Energy Storage

4th lecture

-Fuel cells

-Mechanical energy storage

Chemical energy storage - discharging

Previous lecture - chemical energy storage: Electricity used to make a material that later can be used to generate power again. The more steps in the conversion, the less energy is recovered at the end, but the more manageable and easier to convert back into a final product.

Hydrogen, methane, ammonia, e-diesel…. How can the first three be converted back into electricity (the fourth with a diesel generator, but this is not being produced for energy storage at the moment, but for vehicle fuel).

Power-to-Gas-to-Power ← Fuel cells

Fuel cell

The fuel-cell is a way of using fuels without combustion. A redox reaction takes place in the cell (as in battery cells), but there is a need for continuous supply of fuel and air, and the end products should be removed. Chemically, what goes in and what comes out is the same as in a gas engine, only less heat is generated, with most of the energy release going to direct electricity generation.

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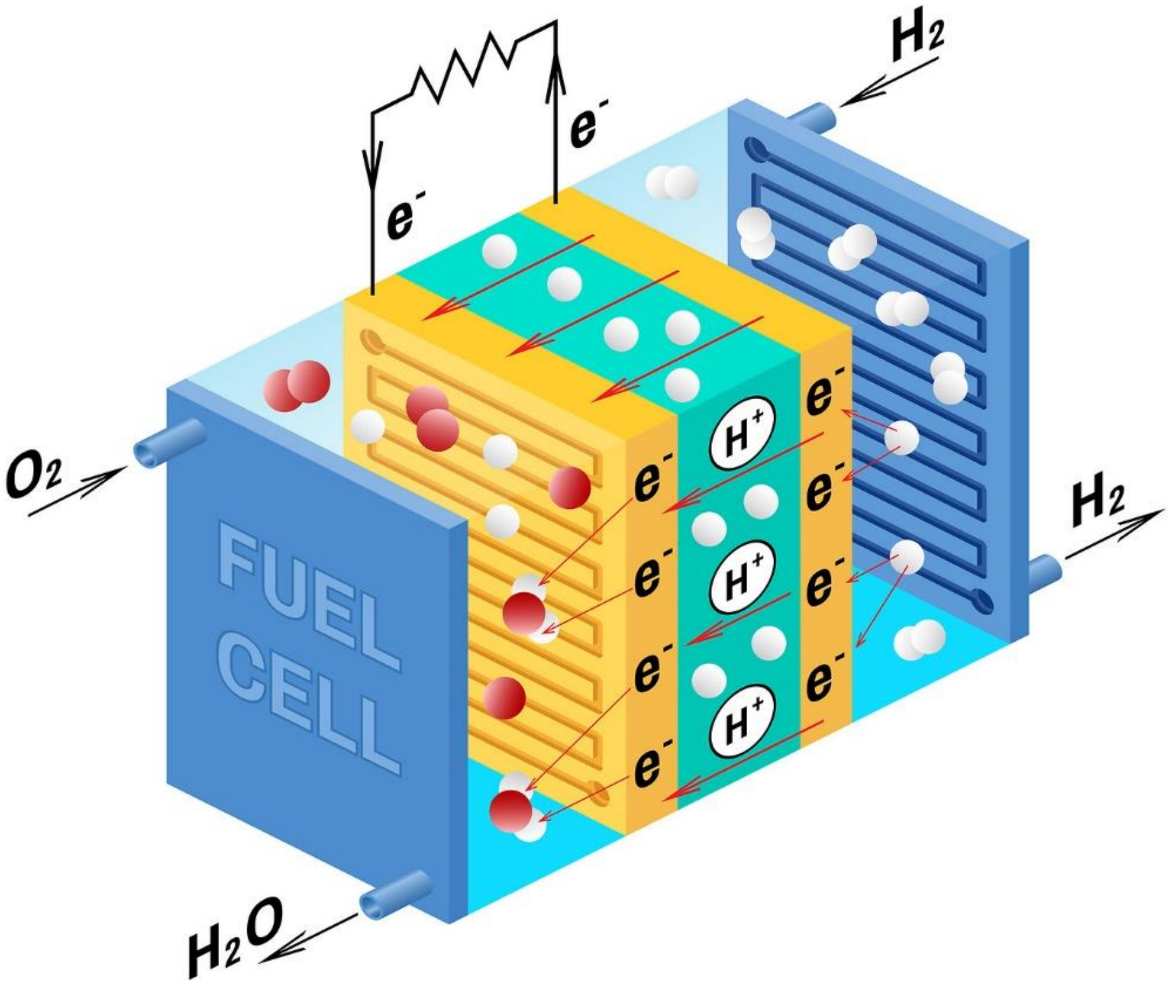
A bit similar to Vanadium-redox batteries

Fuel cell



Types

Low-temperature ones (80–220 °C)

Can be used in transportation, or small- or mid-power heat and/or power production-

Types:

- Alkaline fuel cell [AFC]; needs H2 and pure O2, the electrolyte is KOH, efficiency is 40–50% . Used in the Apollo missions as prime power source. Well-known technology. (70–140 °C)
- Proton-exchange membrane fuel cell [PEMFC]; needs H2, O2 as well as air can be used as oxidizer, the electrolyte is a solid polymer membrane, efficiency is 40–55%. It has a version where methanol used, instead of H2 (do not forget, methanol, is a chemical storage unit for hydrogen) [DMFC]. (60–120 °C)
- Phosphoric acid fuel cell [PAFC], needs H2 and pure O2, the electrolyte is concentrated phosphoric acid, efficiency is 40–45%. (160–220 °C)

Types

High-temperature cells (>220 °C)

Usage: better efficiency, for high-capacity and high-power electricity production

Types:

- Molten carbonate fuel cell [MCFC], 650 °C, can use H_2 or natural gas, needs O_2 or air, lithium potassium carbonate salt as an electrolyte. Efficiency is 50–60%, ised to heat and power (CHP), there are units from 300 kW to 2.8 MW.
- Solide oxide fuel cells [SOFC] , can use H_2 or natural gas, needs O_2 or air, the electrolyte is yttria-stabilized zirconia, 500–1000 °C, efficiency is 50–60%, warms up in 10+ minutes. Can be used as small power station.

Hydrogen - to - power

Gas turbines or engines for hydrogen: up to 5v%, without problem even present models, up to 20 v%, can buy easily, for pure (100%) only a few, expensive models. EU-goal for 100%: 2030.

Presently for pure H2 re-powerinh: fuel cell (good, but a bit expensive).

Roundtrip-efficiency 40-70%

Methane - to - Power

Easiest one, it is just natural gas (SynGas, RNG). Can be converted to power with everything, which can b used with natural gas.

- Gas turbine (Brayton cycle), gas-to-power efficiency is 50-60%
- Gáz engine (Otto-cycle), gas-to-power efficiency is 30-40 %
- Efficiency can be increased by utilizing the Waste heat to power production (for example ORC).

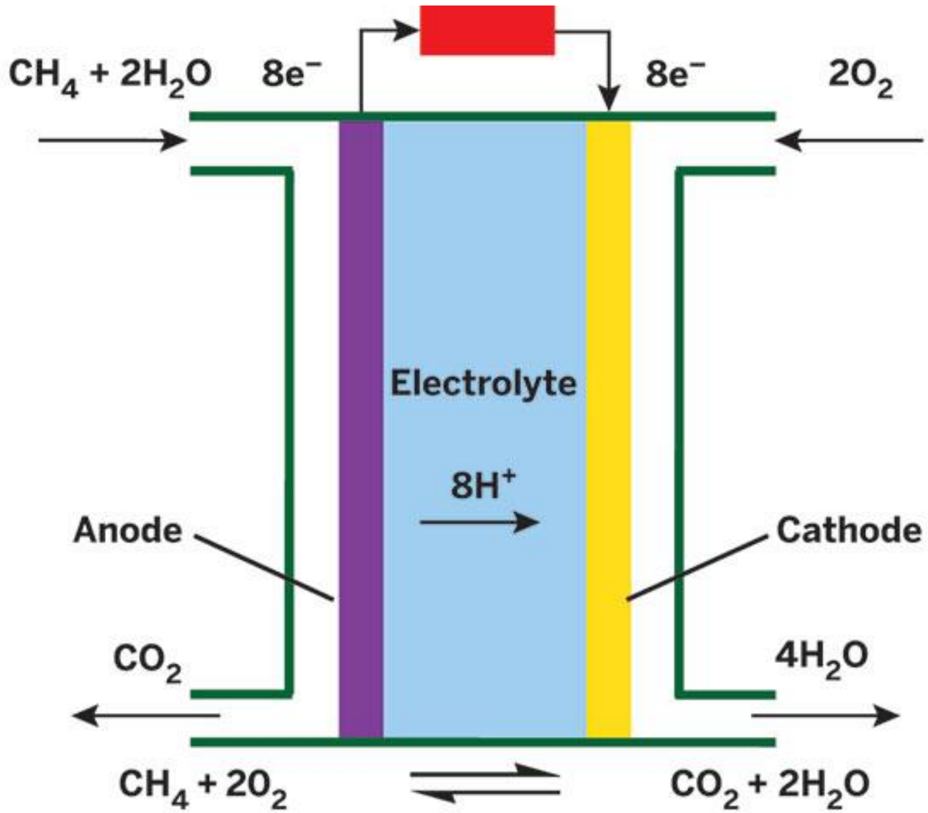
Methane - to - power

Fuel cell

- Indirect ones – first CH_4-to-H_2 (methane reformation), then H_2-to-power. In this case, CH_4 is only a storage unit for H_2.

- Direct: one step methane conversion, it is not combustion, only small amount of waste heat, high efficiency, but difficult. Usually needs high temperature, prefer permanent use.

Methane – to - power



A direct one: it I an experimental one, works on 80 ^{0}C (J. Am. Chem. Soc. 2015, DOI: 10.1021/jacs.5b06392). H is stripped from CH4 with platimum catalyst. Small power, high price!

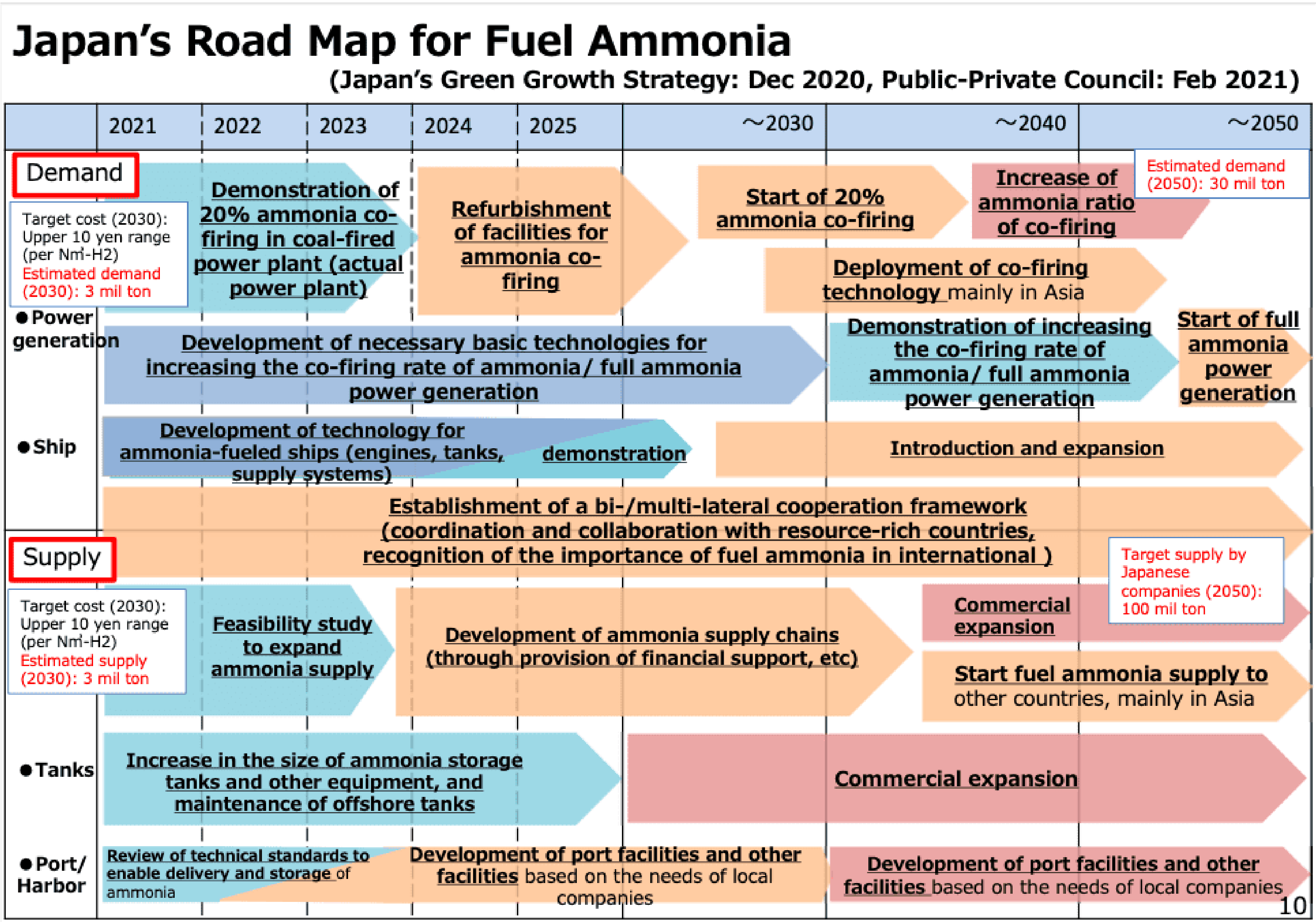
Methane – to - power

High-temperature fuel cell - solide oxyde fuel cell (SOFC); gas-to-power efficiency can reach 60%-os (this is not the power-to-gas-to-power efficiency!!)

Ammonia - to - power

- Gas engines, gas-turbines: new models available for NH_3 are coming soon, NO_x problem.
- Fuel-cells: indirect, two stem (Ammonia-to hydrogen-to-power), ammonia is only the hydrogen-storage unit.

Ammonia - to - power



What is the difference between chemical and electrochemical storage

Definitely NOT the chemical reactions; the reactions in an electrolyzer/fuel cell combo are also electrochemical ones!

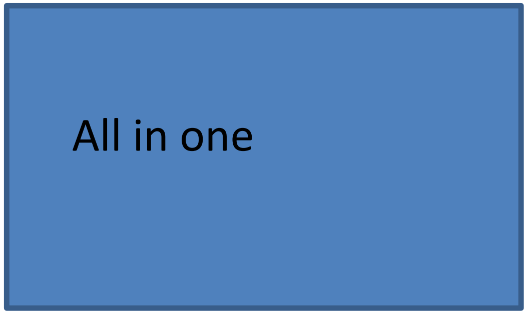
Tradition? Maybe…. Although in the present technology, one can find a well-defined difference.

What is the difference between chemical and electrochemical storage

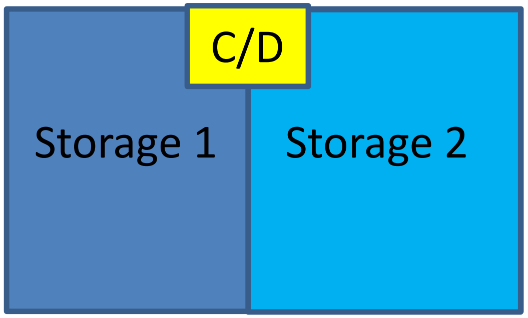
For storage, one need a charger (with charging power (Pc/kW)), a storage media (with storage capacity (Es/kWh)) and a discharger (with discharging power (Pc/kW)). These units can be separated …. or not. In this way, charging power, discharging power and storage capacity sometimes can be changed independently (i.e. you can by a unit with 1/1 kW charging/discharging power and 10 kWh storage capacity and also from the same type you can buy a 1/3/20 – when they are all separated; or you can buy a 1/1/20 when they are partly separated; or a 2/2/20, when they are not separated.

***in chemical/electrochemical storage, sometimes material 1 and material 2 has to be stored separately; in chemical one, usually one of them is not stored, just recovered from the environment.

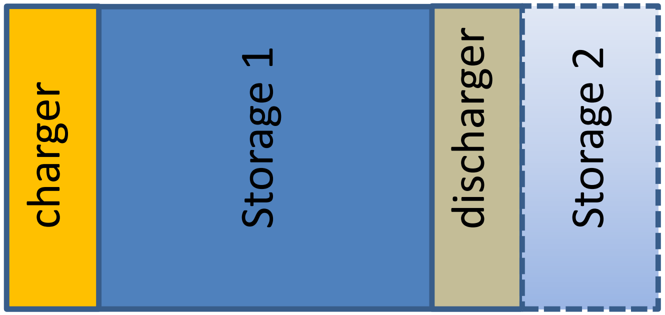
What is the difference between chemical and electrochemical storage



Most battery: charging, storage and discharging are non-separable



Vanadium redox battery: Charging/discharging in one unit ; storage are separated (in two units)



Chemical: Charging and discharging units are separated (like electrolyzer and separate fuel cell); storage(s) are also separated, although "final products" (storage2) are usually not stored.

What is the difference between chemical and electrochemical storage

Future: It is possible to construct reversible fuel cells, they can do charging/discharging in one unit. In that case, a “chemical storage system) and a battery (especially a vanadium/redox one) will be very similar.

But presently, when you have an existing Li-ion battery with given charging/discharging powers and storage capacity, you cannot buy an “upgrade kit” to improve the discharging capacity, while leave the other ones intact; you have to buy an entirely new unit. While for P2H, you can just replace the fuel cell part and keep the old electrolyzer and storage tanks and you will have a upgraded system with higher discharge capacity.

FLEXIBILITY!!!!!

Mechanical energy storages

Types

- In potential energy
- In kinetic energy, mostly in spinning

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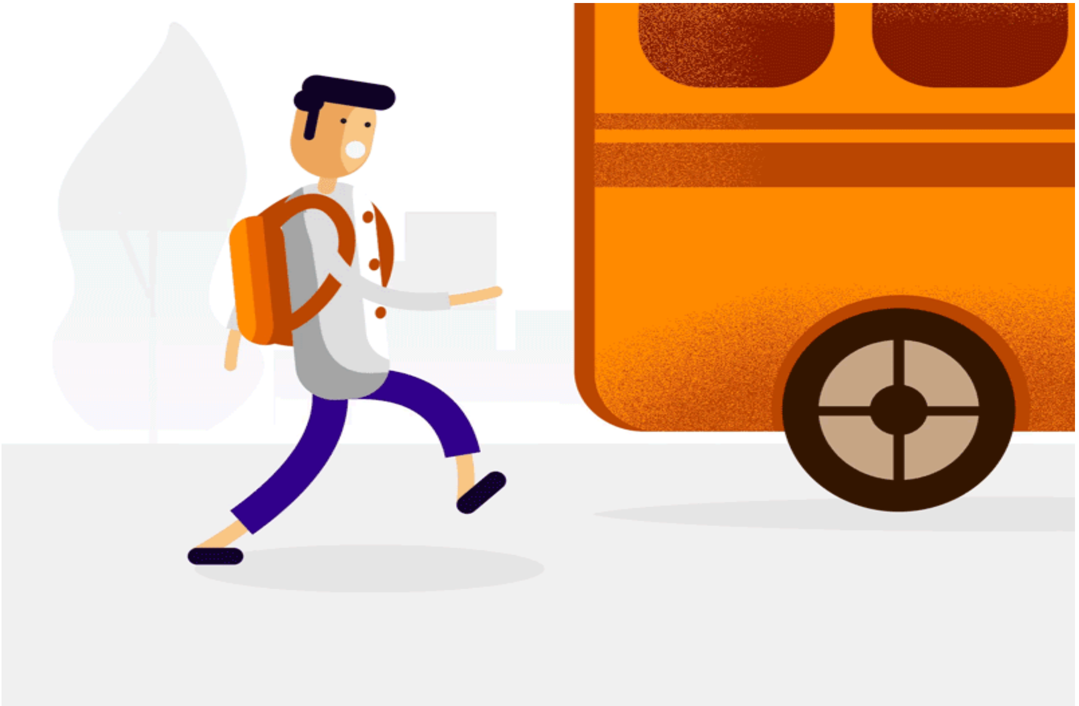
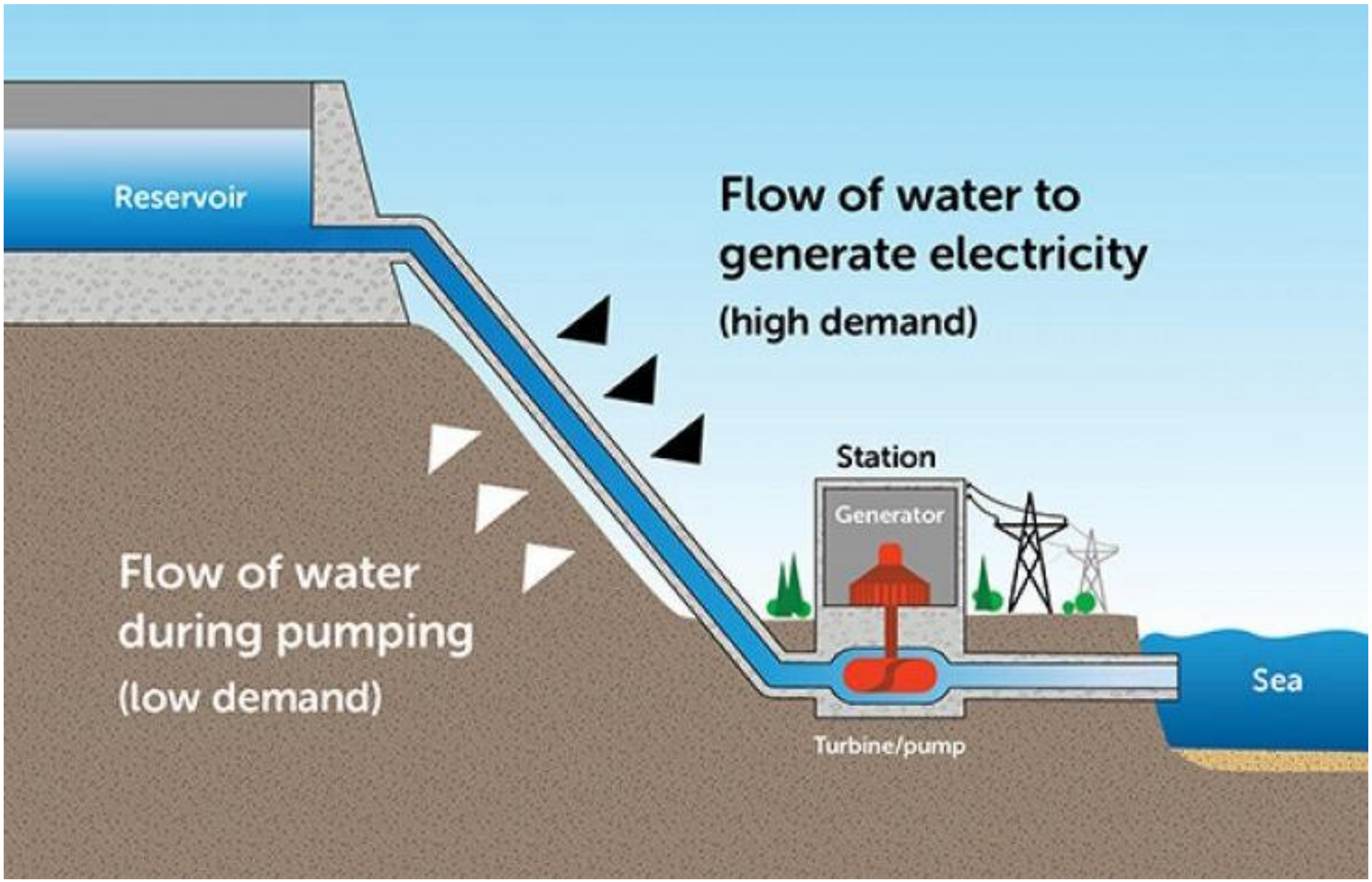


Pumped energy storage



Pumped energy storage

Storing capacity: $m*g*h=\rho*V*g*h$

Even high mass (1 m^3= 1 ton) means low energy – low energy density!

1 liter (1 kg) water on the roof (5 m): 500 J (0.138889 Wh) … just to remember, lead-acid batteries 25-40 Wh/kg

Self-discharge: evaporation, leakage

Pumped energy storage

Pros

Good for seasonal storage, low self-discharge, well-known technology

Contras

- High investment, low energy density, “virtually” high ecological footprint, needs special environment

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Hoover-dam, USA

Colorado River (Lake Mead)
180 m
Approx. 2000 MW
19500 km^3

CAES, Compressed Air Energy Storage

Usually air, but can be other gases.

Compression can go to liquid states (high energy density).

CAES, Compressed Air Energy Storage

Energy recovery with turbines.

Storage of small quantities in tanks and large quantities in underground storages.

Small tanks: usually not for power, but for shaft work.

Current larger storage: Germany, Huntorf, 290 MW (1978); USA, Alabama, McIntosh, 110 MW (1991), USA, Texas, Gaines, 2 MW (2012)

All major reservoirs are geologically pressurised (75 bar; over 700 m depth)

Can be used in very specific locations (geological reservoirs).

Huntorf, Germany

Compressed air in two “”solution-mined”” salt caverns, a total of 310,000 cubic meters. Cavern depth: more than 600 m, specified maximum pressure of 100 bar. One cavern is cycled on a daily basis. The second cavern serves as a black start asset if the nearby nuclear power plant unexpectedly goes down.
321 MW maximum! Works since 1978, can keep air for over six months.

Smaller CAES systems (tanks)

1.0 m3 air, 200 bar, in 5 liter can store 530 kJ. Under good conditions, 300 kJ shaft work can be recovered.

Can be used to kick-start smaller or medium engines (shaft-work).

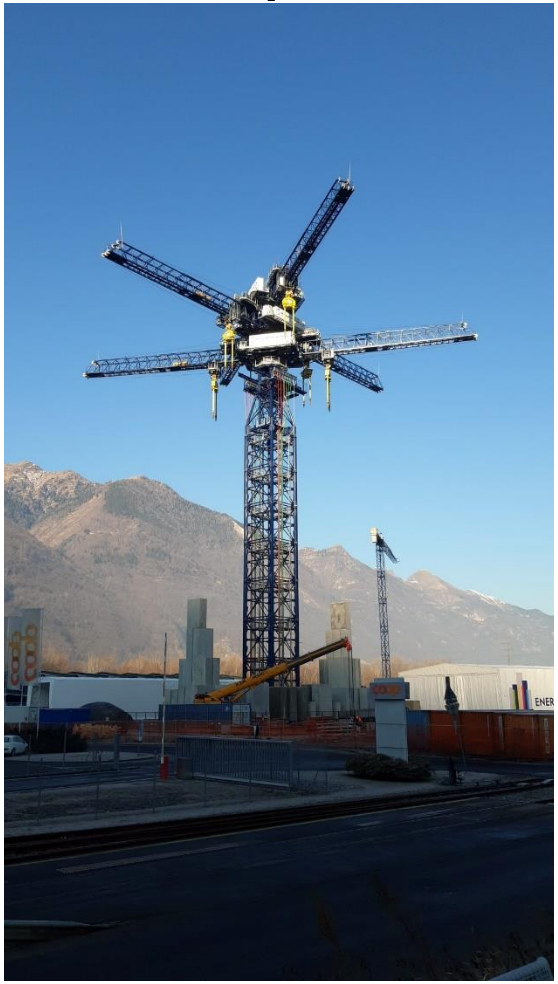
Mass storage

Similar to pumped energy storage, but instead of water, a denser material used. Special concrete can reach six times higher density!

A special case: energy tower (Energy Vault, Switzerland)

Plan: a six-arm crane, to, charge-discharge

Company founded in 2017, now in New York Stock Exchange, worth over USD 400 million…. and still no working storage system:-(



Test tower

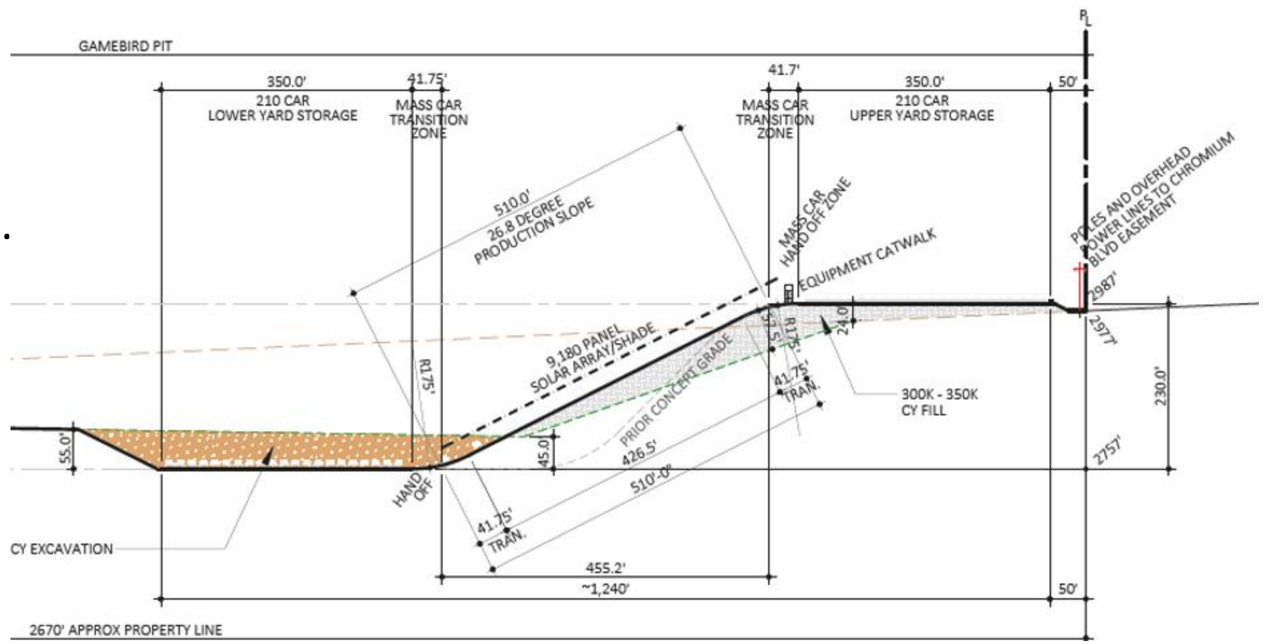
… and an other

Advanced Rail Energy Storage, USA, (ARES)

Loaded railroad cars are towed up during charging (with surplus electricity), discharged by releasing them.

Latest news on the company homepage is 2-years old☹

ARES Nevada, 50MW, 210 cars (75,000 tons, 10 tracks.



What is the self-discharge for an energy tower?

“Solid gravity storage” system: Cheops pyramid

original height was 146.7 m, now 138.8 m

current mass is about six million tons, volume 2.3 million cubic meters, age is about 4500 years.

Both original (freshly charged) and present (still charged, but after 4500 year self-discharge) are approximated as regular pyramid; the size of the bases was assumed to be constant, and the loss was calculated from the loss of mass and height.

Stored at zero time: 634 MWh; current energy content was 567 MWh

“self-discharge” is 10.5% over the whole lifetime, 0.00064%/day (comparable to P2M methods, but the big advantage is the long lifetime in the “no load” condition, which in this case exceeds 1000 years.)

What is the self-discharge for an energy tower?

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Store 57 MWh

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years.)

And finally a kinetic one: flywheel storage

Relatively small in size, they can be "switched on" and used as a power source immediately after a shutdown.

The size of the flywheels is limited in order to ensure running stability (minimum precession). The largest commercially available units built by the market leader have a power output of 100 kW at 25 kWh capacity, a rotor diameter of 3 feet (~914.4 mm), a rotor length of 7 feet (~2133.6 mm), a mass of 2500 pounds (~1134 kg), a speed of 15 500 rpm (258.33 1/s), and a peripheral speed of 742.1 m/s. At this speed, the unit must be placed underground for safety reasons.

The standard design life is 20 years or 125 000 equivalent cycles.

Montezooma's Revenge Roller Coaster

The roller coaster's cars are accelerated to 89 km/h in 4.5 seconds by energy from a flywheel reservoir. It goes through a loop (23 m in diameter), up an incline (45 m ascent), then stops, and when it comes back down, it loops again. The flywheel weighs 7.6 tonnes, slowing from 1044 rpm to 872 rpm at start-up.

Projects

Power-to-ammonia: the present status

Power storage by heat: the Carnot batteries

Heat storage by phase change materials

- for a house
- transportable version for industrial vaste heat

Energy Vault : a tower for energy

Estimation for fueling the transportation of a country entirely with green hydrogen (from PV or wind)

…or anything else!

Next week

- Heat storage

Thanks for your attention