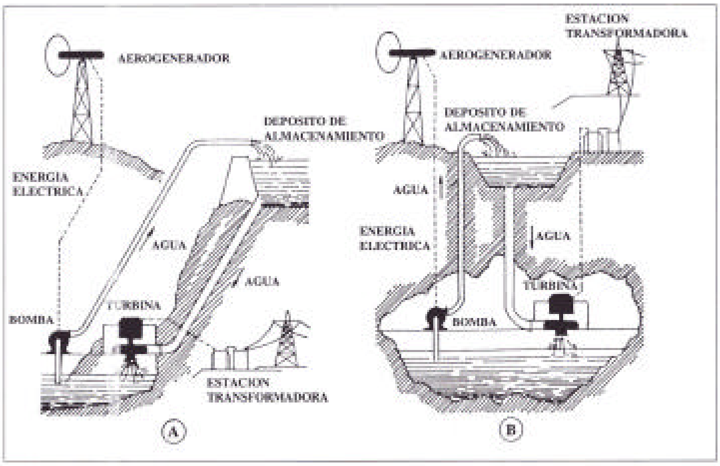
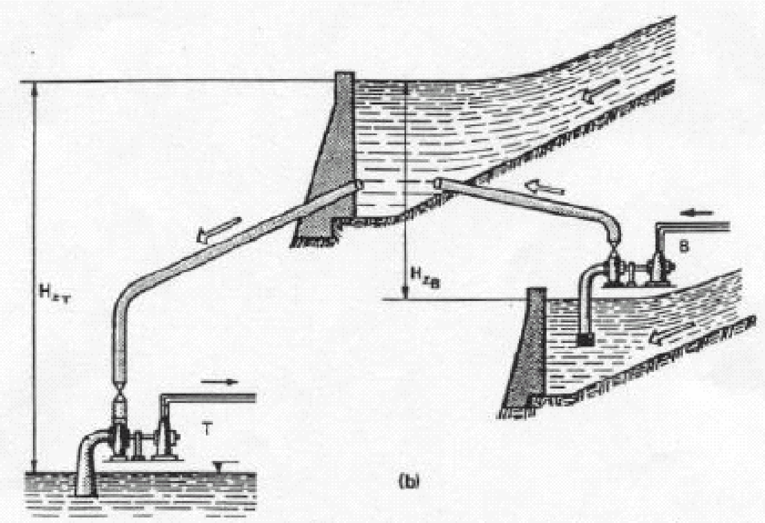


Figura 8.12: Almacenamiento por bombeo de agua:
A) En embalses elevados.
B) En cavernas subterraneas.

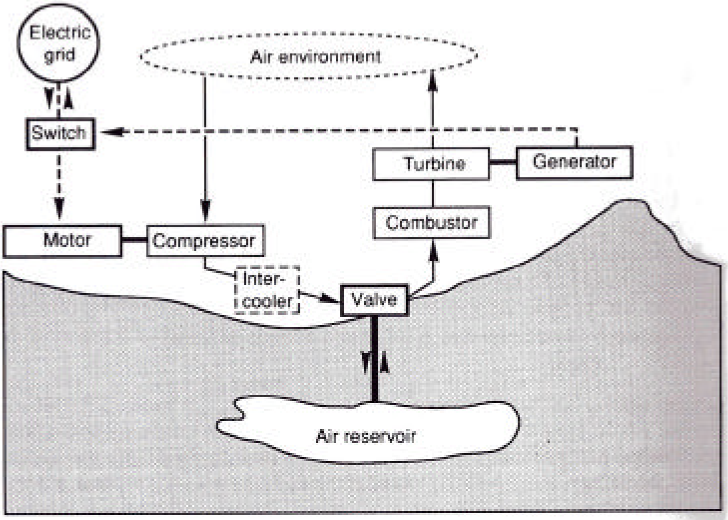
Pumped hydro storage (VII)



Compressed air (I)

- Compressed Air Energy Storage Systems: CAES Systems.
- Spare energy Þ compression of air in a natural underground cavity Þ energy recovered by expansion in a gas turbine.
- The system is a gas turbine engine with a temporal separation of the compression and expansion processes.
- Efficiency similar to pumped hydro storage: 70-75%.
- Cavities: salt caves, aquifers and rock caves.
- Two storage methods: adiabatic and hybrid.

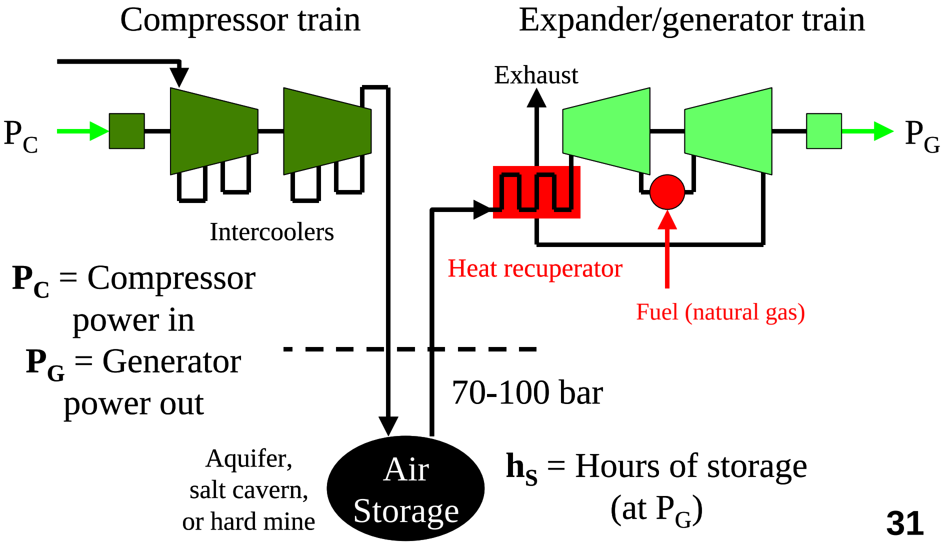
Compressed air (II)



Compressed air (III)

- **Adiabatic method:**
  - **The energy of the heating during the compression is stored in the air or in an auxiliary system and it is returned before the expansion.**
  - **Advantage: For the same pressure ratio, the work of the turbine is proportional to the input temperature.**
- **Hybrid method:**
  - **The compression heat is “removed” to the environment and heat is added by combustion before the expansion.**
  - **Additional costs of operation and maintenance.**

Compressed air (IV)



P_C = Compressor power in

P_G = Generator power out

h_S = Hours of storage (at P_G)

Compressed air (V)

- **System governing equations Þ mass and energy conservation equations:**

$$\frac{dm}{dt} = \frac{d(r\cdot V)}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$\frac{dE_s}{dt} = \frac{d(m\cdot c_v\cdot T)}{dt} = \frac{d(r\cdot V\cdot c_v\cdot T)}{dt} =$$

$$= \frac{1}{g - 1}\frac{d(P\cdot V)}{dt} = \dot{m}_{in}h_{in} - \dot{m}_{out}h_{out} + \dot{Q}$$

where $g = c_p/c_v$ is the adiabatic exponent.

Compressed air (VI)

- **Work in the compressor:**

$$\dot{W}_c = \dot{m}_{in} c_p (T_2 - T_1) = \frac{\gamma}{\gamma - 1} \frac{\dot{m}_{in} c_p T_1 \left[1 - \left(P_2 / P_1\right)^{\gamma - 1/\gamma}\right]}{\eta_c}$$

- **Heat in the combustor:**

$$\dot{Q}_f = \frac{\dot{m}_{out} c_p (T_4 - T_3)}{\eta_{comb}}$$

- **Work in the turbine:**

$$\dot{W}_t = \frac{\gamma}{\gamma - 1} \eta_t \dot{m}_{out} c_p T_4 \left[1 - \left(P_4 / P_3\right)^{\gamma - 1/\gamma}\right]$$

- **Net efficiency:** $\eta_{total} = \dfrac{W_t}{W_c + Q_f}$

Compressed air (VII)

- **The storage volume depends on pressure for the same storage capacity ⇒ we are interested in high storage pressures to reduce volume and costs.**
- **Problems using the adiabatic method in salt caves: at $P = 100$ bar ⇒ $T = 800$ ºC ⇒ salt melts ⇒ auxiliary system to store the heat.**

Compressed air (VIII)

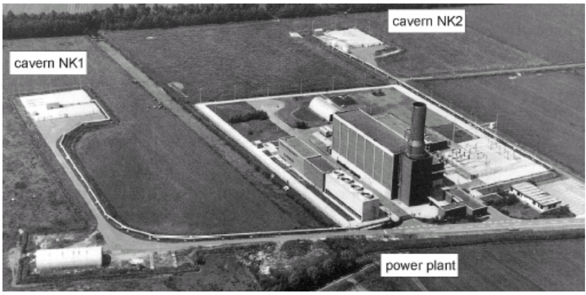
- **CAES plants examples:**
  - **Huntorf, Germany (1978):**

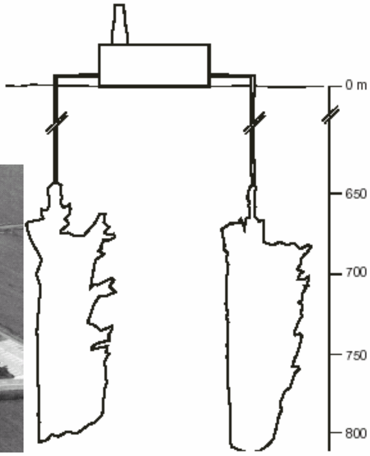
output	
➢ turbine operation	290 MW (≤ 3 hrs)
➢ compressor operation	60 MW (≤ 12 hrs)
air flow rates	
➢ turbine operation	417 kg/s
➢ compressor operation	108 kg/s
air mass flow ratio in/out	1/4
number of air caverns	2
air cavern volumes (single)	≈ 140 000 m³ ≈ 170 000 m³
total cavern volume	≈ 310 000 m³

cavern location – top - bottom	≈ 650 m ≈ 800 m
maximum diameter	≈ 60 m
well spacing	220 m
cavern pressures	
➢ minimum permissible	1 bar
➢ minimum operational (exceptional)	20 bar
➢ minimum operational (regular)	43 bar
➢ maximum permissible & operational	70 bar
maximum pressure reduction rate	15 bar/h

Compressed air (IX)

- **CAES plants examples:**
  - **Huntorf, Germany (1978):**





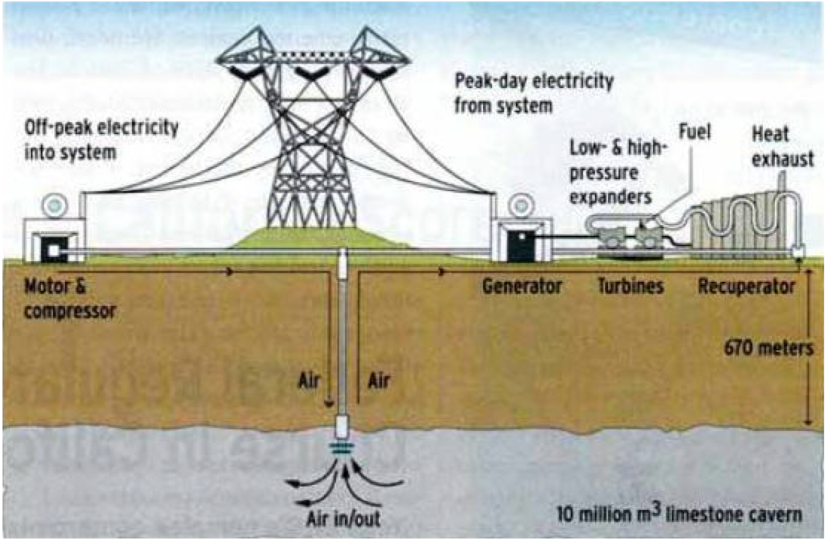
Compressed air (X)

- CAES plants examples:
  - McIntosh, Alabama (1991):
    - Power = 100 MW.
    - Cavern: Top of solution-mined salt cavern is 1,500 feet (457 m) underground and bottom of cavern is 2,500 feet (762 m) underground.
    - The diameter of the cavern is 220 feet (67 m) and the volume is 10 million of cubic feet (283,000 m^3).
    - At full charge, air pressure is 1,100 pounds per square inch (75.8 bar). At full discharge, cavern air pressure is 650 pounds per square inch (44.8 bar).

Compressed air (XI)

- CAES plants examples:
  - McIntosh, Alabama (1991):
    - Capacity: Compressed air flows through the CAES plant generator at a rate of 340 pounds of air per second (154 kg/s).
    - The fuel consumption during generation is equal to 4,600 Btu (1,35 kWh) (HHV) per kilowatt-hour (kWh) of electricity. There are about 20,750 Btu in each gallon of gasoline.
    - The electricity consumed during compression is 0.82 kWh of peak load generation.

Compressed air (XII)



Compressed air (XIII)

- CAES plants examples:
  - Norton, Ohio (under development):
    - A 2,200-foot-deep limestone (cal) mine.
    - Working pressures: 800-1,600 psi (55-110 bar).
    - The power plant will be built in units brought on line in increments of 300 megawatts as units are completed. Ultimately up to about 2,700 megawatts will be built, which will be enough generating capacity for about one million homes.

Compressed air (XIV)

Flywheels (I)

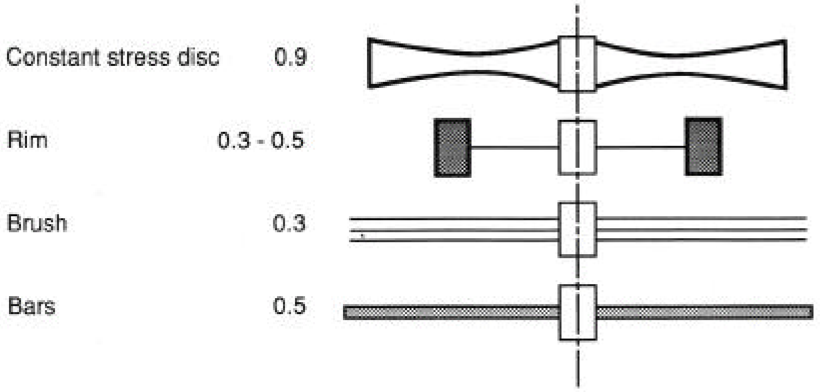
- **Flywheels Energy Storage: FES.**
- **Energy stored in a rotating wheel: $E = I \cdot w^2/2$.**
- **Stored energy limit: mechanical strength of the material (*Y*, elasticity or Young’s modulus).**
- **The stored energy is proportional to *Y* and to the volume Þ on blackboard.**
- **The stored energy per unit mass is directly proportional to *Y* and inversely proportional to *r* Þ on blackboard.**
- **This last point implies that we are interested in materials of low density.**

Flywheels (II)

- The stored energy per unit mass is directly proportional to (explained on blackboard):
  - The ratio R_G/R_{max} Þ thin annular ring Þ low energy stored per unit volume.
  - The tip speed of the outermost element, V_T Þ limited by the force balance between the centrifugal force and the stress of the material.
  - The geometric parameter, K_s.
  - The speed asociated with the material properties, a_m.

Flywheels (III)

- Values of the geometric parameter for different flywheels designs:



Constant stress disc	0.9
Rim	0.3 - 0.5
Brush	0.3
Bars	0.5

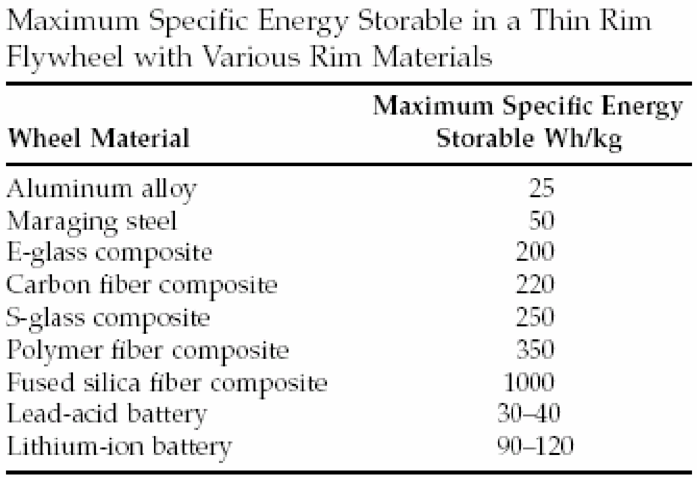
Flywheels (IV)

- **Properties of flywheel materials:**

Material	Density (kg/m^3)	E_{max} (Wh/kg)	a_m (m/s)
Aluminium	2,700	20	190
Treated steel	8,000	55	280
E-glass fiber	2,500	190	570
Carbon fiber	1,800	200	600
S-glass fiber	2,500	240	660
Fused silica	2,100	870	1,200

Flywheels (V)

- **Properties of flywheel materials:**



Maximum Specific Energy Storable in a Thin Rim Flywheel with Various Rim Materials

Wheel Material	Maximum Specific Energy Storable Wh/kg
Aluminum alloy	25
Maraging steel	50
E-glass composite	200
Carbon fiber composite	220
S-glass composite	250
Polymer fiber composite	350
Fused silica fiber composite	1000
Lead-acid battery	30–40
Lithium-ion battery	90–120

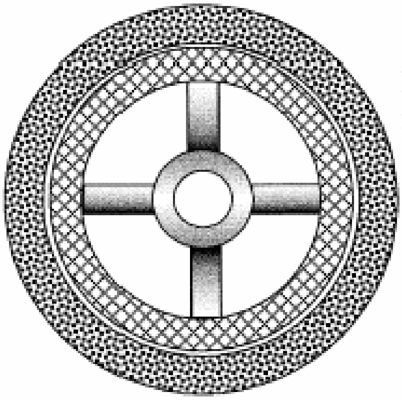
Flywheels (VI)

- Properties of flywheel materials:
  - Steels: very dense, small stress, danger if breakage (fragments dispersed).
  - Fiber materials:
    - Disadvantages: very expensive and low availability.
    - Advantages: anisotropy of properties and no danger if breakage (dust).
- Reference values: D = 4.75 m and m = 100 - 200 t Þ E = 10 MWh at 3.500 rpm with Power = 3 MW and h = 90%.

Flywheels (VII)

- Whole system:
  - Housing for protection and sealing up: to avoid danger in case of breakage.
  - Mechanical or magnetic bearings: to reduce the transmision and the friction losses.
  - Vacuum pump: to eliminate the aerodynamic losses.

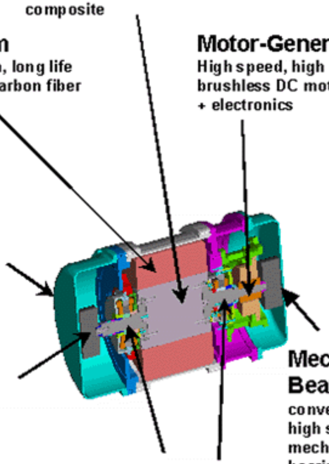
Flywheels (VIII)



Rotor of two-composite fiber rim for high specific energy and safety

Graphite/epoxy outer rim for strength.
Glass/epoxy inner rim for economy.
Interface fit.
Hub single pieces aluminum with radial flexibility to relieve the interface stress.

Flywheels (IX)



Rotor Hub
high strength, long life
lightweight carbon fiber
composite

Rotor Rim
high strength, long life
lightweight carbon fiber
composite

Motor-Generator
High speed, high efficiency
brushless DC motor
+ electronics

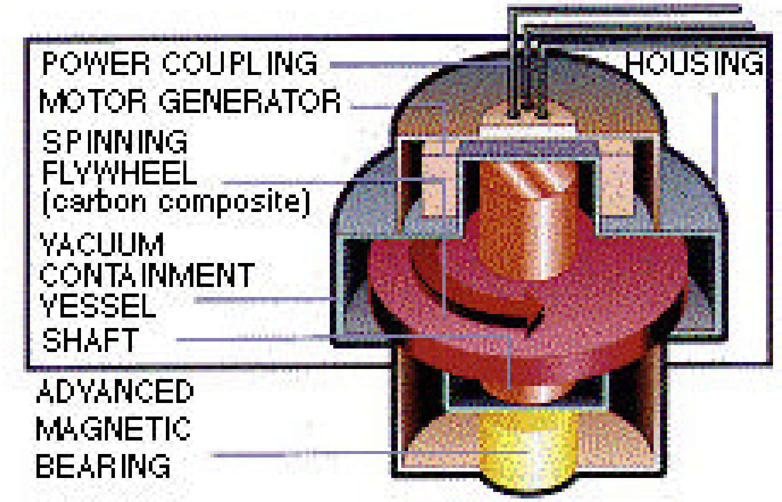
Enclosure

Mechanical Bearing

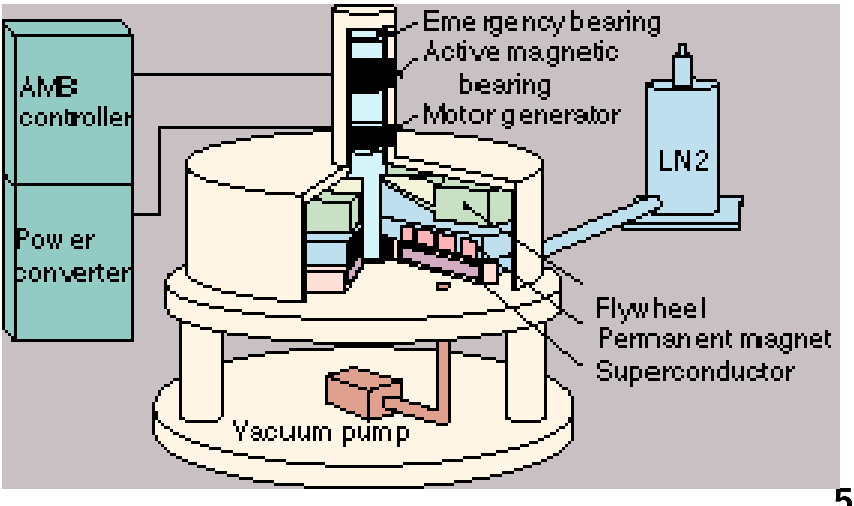
Mechanical Bearing
conventional,
high speed,
mechanical
bearings

Magnetic Bearings
high force, efficient
homopolar magnetics +
electronics

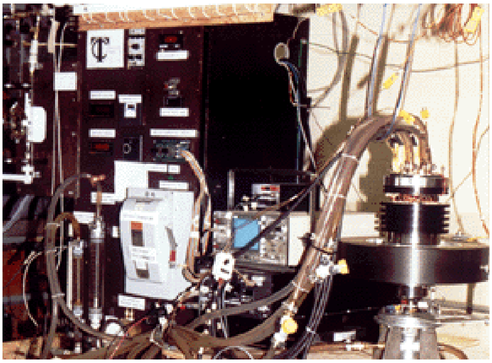
Flywheels (X)



Flywheels (XI)



Flywheels (XII)



Lab Set-up of Instrumentation and 500 Wh/40kw FESS Rotor

Hydrogen (I)

- Chemical storage methods: Production of chemical compounds by means of electrical or thermal spare energy for later conversion in electrical energy.
- Hydrogen advantages:
  - Compatible with any type of primary energy.
  - Unlimited quantities (water) and cyclic use.
  - Not pollutant. Combustion products: H_2O and traces of NO_x.

Hydrogen (II)

- Production methods: Thermochemical and Electrochemical.
- Thermochemical production method:
  - Fossil fuels reforming.
  - Efficiencies: 65-75%.
  - High temperatures are required.
  - Pollution: CO_2, NO_x, incomplete reactions.
  - It requires water and heat.

Hydrogen (III)

- Thermochemical production method:
  - Types of reforming processes:
    - Steam reforming: Hydrogen production from natural gas reacting with steam over a nickel catalyst at high temperature (840-950 ºC) and high pressure (20-30 bar). Endothermic.
    - Partial oxidation reforming: At high temperature (1,200-1,500 ºC) and high pressure (20-90 bar). With oxygen and steam. Used for oil and coal. Exothermic.
    - Autothermal reforming: Combination of the two previous processes.
    - Thermal decomposition reforming: heat + hydrocarbon ® coal + hydrogen.

Hydrogen (IV)

- Electrochemical production method:
  - Electrolysis: water decomposition by passing an electric current through it.
  - Low pressure electrolyser: temperature = 70-90 ºC; voltage = 1.85-2.25 V; electricity consumption = 4.5 kWh/m^3; hydrogen purity > 99.8%.
  - Efficiency > 50%, but it is expensive due to the high energy consumption and to the cost of the equipment.

Hydrogen (V)

- Electrochemical production method:
  - Only 4% of hydrogen produced by electrolysis.
  - Electrolysis can be suitable when coupled with a renewable energy source.
  - Components of an electrolyser:
    - Electrolyte: conductor saline solution. Normally potassium hydroxide (KOH).
    - Electrodes: nickel or low-carbon nickeled steel.
    - Porous membrane: to avoid mixture of oxygen and hydrogen (ions).

Hydrogen (VI)

- **Electrochemical production method:**
  - **Anode reaction (oxidation):**

2 H_2O (l) ® O_2 (g) + 4 H^+ (sol) + $4e^-$.

4 OH^- (sol) ® O_2 (g) + 2 H_2O (l) + $4e^-$.

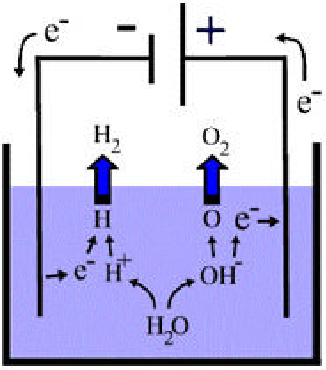
  - **Catode reaction (reduction):**

4 H_2O (l) + 4 e^- ® 2 H_2 (g) + 4 OH^- (sol).

4 H^+ (sol) + 4 e^- ® 2 H_2 (g).

  - **Global reaction:**

2 H_2O (l) ® 2 H_2 (g) + O_2 (g).



Hydrogen (VII)

- **Other production methods (under development):**
  - **Water photolysis: use of photosensible substances to split water directly from solar light (like in photosynthesis).**
  - **Photobiological: using organisms (algae and bacteria) that produce hydrogen in their metabolic processes.**
  - **Biomass gasification.**

Hydrogen (VIII)

- Hydrogen storage:
  - Low volumetric energy density Þ bigger storage tank.
  - Higher mass energy density (140 MJ/kg). Unbalanced by the weight of the storage tanks.
  - Great scale storage: like compressed air in salt caves, aquifers, rock caves or artificial caves.
  - Low scale storage: compressed (gas), liquid or metal hydride.

Hydrogen (IX)

- Compressed hydrogen storage:
  - Energy required to compress the gas.
  - Weight of the tank.
  - Most widely used method.
- Liquid hydrogen storage:
  - Cryogenic tanks (-253 ºC).
  - Liquefying process requires energy.
  - Under development.

Hydrogen (X)

Hydrogen (XI)

- **Metal hydrides:**
  - **Combination of metallic alloys that absorb hydrogen and release it through a reversible process, changing the conditions of pressure or temperature.**
  - **Advantage: safety.**
  - **Disadvantages: low hydrogen absorption (2-7% in weight), purity of hydrogen, weight of the metal and high costs.**
  - **Under development.**

Hydrogen (XII)

- Hydrogen energy extraction:
  - Brayton cycle.
  - Gas turbine.
  - Fuel cells.

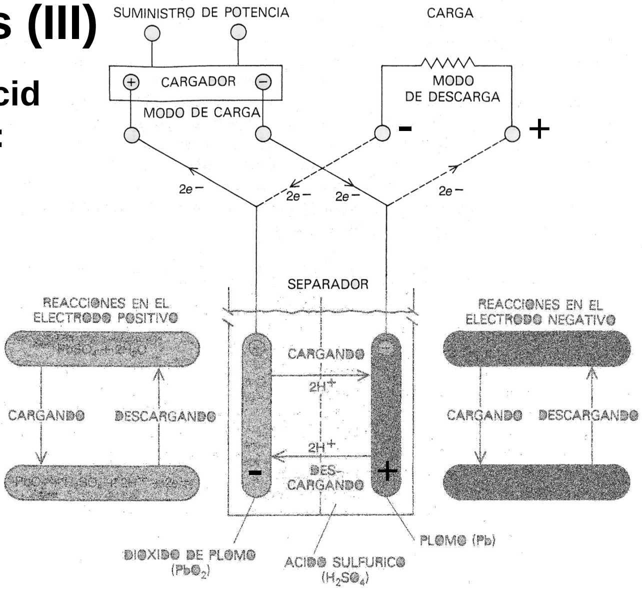
Batteries (I)

- Electrochemical storage batteries: electric energy Þ chemical energy.
- Battery: two electrodes immersed in an electrolyte where they exchange ions and connected to an external circuit to exchange electrons.
- The lead-acid batteries used in vehicles are not suitable for great scale energy storage due to its:
  - Low energy density per unit of weight and per unit of volume.
  - High cost.
  - Small useful life (charge-discharge cycles).
- R+D to eliminate these disadvantages.

Batteries (II)

Batteries (III)

- **Lead-acid battery:**



Batteries (IV)

- Ni-Cd battery. Compared with lead-acid, they have:
  - Half the weight.
  - Longer useful life.
  - More temperature tolerance.
  - Lower power density.
  - Greater cost.
  - Environmental problems with Cd.

Batteries (V)

- Nickel-Metal Hydride battery:
  - Anode of metal hydride
  - Improvement in energy and power density.
  - High self-discharge rate.
  - Expensive.
- Ag-Zn battery: high storage density, but small useful life (30-300 cycles).
- Na-S battery: high storage density and long useful life, but it works at 300 ºC and has problems of leakage.

Batteries (VI)

- **Lithium-ion battery:**
  - **Three times energy density of lead-acid.**
  - **More expensive.**
- **Lithium-polymer battery: with solid polymer electrolyte.**
- **Li-Cl and Li-Te batteries: similar to Na-S.**
- **Zn-Cl battery: it supplies a constant power during discharge.**
- **Zinc-air batteries: it absorbs oxygen from the air during discharge.**

Batteries (VII)

Type of battery	Pb-acid	Ni-Cd	Ni-metal hydride	Na-S	Li-ion	Li-poly	Zn-Cl	Zn-air	Li-FeS_2
V_{max} (V)	2.5	1.35	-	2.75	-	-	2.12	-	2.4
V_{min} (V)	1.75	-	-	1.83	-	-	1.98	-	1
T (ºC)	25	25	25	300-350	25	50-70	30-50	-	400-450
h_e	70-80	-	-	85	-	-	70	-	70
Life (No. of cycles)	1,500-2,000	1,500-3,000	1,000-2,000	1,000-2,000	500-1,000	500-1,000	500-1,000	200-300	200-1,000
Energy density (Wh/kg)	150-200	200	150-200	200	100	100-200	150	200	170
Power density (W/kg)	100-150	150-200	150	100	200	>200	90	150	>100
Self-discharge rate (%/month)	3-5	20-30	20-30	-	5-10	1-2	-	4-6	-

Batteries (VIII)

Batteries (IX)

- **Performance parameters:**
  - **Capacity, *C*:**
    - **The electrical charge capable of storing (measured in A·h = 3,600 C).**
    - **Function of charge-discharge regime and temperature: *C* decreases if discharge is faster and increases slightly with *T*.**
    - **Usually given for different times of discharge, 10 and 100 hours, C_{10} and C_{100}.**
    - ***C* is reduced with the number of accumulated cycles.**
    - **End of life: when *C* is reduced by 80% of nominal value.**

Batteries (X)

- **Performance parameters:**
  - **Discharge depth:**
    - **Percentage of full charge used.**
    - **The higher the discharge depth, the longer the battery life.**
    - **The opposite parameter, percentage of full charge remaining, is called the state of charge (*SOC*).**
  - **Charge or capacity efficiency, h_c:**

$$h_c = \frac{\text{Capacity in discharge}}{\text{Capacity in charge}} \cdot 100$$

- **The inverse parameter is called the charge-discharge ratio (>1). Depends on temperature.**

Batteries (XI)

- **Performance parameters:**
  - **Energy efficiency, h_c:**

$$h_e = \frac{\text{Battery usable energy}}{\text{Energy used during the charge}} \cdot 100 \text{ @ } 70 - 90\%$$

$$h_e = \frac{\text{Discharge Voltage} \cdot \text{Capacity in discharge}}{\text{Charge Voltage} \cdot \text{Capacity in charge}}$$

- **Internal resistance, R_i: to take into account the energy losses in form of heat.**

Batteries (XII)

- **Performance parameters:**
  - Charge efficiency: Ratio of charge internally deposited to charge delivered to the external terminals.
    - Depends on the *SOC* and on the rate of charge.
  - Specific energy and energy density:
    - Product of the charge stored by the voltage divided by weight or volume, respectively.

$$E_m = \frac{C \cdot V}{m} \left[\frac{Wh}{kg}\right] \qquad E_{vol} = \frac{C \cdot V}{Vol} \left[\frac{Wh}{l}\right]$$

Batteries (XIII)

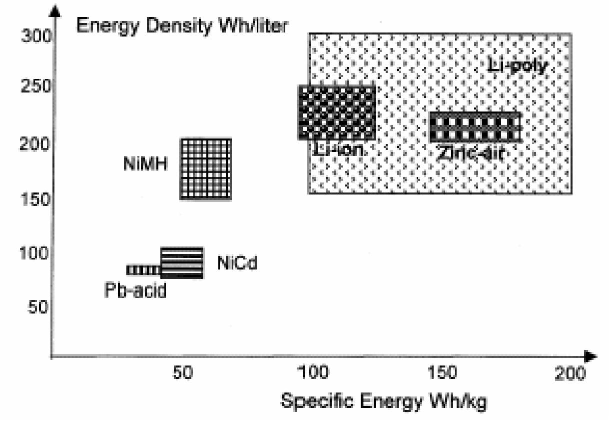
- **Performance parameters:**
  - Specific power:
    - It relates the energy density with the discharge time at a given discharge rate.
    - It indicates how rapidly the cell can be discharged and how much power generated.

$$P_m = \frac{E_m}{t} = \frac{C \cdot V}{t \cdot m} \left[\frac{W}{kg}\right]$$

  - Operating voltage.
  - Number of charge/discharge cycles.
  - Self-discharge rate: how rapidly the cell loses potential (while unused) in the charged state.

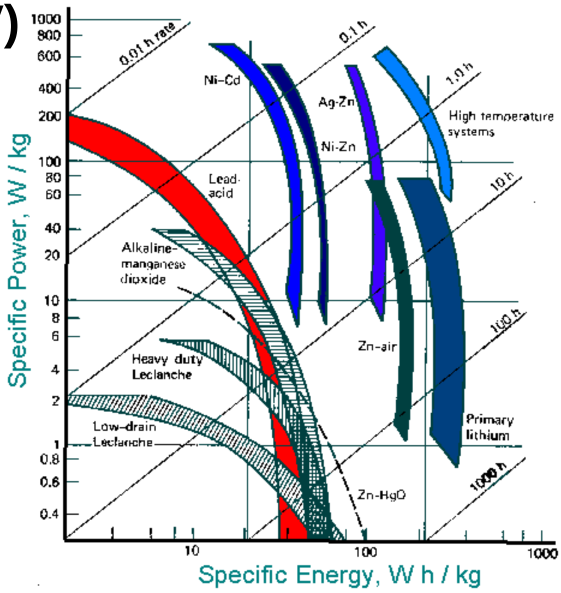
Batteries (XIV)

- **Performance parameters:**
  - **Ragone plot: specific power versus specific energy.**



Batteries (XV)

- **Performance parameters:**
  - **Ragone plot.**



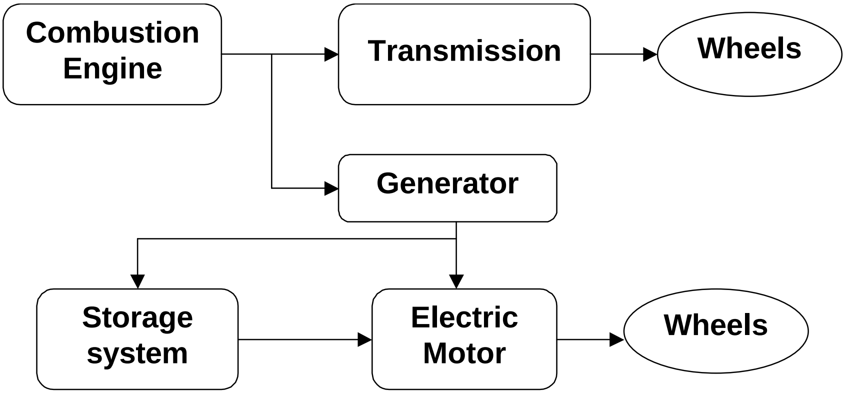
Batteries (XVI)

Hybrid electric vehicles (I)

- **Pollutant emisions reduction Þ development of Hybrid Electric Vehicles (HEVs).**
- **It is not possible a pure electric vehicle powered by batteries only: for a 1,500 kg vehicle and a stored energy of 25 kWh it is necessary a Ni-Cd battery of 400 kg.**
- **Development of HEVs: utilizing either diesel or gasoline engines, alternative fuels (methanol, etahnol, LPG or CNG) engines, gas turbines, fuel cells or electric motors with an storage system (batteries or flywheels).**

Hybrid electric vehicles (II)

- General diagram of a HEV:



Hybrid electric vehicles (III)

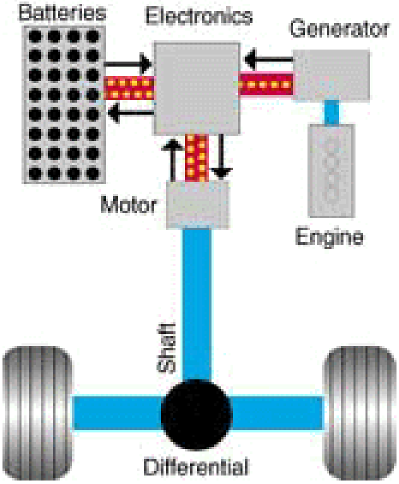
- Comparision between en Internal Combustion Engine (ICE) and a HEV:

	ICE	HEV
Fuel	100	50 (+50)
Transmission losses	-6	-6
Idling losses	-11	0
Accessory loads	-2	-2
Engine losses	-65	-32
Regenerative braking	0	+4
Total energy remaining	16	14 (+50)

- There are three main types of configurations and designs of HEVs: series, parallel, and dual-mode.

Hybrid electric vehicles (IV)

- **Series HEV:**
  - **Example:**
    - **A 22-foot bus owned and operated by the Chattanooga Regional Area Transportation Authority (CARTA, Tennessee, USA).**
    - **Vehicle manufactured by Advanced Vehicle Systems (AVS, http://www.avsbus.com).**
    - **It has a Capstone turbine that rotates at 96,000 rpm and runs on compressed natural gas.**

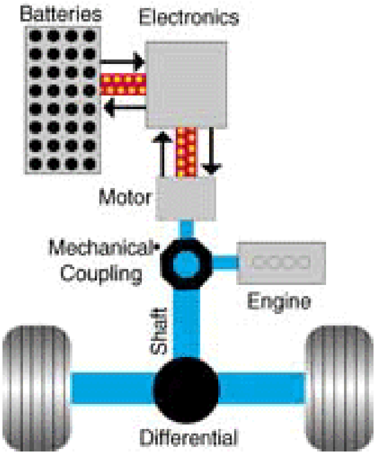


Hybrid electric vehicles (V)

- **Series HEV:**
  - **Entire drive power transmitted electrically.**
  - **May require larger batteries.**
  - **Requires on-board charging.**
  - **Requires some off-board charging.**
  - **Optimisation by separating engine speed from vehicle speed.**
  - **Engine never idles, thus reduces overall emissions.**
  - **Requires heavy-duty motor.**

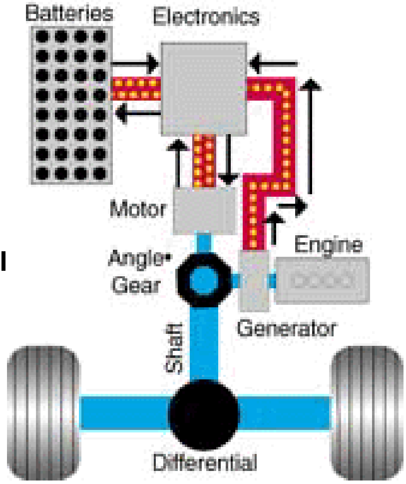
Hybrid electric vehicles (VI)

- **Parallel HEV:**
  - **Electric motor and engine both coupled directly to wheels.**
  - **Can operate with smaller batteries.**
  - **Requires off-board charging.**
  - **Accelerates faster due to dual power sources.**
  - **Engine idles.**
  - **Packaging of components less flexible.**
  - **Requires medium-duty motor.**
  - **Example: the HIMR bus (HINO Motors, Japan). http://www.hino.co.jp.**



Hybrid electric vehicles (VII)

- **Dual-mode HEV:**
  - **Engine can fuel batteries as well as drive wheels.**
  - **Requires medium - large batteries.**
  - **Requires on and off-board charging.**
  - **Accelerates faster due to dual power sources.**
  - **Engine idles.**
  - **Packaging of components less flexible.**
  - **Requires heavy-duty motor.**
  - **Example: Toyota Prius. http://www.toyota.es. http://www.toyota.com.**

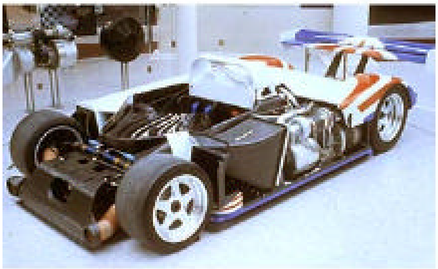


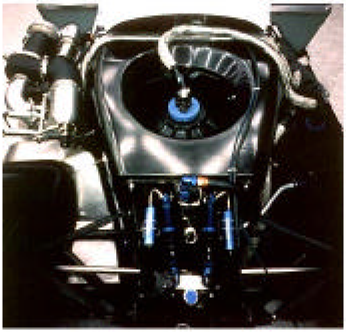
Hybrid electric vehicles (VIII)

- Charge Sustaining and Charge Non-Sustaining Hybrids:
  - Charge sustaining HEV: the hybrid power source is capable of providing sufficient energy independent of the storage device to drive the vehicle just as it were a conventional vehicle.
  - Charge non-sustaining HEV: the hybrid power source is only able to provide recharging energy and cannot supply the necessary energy to drive the vehicle by itself. This system must have additional energy from the storage device to meet the energy needs of the vehicle.

Hybrid electric vehicles (IX)

- Flywheel Energy Storage technology developed for NASA by SatCon Technology Corporation plays a role in the drive train of experimental hybrid-electric automobiles.
- The SatCon Flywheel Energy Storage system provides 50 times the energy storage capacity of a conventional lead-acid battery.





Reaction enthalpies (I)

- Chemical reactions and other reversible endothermic processes (solutions of solid in liquid and gas in solid).
- The energy is recovered with the inverse exothermic process. High storage density.
- Uses: at low temperature for the heating and air conditioning of buildings and at high temperature in power plants.
- Example:

  $CO + Cl_2$ Û $COCl_2$ (fosgeno) DH_o = 112,6 kJ/g·mol

Reaction enthalpies (II)

- Example:

  $Ca(OH)_2$ (s) Û CaO (s) + H_2O (g) DH_o = 148,6 kJ/mol

  - Process:
    1. Heat $Ca(OH)_2$ from 25 ºC to 510 ºC: DH_o = +54,0 kJ/mol.
    2. Decomposition at 510 ºC by heating: DH_o = +94,6 kJ/mol.
    3. Cool the components to 25 ºC for storage only of the CaO: DH_o = -85 kJ/mol.
    4. Add H_2O (l) to close the cycle: DH_o = -63,6 kJ/mol.
  - Efficiency: 63,6/148,6 = 42,8%.

Reaction enthalpies (III)

- Example:

  $CO + 3H_2$ Û $CH_4 + H_2O$ DH$_o$ = 250,3 kJ/g·mol
  - Endothermic reaction from right to left.
  - For the inverse reaction at low *T* it is necessary a catalyst Þ a long storage time.
- Disadvantages:
  - Development: it is necessary to work at high *T* and a suitable catalyst.
  - Security: storage at high *P* of poisonous and inflammable gases.

Thermal storage methods

- Wide *T* ranges: from refrigeration to 1.250 ºC.
- Uses:
  - Manufacture of cement, iron and steel, glass, aluminium, paper, plastics and rubbers.
  - Food industry.
  - Air conditioning for buildings.
- Main problems:
  - To set a suitable surface for a fast heat exchange.
  - Avoid heat leakages.

Sensible heat (I)

- **The thermal energy is stored by raising the *T* of some material (water, an organic liquid or a solid).**
- **Storage density:** $\rho\left[\frac{kg}{m^3}\right] c_p\left[\frac{J}{kg\cdot K}\right]\Delta T[K]=\left[\frac{J}{m^3}\right]$
- **Materiales with high values of $\rho\cdot c_p$ and α.**
- **Disadvantages: working at variable *T*, small density and possible volume variations (thermal expansion coefficient).**

Sensible heat (II)

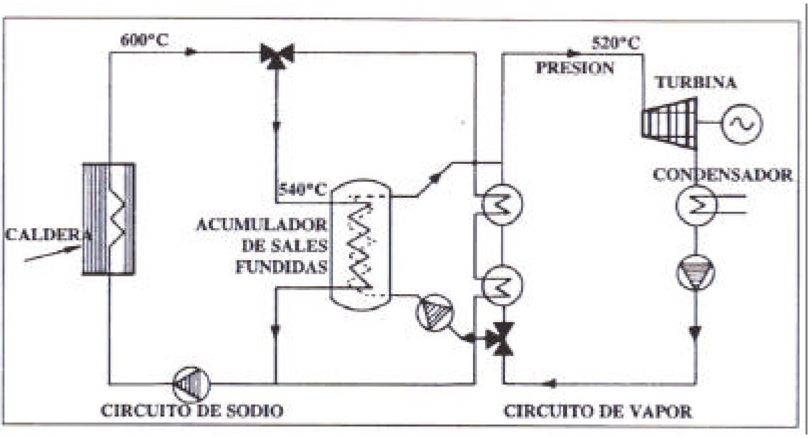
- **Air conditioning: solid walls of high c_p. Store the energy during the day and return it during night.**
- **Water ponds to store solar heat for domestic hot water (d.h.w.) uses.**
- **Thermal power plants with steam turbine: pressured water. Excess of steam extracted from turbine and mixed with water $\Rightarrow$ pressured saturated water. Then it is re-evaporated and expanded in an auxiliary turbine. Storage *T*: 100 - 300º C.**

Sensible heat (III)

- For *T* > 500º C not toxic neither expensive molten metals are used.
  - Heat storage materials (high specific heat and molten heat): aluminium, barium, magnesium, zinc.
  - Heat bearing materials (high *k*, low viscosity and good pumping conditions): sodium, tin (estaño), lead.
- Rock and stone heat sils: they use spare thermal energy or sun energy. Injection and extraction of heat with air. Efficiencies about 50%.

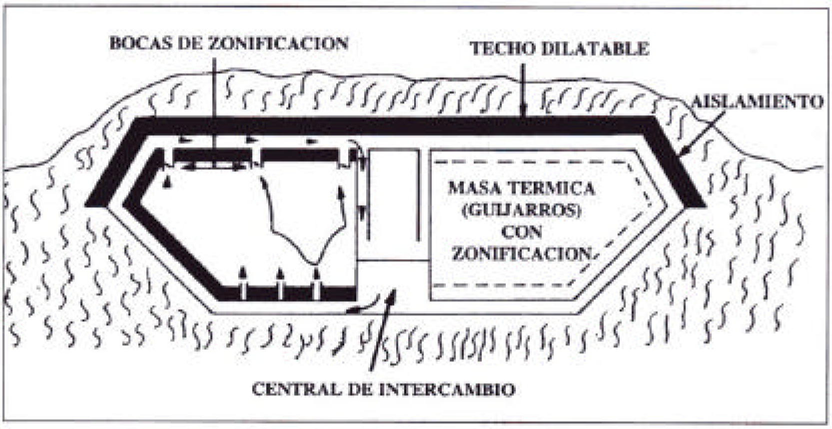
Sensible heat (IV)

- Thermal power plant with high *T* storage:



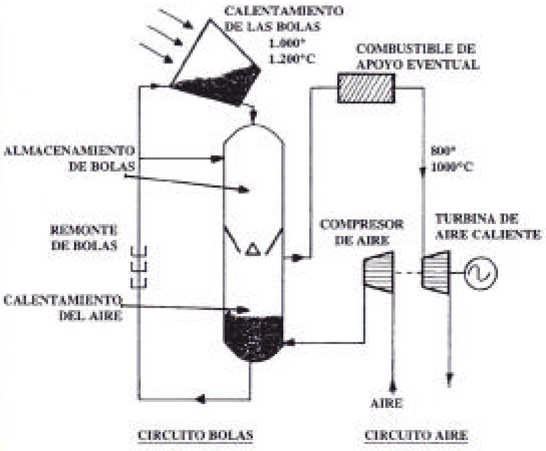
Sensible heat (V)

- **Heat sil:**



Sensible heat (VI)

- **Fireproof ball sils and heat exchangers: sun concentrating collectors heat the balls (1,000-1,100º C), compressed air is heated with them and the air is expansioned in a turbine (900-1,000º C).**



Latent heat (I)

- Energy stored by means of a phase change, melting of a solid or vaporizing of a liquid. The energy is recovered with the inverse process, solidifying the liquid or condensing the steam.
- Storage density: $\rho\left[\frac{kg}{m^3}\right]\lambda_{c.f.}\left[\frac{J}{kg}\right]=\left[\frac{J}{m^3}\right]$
- Densities higher than in sensible heat.
- Advantages: process at a constant *T*, without volume change and with a wide variety of materials and working *T*.

Latent heat (II)

- It can be combined with the storage by means of sensible heat.
- Maximum storage capacity: water vaporization (2,257 J/kg), but the problem is to store the steam in a suitable container. It is not used.
- Phase Change Materials (PCMs): they can be organic or inorganic.
- Disadvantages:
  - The organic materials suffer a great change of volume.
  - The inorganic materials have problems of corrosion of metals and of stability after a lot of cycles.

Latent heat (III)

- **Materials requirements:**
  - **High phase change latent heat.**
  - **Suitable properties during the phase change.**
  - **High *k*.**
  - **Storage easiness.**
  - **Stability.**
  - **Absence of toxicity.**
  - **Low cost.**
- **Best material: eutectic fluorine mix (T_f = 680 ºC and density = 1,500 MJ/m^3). But problems of corrosion and erosion due to the entry of oxygen and steam during the heat exchanges.**

Latent heat (IV)

- **Applications:**
  - **Preservation and transport of temperature sensitive materials (biomedic products, organs, plants, electronic components...).**
  - **Building heating and air conditioning applications.**
  - **Water storage tanks (to avoid stratifying due to density variations).**
  - **In air-air heat pumps to increase COP.**
- **In power plants is not used Þ there is no suitable material for a large scale storage.**

Capacitors

- Simpler system to store electric energy. It absorbs electric charges when subject to an electric field. A dielectric material between two plates.
- Stored energy: $E = CV^2/2$
- Volume unit energy: $E_V = eV^2/2d$
- It depends on the dielectric material. Currently densities of 0.15 Wh/m³ with a field of 10 million of V/m.
- Advantage of the capacitors: huge power density supply when short-circuited.

Magnetic fields (I)

- A coil conected to a voltage source Þ intensity provokes a magnetic field. This energy absorption can be released as a electric current in other circuit.
- Stored energy in the solenoid: $E = VB^2/2m$
- Volume unit energy: $E_V = mN^2I^2/2L$
- Dense coils and materials with high values of magnetic permitivity are needed.
- Disadvantages: density values similar to capacitors and they unload quickly if the electric field stops.

Magnetic fields (II)

- Materials called superconductors are being investigated: at *T* close to 0 K show electric resistance null and high magnetic permitivity.
- Critical temperatures between –263 and –253 ºC. Criogenic tanks of liquid He vacuum insulated.
- With the superconductors the current can be cut and the energy can be stored, theoretically, until infinity.
- Global efficiencies higher than 90%. The future choice.

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