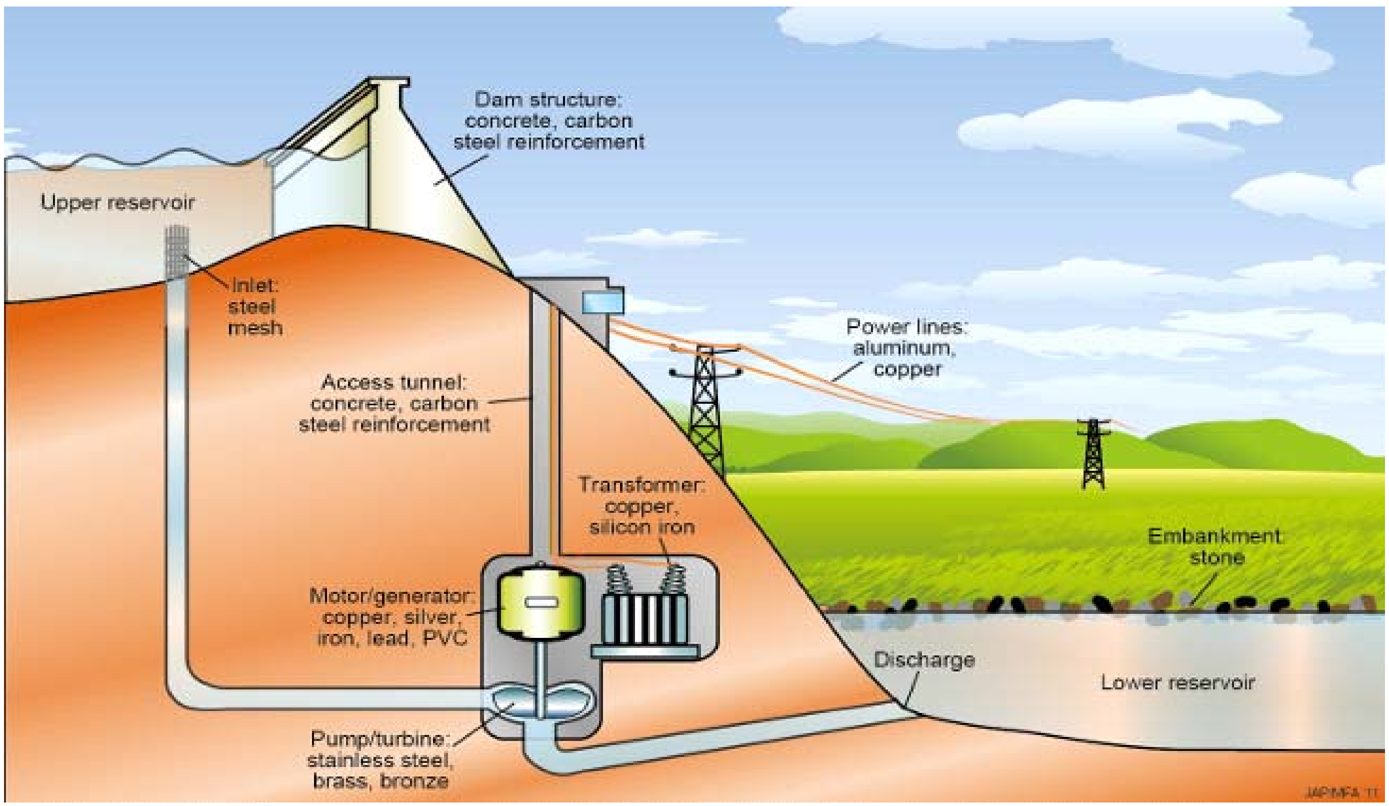
L7 – Energy storage, information pack

The upper reservoir of Ffestiniog pumped hydro storage system in Wales, UK.

Pumped Hydro Storage

- Pumped hydro storage is the storage of energy by pumping water from a lower reservoir, to an upper reservoir which is 100-1,000m higher
- Because it is so simple, it is the prevalent method of utility scale energy storage, accounting for 99% of world-wide capacity.
- As further implementation is carried out in the future, pumped hydro will become more difficult. It requires locations where two large bodies of water exist at different heights, or where they can be constructed economically. As these locations are used, it will become more expensive and less economical.



Pumped hydro – useful numbers

Resource intensity	
Capital intensity (construction)	56.1 - 150 CAD/MJ
Area intensity (construction)	0.025 - 0.083 m^2/MJ
Material intensity (construction)	60 – 120 kg/MJ
Energy intensity (construction)	100 – 200 MJ/MJ
CO2 intensity (construction)	8 – 16 kg/MJ
Operational parameters	
Specific energy	0.002 - 0.005 MJ/kg
Energy density	2 – 5 MJ/m^3
Specific power	0.02 - 0.3 W/kg
Economic energy storage capacity	1000 000 – 1 000 000 000 MJ
Economic power capacity	100 - 1000 MW
Cycle efficiency	70 – 80 %
Cycle life	40 000 cycles
Operating cost	0.00069 - 0.00175 CAD/MJ/cycle
Adaptable for mobile systems	False
Status	
Current installed capacity	6 900 000 GJ
Growth rate	15 %/year

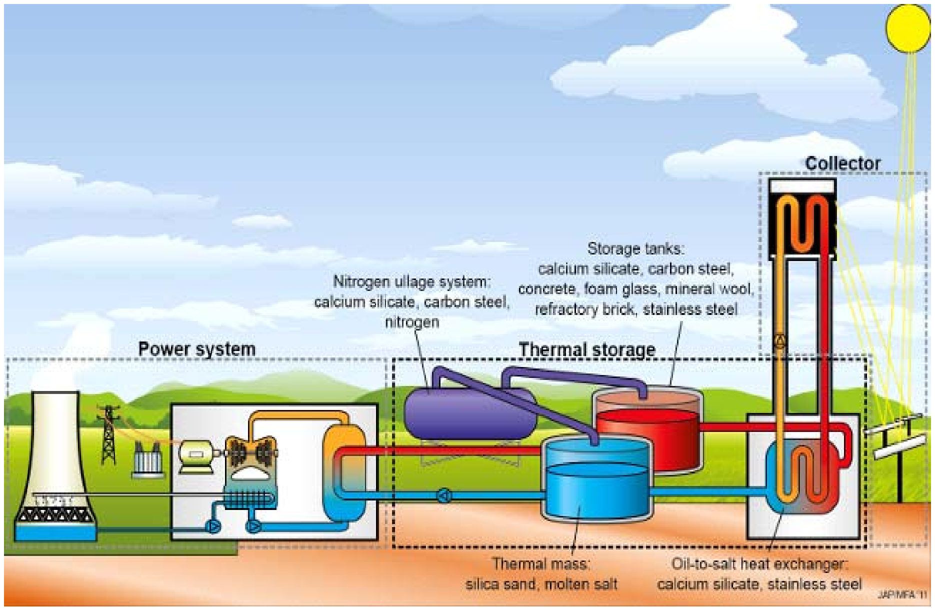
We'll treat pumped hydro as state-of-the-art for off-grid storage and gasoline/diesel for portable energy storage.

Energy density (useful work/kg)

Gasoline: 13 MJ work/kg

Diesel: 21.6 MJ work/kg

Thermal storage



- Thermal storage is the storage of energy by heating up a material.
- When there is excess energy, it is used to create a temperature gradient (either by heating or cooling), thereby storing energy as heat.
- Alternatively, the energy can be used to melt or freeze material, thereby storing energy as latent heat.
- The energy is released by using the temperature gradient either to directly heat/cool space, or to run an engine and generate electricity.

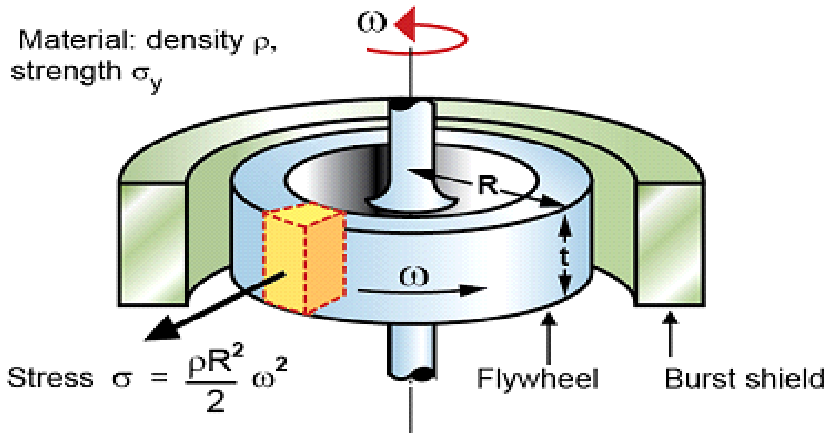
- Utility scale thermal energy storage is increasingly being used as part of concentrated solar plants.
- The sun's heat is used to heat up molten salt from a cold tank (typically 40% potassium nitrate, 60% sodium nitrate), which is then held in a hot tanks until the energy is needed.
- The molten salt from the hot tank then returns to the cold tank via a steam generator, which runs a turbine and generates power.

Doesn't have to be coupled to solar; talk about bricks in JD's house…

Thermal Storage – Useful numbers

Resource intensity	
Capital intensity (construction)	17.5 - 32.4 CAD/MJ
Area intensity (construction)	0.0025 - 0.0034 m^2/MJ
Material intensity (construction)	0.4 – 50 kg/MJ
Energy intensity (construction)	120 – 130 MJ/MJ
CO2 intensity (construction)	8.9 – 9 kg/MJ
Operational parameters	
Specific energy	0.032 - 0.28 MJ/kg
Energy density	130 – 160 MJ/m^3
Specific power	1.5 - 1.7 W/kg
Economic energy storage capacity	1000 - 1e8 MJ
Economic power capacity	1 – 1000 MW
Cycle efficiency	72 – 85 %
Cycle life	1000 – 15 000 cycles
Operating cost	0.00104 - 0.00237 CAD/MJ/cyc
Adaptable for mobile systems	False
Status	
Current installed capacity	41 000 GJ
Growth rate	36 %/year

Flywheel



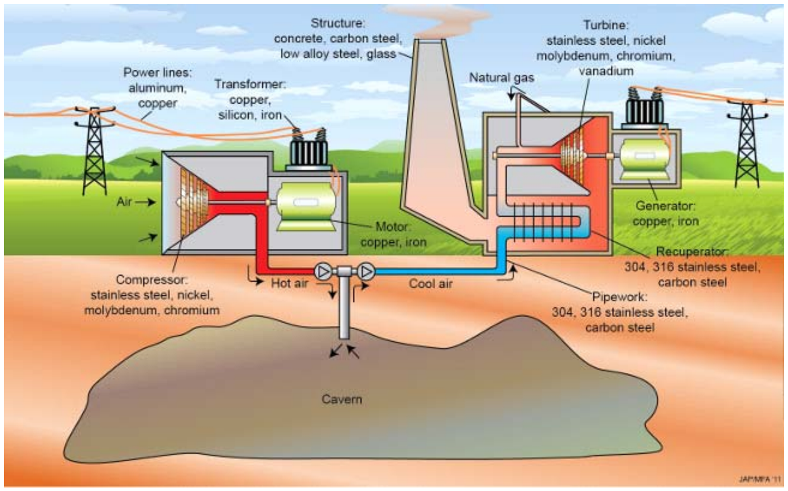
- Energy can be stored as kinetic energy by spinning a flywheel
- Energy is released by allowing the flywheel to run a generator. The flywheel is designed to have as large a moment of inertia as possible in order to maximize the energy stored.

- Because of the fast motion, frictional losses mean that the efficiency deteriorates as the mass spins for longer, so flywheels are usually only used for short term storage.
- The flywheel is placed in a vacuum to reduce air resistance, and in higher end systems, superconducting magnetic bearings can be used to levitate the mass. However, these require an energy input for pumping or cooling, so efficiency still decreases with time.

Flywheel

Resource intensity	
Capital intensity (construction)	499 - 8730 CAD/MJ
Area intensity (construction)	0.077 - 0.17 m^2/MJ
Material intensity (construction)	17 – 500 kg/MJ
Energy intensity (construction)	750 – 760 MJ/MJ
CO2 intensity (construction)	90 – 100 kg/MJ
Operational parameters	
Specific energy	0.002 - 0.06 MJ/kg
Energy density	1.7 - 23 MJ/m^3
Specific power	100 – 10 000 W/kg
Economic energy storage capacity	0.01 - 1000 MJ
Economic power capacity	0.01 – 10 MW
Cycle efficiency	85 %
Cycle life	150 000 cycles
Operating cost	0.00104 - 0.00212 CAD/MJ/cycle
Adaptable for mobile systems	True
Status	
Current installed capacity	23 GJ
Growth rate	34 %/year

Compressed air



An “energy bag” for storing compressed air under the sea

- Compressed air energy storage (CAES) is the name given to the storage of energy by compressing air.
- Energy is then released by expanding the air through a pneumatic motor or turbine, connected to a generator.
- The compressed air can be stored in small tanks for mobile (e.g. automotive) applications, or in underground caverns or large balloons under the sea (which keeps it at high pressure) for utility scale applications.
- Compressing air increases its temperature, which inevitably results in some loss of energy as heat.
- When the air is expanded again, it cools rapidly and can freeze the turbine.
- Today’s CAES systems combine the compressed air with gas. The gas burns to heat the air, and then the mixture is passed through a gas turbine. This is a hybrid CAES system, and is similar to a conventional gas power plant; however, in a conventional gas power plant, 60% of the output is used to compress air – The stored compressed air removes the need for this, increasing the efficiency of the gas plant. Taking out the contribution of the gas, this leads to an efficiency of 70% for round-trip compressed air storage.

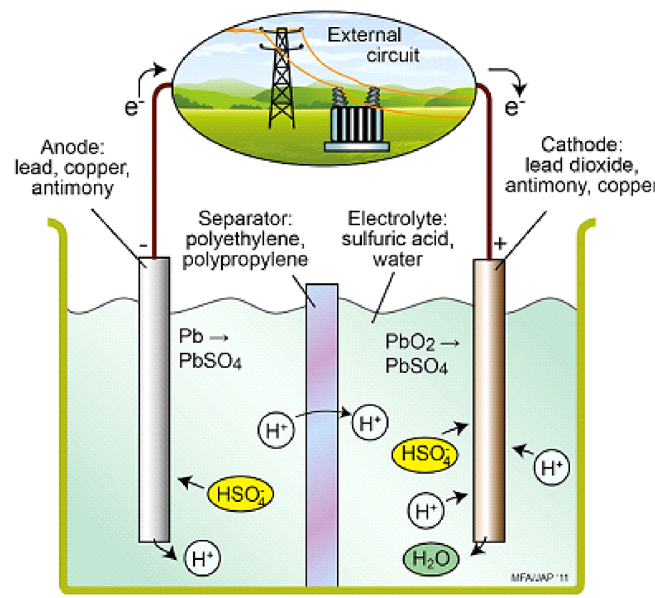
Compressed air – useful

Resource intensity		
Capital intensity (construction)	4.99 - 24.9 CAD/MJ	
Area intensity (construction)	0.0083 m^2/MJ	
Material intensity (construction)	2 – 12 kg/MJ	
Energy intensity (construction)	74 MJ/MJ	
CO2 intensity (construction)	5.3 kg/MJ	
Operational parameters		
Specific energy	0.06 - 0.36 MJ/kg	
Energy density	25 MJ/m^3	
Specific power	8 W/kg	
Economic energy storage capacity	1000 - 1e8 MJ	
Economic power capacity	1 – 1000 MW	
Cycle efficiency	65 – 70 %	
Cycle life	1500 cycles	
Operating cost	0.000175 - 0.00237	CAD/MJ/cycle
Adaptable for mobile systems	True	
Status		
Current installed capacity	24 000 GJ	
Growth rate	66 %/year	

Explain black star of death!

The rest are electrochemical in nature

- Fuel cell
- Batteries
- Supercapacitors
- Flow batteries



Batteries

Introduction to batteries

- Batteries store energy as chemical energy.

- A battery consists of two half cells, each containing a metal and a salt solution of that metal (e.g. metal sulfate).

- The half cell with the more reactive metal (metal A, in this example) is the anode. The metal is oxidized, becoming a metal A ion (A[+2x]) and releasing some electrons (e[-]):

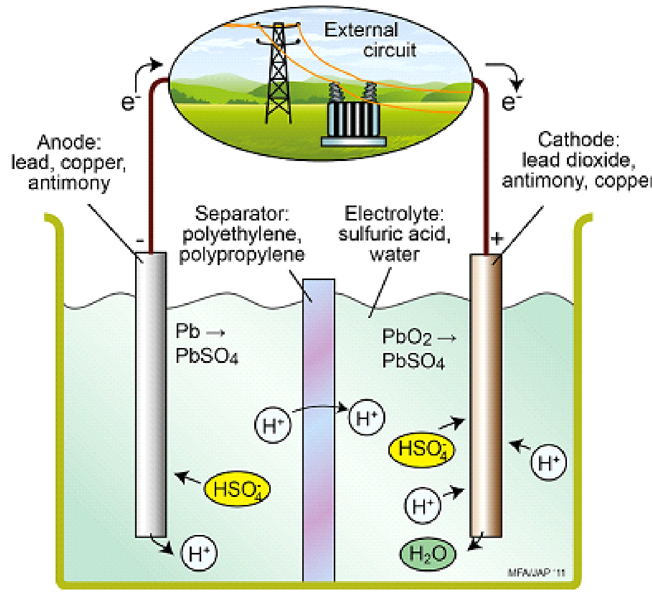
  A -> A[+2x] + 2xe[-]

- The half cell with the less reactive metal (metal B) is the cathode. The metal ions (B[+2x]) from the solution are reduced:

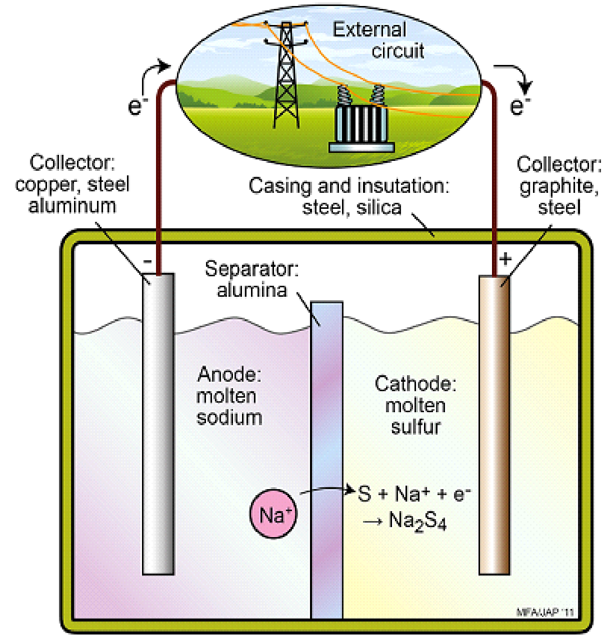
  B[+2x] + 2xe[-] -> B

- The metals from each half cell are connected through a conducting circuit. The electrons are transported from the anode to the cathode through this circuit, where they provide electricity.

- In order to maintain balance of charge, anions (negatively charged ions) are allowed to pass through a porous disk or salt bridge from one solution to the other.



Sodium-Sulfur Battery (or molten sodium battery)



Description

Sodium-sulfur batteries have an anode of molten sodium (Na), and a cathode of molten sulfur (S).

On discharge, the sodium is oxidized, and the ions pass through an alumina electrolyte to reduce the sulfur and create sodium polysulfide (Na2S4). The overall reaction is:

2Na + 4S -> Na2S4

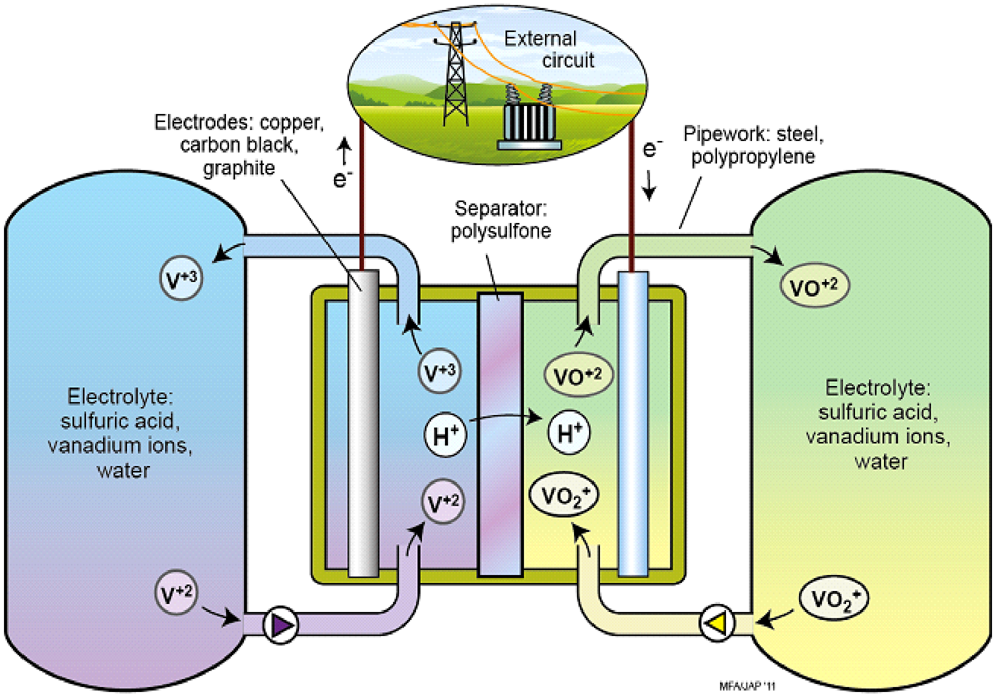
Battery must run at 300 – 350 C to keep the sodium and sulfur molten. When running, the heat produced is sufficient to maintain this temperature.

Sodium-Sulfur Battery (or molten sodium battery) – useful numbers

Resource intensity	
Capital intensity (construction)	34.9 – 349 CAD/MJ
Area intensity (construction)	0.0053 - 0.0083 m^2/MJ
Material intensity (construction)	1.4 – 5 kg/MJ
Energy intensity (construction)	360 – 640 MJ/MJ
CO2 intensity (construction)	30 – 50 kg/MJ
Operational parameters	
Specific energy	0.2 - 0.7 MJ/kg
Energy density	140 – 540 MJ/m^3
Specific power	12 – 13 W/kg
Economic energy storage capacity	1 - 1e7 MJ
Economic power capacity	0.02 – 200 MW
Cycle efficiency	75 – 83 %
Cycle life	3600 – 4700 cycles
Operating cost	0.00474 - 0.00486 CAD/MJ/cycle
Adaptable for mobile systems	False
Status	
Current installed capacity	6 800 GJ
Growth rate	52 %/year

Vanadium Flow Batteries

A vanadium flow battery. (Image courtesy of Qingdao wuxiao tower co. ltd Country/Region, Shan Dong, China).



Description

- Redox flow batteries operate differently than other batteries.
- The electrode materials are salts kept in solution in solvent and are those called catholyte and anolyte.
- These solutions are stored in tanks, and are pumped through the battery cell, where they are reduced or oxidized.
- The anode and cathode electrolytes are made up of a solution of vanadium in different oxidation states.
- The anode electrolyte is a solution of vanadium (II) ions (V[+2]), which are oxidized to vanadium (III) ions (V[+3]) on discharge:

  V[+2] -> V[+3] + e[-]
- The cathode electrolyte is a solution of vanadium (V) oxide ions (VO2[+}), which are reduced with hydrogen ions (H[+]) and electrons, to form vanadium (IV) oxide ions (VO[+2]) and hydroxide ions (OH[-]):

  VO_2[+] + H[+] + e[-] -> VO[+2] + OH[-]

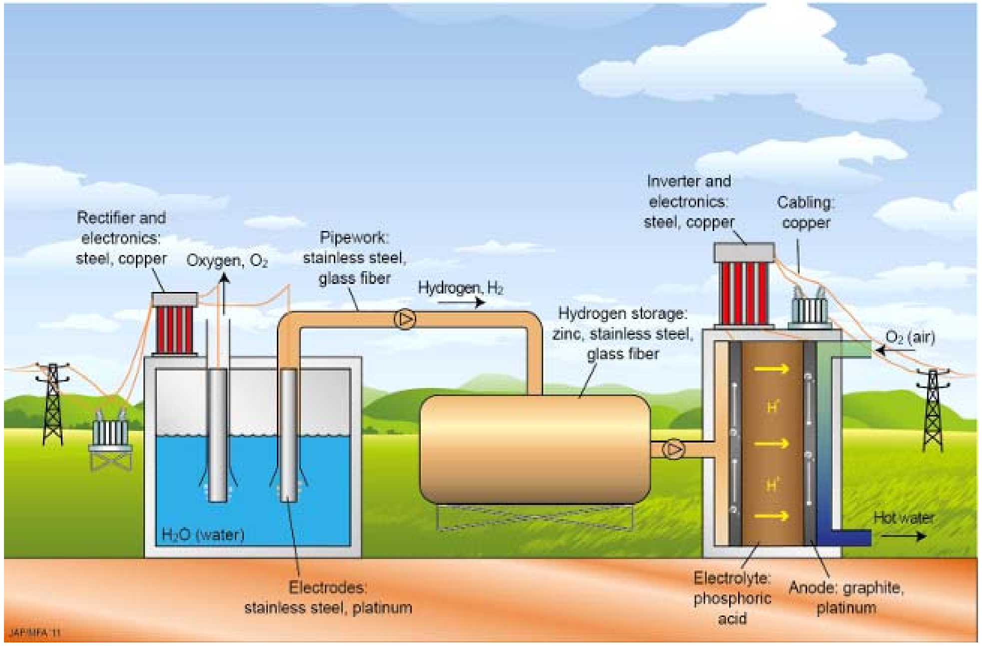
Vanadium Flow Batteries – useful numbers

Resource intensity	
Capital intensity (construction)	125 – 374 CAD/MJ
Area intensity (construction)	0.01 m^2/MJ
Material intensity (construction)	3.8 – 7 kg/MJ
Energy intensity (construction)	170 – 180 MJ/MJ
CO2 intensity (construction)	25 – 26 kg/MJ
Operational parameters	
Specific energy	0.072 - 0.13 MJ/kg
Energy density	110 – 170 MJ/m^3
Specific power	2.3 - 3.1 W/kg
Economic energy storage capacity	10 - 1e7 MJ
Economic power capacity	0.01 – 500 MW
Cycle efficiency	71 – 88 %
Cycle life	10 000 – 16 000 cycles
Operating cost	0.00474 - 0.00486 CAD/MJ/cycle
Adaptable for mobile systems	True
Status	
Current installed capacity	43 GJ
Growth rate	52 %/year

Hydrogen Storage (utility scale)

Introduction

- Energy can be stored as the chemical energy of hydrogen.
- Energy is used to electrolyze water into hydrogen and oxygen, and the hydrogen stored.
- When energy is needed again, the stored hydrogen can be passed through a fuel cell to generate electricity.



Description

- The water electrolyzer works by passing a current through water. The only way this current can flow is if the water (H2O) is broken up into positive hydrogen ions (H[+]) and oxygen gas (O_2).
- At the anode:

$$2H_2O \rightarrow O_2 + 4H[+] + 4e[-]$$

- The hydrogen ions then recombine at the cathode to produce hydrogen (H_2):

$$2H[+] + 2e[-] \rightarrow H_2$$

- The fuel cell works in a similar way to a battery. Hydrogen passes the anode, where it is oxidized into hydrogen ions and electrons at the anode:

$H_2 \rightarrow 2H[+] + 2e[-]$

At the cathode, oxygen is reduced with hydrogen to form water:

$O_2 + 4e[-] + 4H[+] \rightarrow 2H_2O$

- An electrolyte sits between the anode and cathode, and only allows hydrogen ions to pass.
- The electrons are then forced through an external circuit, where they deliver energy.
- Catalysts are required at the cathode and anode of the hydrogen fuel cell to encourage these reactions to occur. At the anode, platinum is used; at the cathode, nickel is typically used.

Hydrogen Storage (utility scale) – useful numbers

Resource intensity	
Capital intensity (construction)	68.6 – 2870 CAD/MJ
Area intensity (construction)	0.0013- 0.015 m^2/MJ
Material intensity (construction)	1.3 – 50 kg/MJ
Energy intensity (construction)	140 – 150 MJ/MJ
CO2 intensity (construction)	9.7 - 9.8 kg/MJ
Operational parameters	
Specific energy	0.02 - 0.8 MJ/kg
Energy density	1 – 70 MJ/m^3
Specific power	5 – 20 W/kg
Economic energy storage capacity	1 – 1 000 000 MJ
Economic power capacity	0.001 – 2 MW
Cycle efficiency	★ 27 – 35 %
Cycle life	5000 – 10000 cycles
Operating cost	6.86e-4 - 0.00511 CAD/MJ/cycle
Adaptable for mobile systems	True

Fuel cell doesn't seem to be used yet on the grid, efficiency is pretty close to a deal breaker…

Li-ion Batteries

- Lithium-ion batteries have an anode of graphite intercalated with lithium, and a cathode of lithium compounds.
- During discharge:
  - lithium ions (Li+) move from the graphite/lithium (LixC6) anode :

    $$Li_xC_6 \text{ -> } xLi[+] + xe[-] + 6C \text{ (x is at most 1)}$$

  - Lithium is then inserted into the lithium compounds (typically a lithium metal oxide compound ($Li(1\text{-}x)MO_2$)), to become lithium compounds with more lithium (LiMO):

    $$Li(1\text{-}x)MO_2 + xLi[+] + xe[-] \text{ -> } LiMO_2 \text{ (x is most commonly 0.5 here)}$$

Li-ion Batteries

Resource intensity	
Capital intensity (construction)	175 – 549 CAD/MJ
Area intensity (construction)	0.0021 - 0.009 m^2/MJ
Material intensity (construction)	1.5 - 3.5 kg/MJ
Energy intensity (construction)	330 – 580 MJ/MJ
CO2 intensity (construction)	19 – 50 kg/MJ
Operational parameters	
Specific energy	0.29 - 0.68 MJ/kg
Energy density	720 – 1400 MJ/m^3
Specific power	340 – 470 W/kg
Economic energy storage capacity	1 – 10000 MJ
Economic power capacity	0.01 – 1 MW
Cycle efficiency	80 – 95 %
Cycle life	300 – 2000 cycles
Operating cost	0.00237 - 0.00586 CAD/MJ/cycle
Adaptable for mobile systems	True
Status	
Current installed capacity	18 GJ
Growth rate	52 %/year

NOTE: Tesla's batteries (2170 format) are at about 0.89 MJ/kg!!!

Energy density (useful work/kg)

Gasoline: 13 MJ work/kg

Diesel: 21.6 MJ work/kg

Lead-Acid Battery

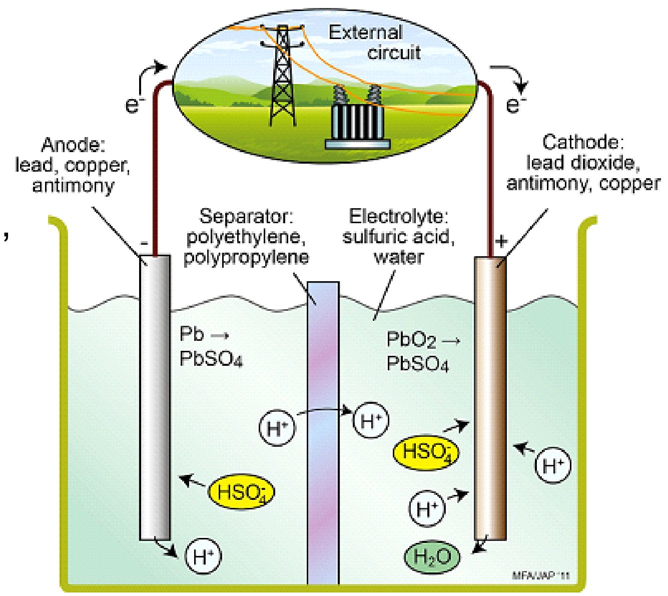
- Lead acid batteries have a lead anode and a lead dioxide cathode.

- On discharge, both of these become lead sulfate. At the anode lead (Pb) reacts with bisulfate ions (HSO4[-]) to form lead sulfate (PbSO4), hydrogen ions (H[+]) and electrons:

  Pb + HSO4[-] -> PbSO4 + H[+] + 2e[-]

- At the cathode, lead dioxide (PbO2) reacts with hydrogen ions and bisulfate ions to form lead sulfate and water (H2O):

  PbO2 + 3H[+] + HSO4[-] + 2e[-] -> PbSO4 + 2H2O



Lead-Acid Battery – Useful numbers

Resource intensity	
Capital intensity (construction)	62.4 – 274 CAD/MJ
Area intensity (construction)	0.0091 - 0.033 m^2/MJ
Material intensity (construction)	4.5 – 12 kg/MJ
Energy intensity (construction)	110 – 980 MJ/MJ
CO2 intensity (construction)	5 – 125 kg/MJ
Operational parameters	
Specific energy	0.07 - 0.18 MJ/kg
Energy density	200 – 430 MJ/m^3
Specific power	4 – 180 W/kg
Economic energy storage capacity	0.01 – 1 000 000 MJ
Economic power capacity	0.001 – 100 MW
Cycle efficiency	70 – 90 %
Cycle life	200 – 1500 cycles
Operating cost	0.00104 - 0.00349 CAD/MJ/cycle
Adaptable for mobile systems	True
Status	
Current installed capacity	500 GJ
Growth rate	52 %/year

Nickel-Cadmium Battery

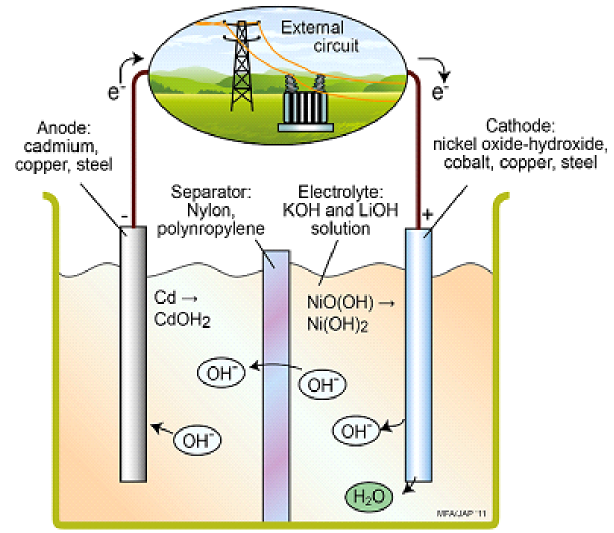
- Nickel-cadmium batteries have a cadmium plated anode and a nickel oxide-hydroxide plated cathode.

- On discharge, the cadmium (Cd) at the anode is oxidized with hydroxide ions (OH[-]) to form cadmium hydroxide (Cd(OH)2) and electrons:

  Cd + 2OH[-] -> Cd(OH)2 + 2e[-]

- The nickel oxide-hydroxide (NiO(OH)) is reduced with water (H2O) and electrons to form nickel hydroxide (Ni(OH)2) and hydroxide ions:

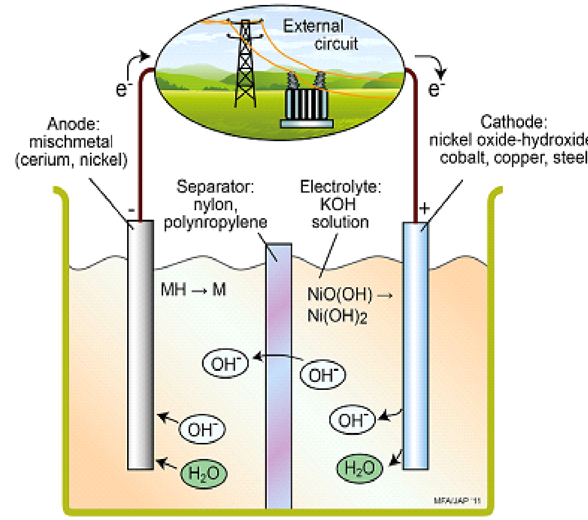
  NiO(OH) + H2O + e[-] -> Ni(OH)2 + OH[-]



Nickel-Cadmium Battery

Resource intensity	
Capital intensity (construction)	249 – 412 CAD/MJ
Area intensity (construction)	0.0062 - 0.031 m^2/MJ
Material intensity (construction)	3.8 – 11 kg/MJ
Energy intensity (construction)	390 – 640 MJ/MJ
CO2 intensity (construction)	28 – 47 kg/MJ
Operational parameters	
Specific energy	0.08 - 0.23 MJ/kg
Energy density	72 – 310 MJ/m^3
Specific power	30 – 150 W/kg
Economic energy storage capacity	0.1 – 1 000 000 MJ
Economic power capacity	0.01 – 100 MW
Cycle efficiency	60 – 85 %
Cycle life	800 – 1200 cycles
Operating cost CAD/MJ/cycle	0.00104 - 0.00686
Adaptable for mobile systems	True
Status	
Current installed capacity	24 GJ
Growth rate	52 %/year

Nickel-Metal Hydride Battery



Picture caption
Nickel metal hydride battery pack in 2010 Toyota Prius. (Image courtesy of Hybrid Cars).

Description

- Nickel-metal hydride batteries are similar to nickel-cadmium batteries, but the anode is plated with a metal hydride rather than cadmium. The metal in this metal hydride can be one of a series of different metals, common examples of which are lanthanum, neodymium, praseodymium or cerium.
- On discharge, the metal hydride (MH) is oxidized with hydroxide ions (OH[-]) to form solid metal (M), water (H2O) and electrons:

MH + OH[-] -> M + H2O + e[-]

And the nickel oxide hydroxide (NiO(OH)) is reduced with water and electrons to form nickel hydroxide (Ni(OH)2) and hydroxide ions:

NiO(OH) + H2O + e[-] -> Ni(OH)2 + OH[-]

Nickel-Metal Hydride Battery

Resource intensity	
Capital intensity (construction)	162 – 549 CAD/MJ
Area intensity (construction)	0.0033 - 0.025 m^2/MJ
Material intensity (construction)	2 – 7 kg/MJ
Energy intensity (construction)	550 – 940 MJ/MJ
CO2 intensity (construction)	28 – 67 kg/MJ
Operational parameters	
Specific energy	0.1 - 0.43 MJ/kg
Energy density	190 - 1300 MJ/m^3
Specific power	4 – 140 W/kg
Economic energy storage capacity	0.01 – 10000 MJ
Economic power capacity	0.01 – 1 MW
Cycle efficiency	65 – 85 %
Cycle life	300 – 1000 cycles
Operating cost	6.86e-4 - 0.00349 CAD/MJ/cycle
Adaptable for mobile systems	True
Status	
Growth rate	52 %/year

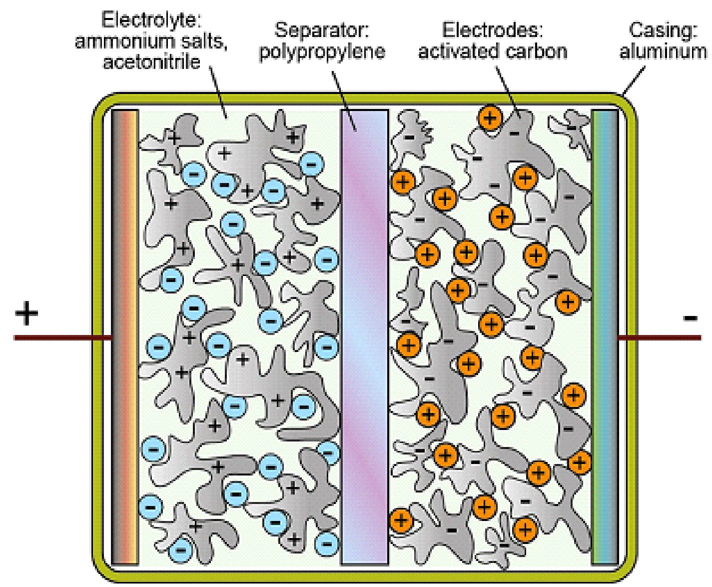
Super-Capacitors

Introduction to capacitors

- Capacitors store electrical energy directly.
- Conventional capacitors consist of two plates placed in close proximity, with a dielectric insulator between them.
- Energy is used to remove charge from one and place it on the other, creating a potential difference between them.
- Energy is extracted by allowing the charge to return, after passing through an external circuit where it delivers energy.
- Although these can be charged and discharged very quickly, their specific energy is very small at 0.00005-0.0001MJ/kg.

Introduction to Super-Capacitrs:

- electric double-layer capacitors (EDLCs, or "super-capacitors") offer scope for further improvements.
- EDLCs store the charges at the interface between activated carbon and a liquid electrolyte, rather than between two plates.
- Because of the large surface area to volume ratio of activated carbon, and the vanishingly thin distance over which the charge is stored, ultra capacitors have much greater capacitance densities and consequently much greater energy densities of 0.01-0.1MJ/kg.



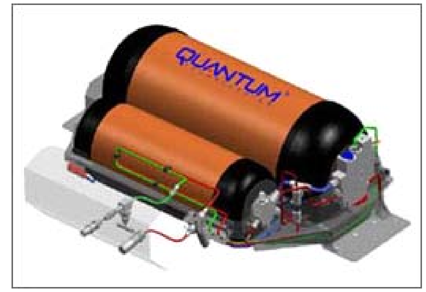
A 35 Farad super-capacity. (Image courtesy of Qingdao wuxiao tower co.)

Super-Capacitors – Useful numbers

Resource intensity	
Capital intensity (construction)	18 700 – 51 100 CAD/MJ
Area intensity (construction)	0.11 - 0.13 m^2/MJ
Material intensity (construction)	45 – 65 kg/MJ
Energy intensity (construction)	3700 – 6500 MJ/MJ
CO2 intensity (construction)	210 – 360 kg/MJ
Operational parameters	
Specific energy	0.01 - 0.02 MJ/kg
Energy density	10 – 25 MJ/m^3
Specific power	1000 – 2000 W/kg
Economic energy storage capacity	1e-4 – 100 MJ
Economic power capacity	0.001 – 3 MW
Cycle efficiency	90 – 95 %
Cycle life	1 -10 million cycles
Operating cost	0.00104 - 0.00237 CAD/MJ/cycle
Adaptable for mobile systems	True

Super-capacitors are the better choice for high power applications only!

Hydrogen Storage (onboard system)



Energy can be stored as hydrogen in a portable tank, then ran through a fuel cell to generate energy. This will be revisited in greater detail in the fuel cell section of the course.

Resource intensity	
Capital intensity (construction)	68.6 - 2870 CAD/MJ
Area intensity (construction)	0.0013 - 0.015 m^2/MJ
Material intensity (construction)	1.3 – 50 kg/MJ
Energy intensity (construction)	140 – 150 MJ/MJ
CO2 intensity (construction)	9.7 - 9.8 kg/MJ
Operational parameters	
Specific energy	0.4 – 4 MJ/kg
Energy density	200 - 3000 MJ/m^3
Specific power	50 – 200 W/kg
Economic energy storage capacity	1 - 1e6 MJ
Economic power capacity	0.001 – 2 MW
Cycle efficiency	★ 27 – 35 %
Cycle life	5000 – 10 000 cycles
Operating cost	6.86e-4 - 0.00511 CAD/MJ/cycle
Adaptable for mobile systems	True

* Neglected here is that hydrogen is a fuel with significant energy/CO_2 footprint (made with electricity off the grid at low efficiency…)