LARGE-SCALE ENERGY STORAGE

Renewable. Rechargeable. Remarkable.

THE ENERGY PROBLEM

- **Energy Demand varies** unpredictably, operators need to react by
  - fine-tuning the output of coal-fired power plants
  - turn on *peaker* gas plants during high demand
- In order to keep the extra plants to a minimum, utilities companies adopt demand side management

With the advent of the **renewable revolution**, things got even worse!

The **unpredictability** is now not only in the demand,

but also, and mostly, **in the supply**.

Possible answer:

- demand dispatch, software-driven *smart* energy-consuming equipment in order to use electricity when abundant, cheap or green. This approach still faces unsurmountable challenges
  - regulatory uncertainty
  - doubts on whether grid companies or users should pay for its adoption [1]

IF WE WANT A SIGNIFICANT PART OF OUR ENERGY TO COME FROM RENEWABLE SOURCES, **STORAGE IS A MUST.**

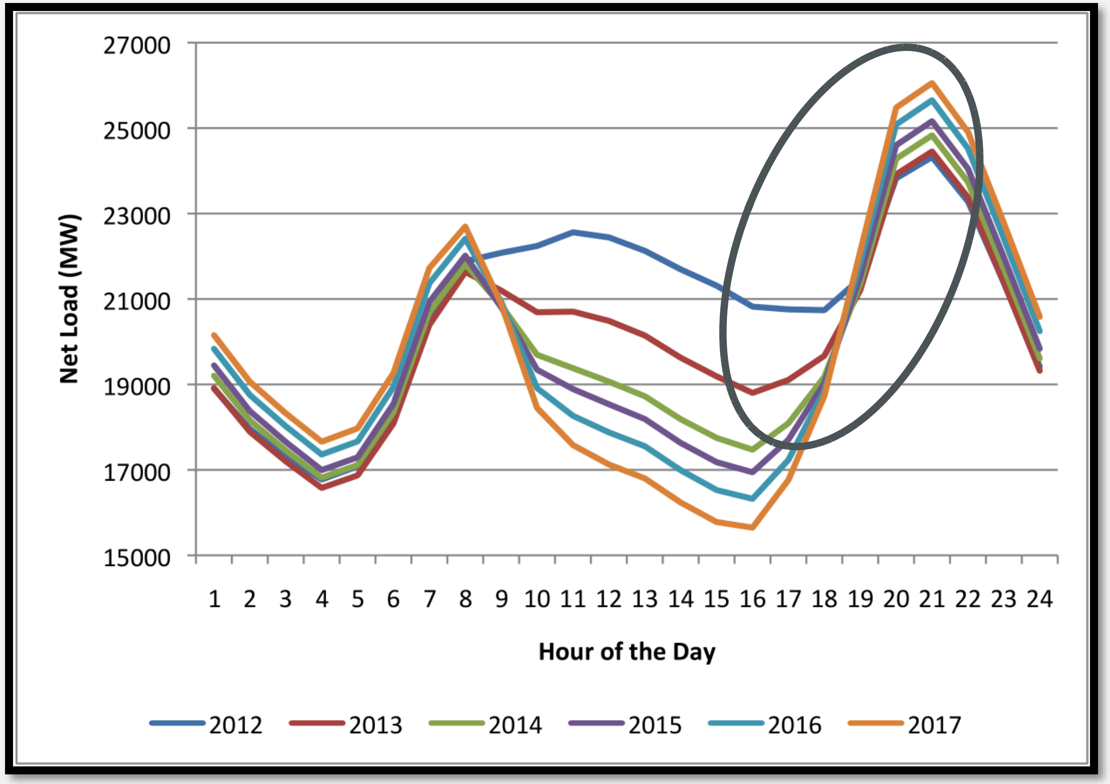
The **expense for downtime** due to blackouts is estimated at **$135 billion** per year in the US alone [2].

Energy that is **not exploited** in Italy due to *curtailing* of wind and solar plants is assessed at 166 GW in 2012 [3].

The European **infrastructure system** needs investments up to **€500 billion** to allow for renewables penetration [4].

Storage technology, if adopted in a sufficiently large scale, can

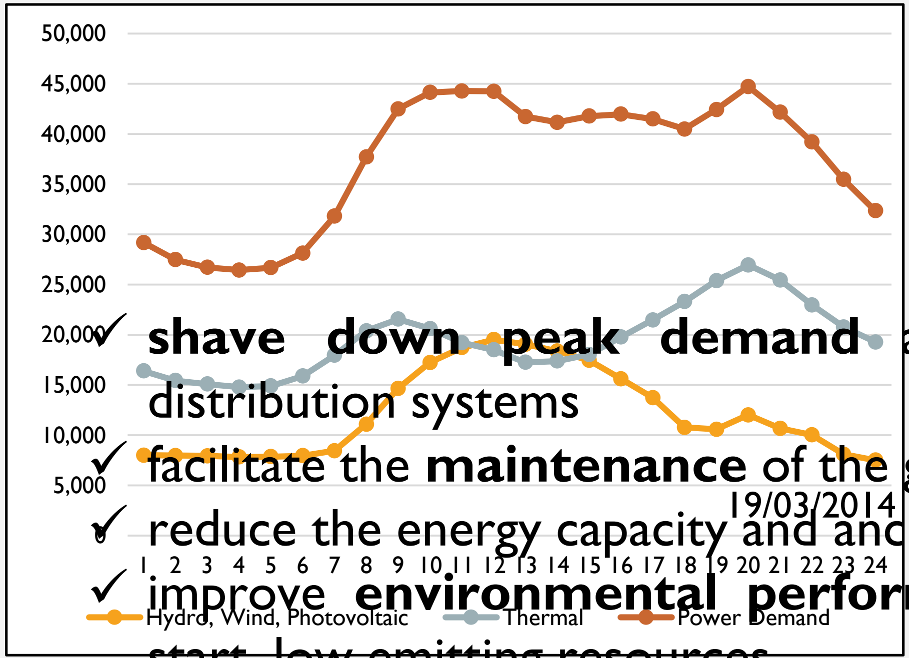
- help with the short, steep ramps in power demand, shown in the *duck graph*, that are due to the effects of **self generation** from renewable sources
- reduce the risks of **over-generation**, which causes imbalances to the grid
- increase the frequency response → less resources are required in order to adapt to the energy demand

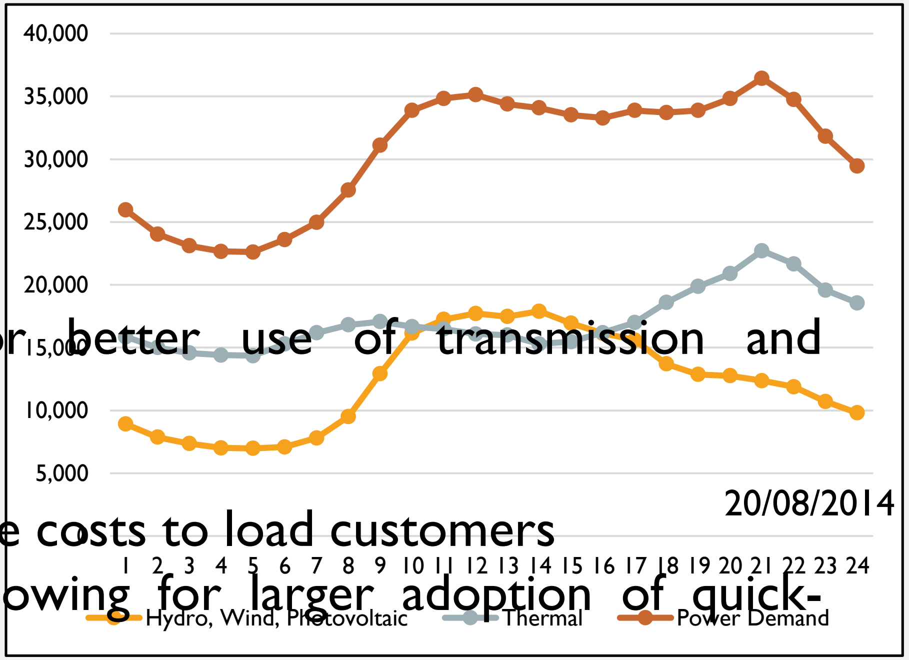


Power Demand in California, USA. Data from California Energy Commission staff, Energy Assessment division 2015

Most of them are better suited for sustaining **ramps**, even with sudden changes in direction, **reacting quickly** to meet the required operating levels; starting and stopping with short notice, multiple times per day.

BENEFITS





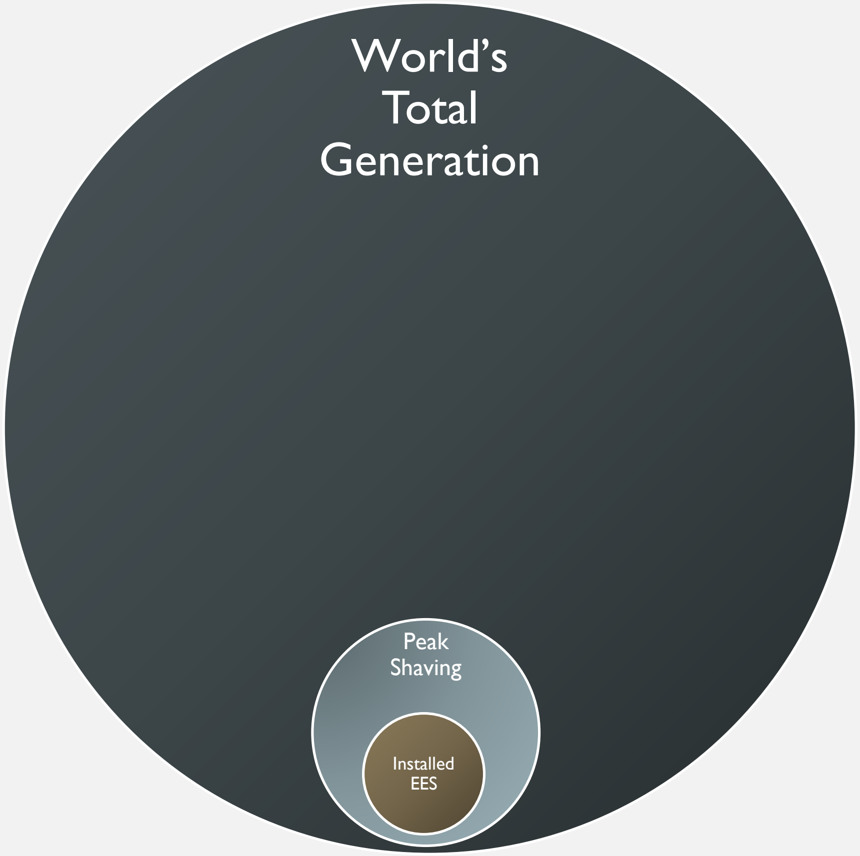
- ✓ **shave down peak demand** allowing for better use of transmission and distribution systems
- ✓ facilitate the **maintenance** of the grid
- ✓ reduce the energy capacity and ancillary service costs to load customers
- ✓ improve **environmental performance**, allowing for larger adoption of quick-start, low emitting resources
- ✓ assist the successful integration of **Variable Renewable Energy Sources** [5]

The power demand for Italy doesn't look quite as skewed as the one California has to face.
What are the benefits for introducing storage systems in such a market?

Production From Renewables in Italy

Data from "Statistical Data on electricity in Italy", Terna, 2014

CURRENT SITUATION



As we speak, the **installed** Electrical Energy Storage (EES) capacity is approximately **125 GW** worldwide.

This is about 3% of the world's total generation, amounting to **3.9 TW**.

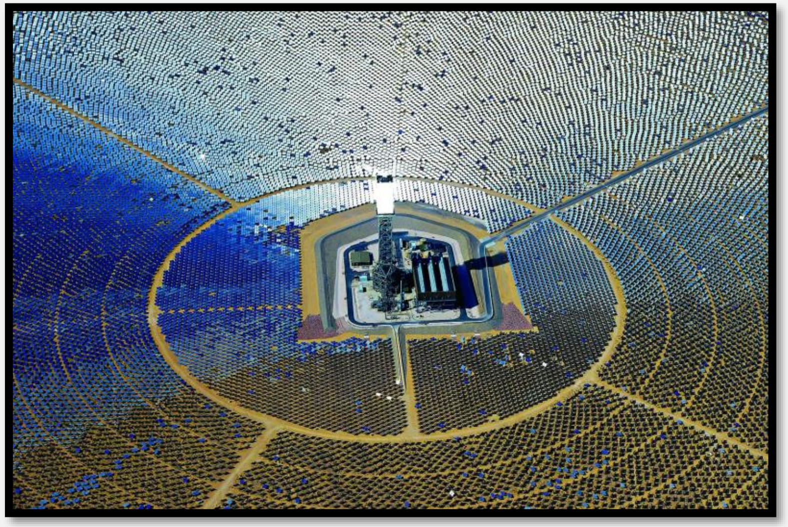
On the other hand, performance studies have suggested that about **8%** of the total power capacity should be enough to accomodate **peak shaving** purposes [6].

APPROACHES

- Pumped Hydroelectric Storage (PHS)
- Compressed Air Energy Storage (CAES)
- Hydrogen Storage
- Battery Storage
- Thermal Energy Storage (TES)
- Flywheels, Capacitors, etc.

PHS plant in Wendefurth, Germany

CAES plant in Huntorf, Germany



CSP in Ivanpah, California, USA

PUMPED HYDROELECTRIC STORAGE (PHS)

- Most established technology for utility-scale electricity storage since the 1890s
- Only large-scale technology available commercially for grid-tied electricity storage
- In Italy, there are 22 PHS stations with a total capacity of 7669 MW [Terna]

Reversible pumps/generators connect an upper and a lower reservoir. Water is pumped during times of high availability and released to generate power during peak hours.

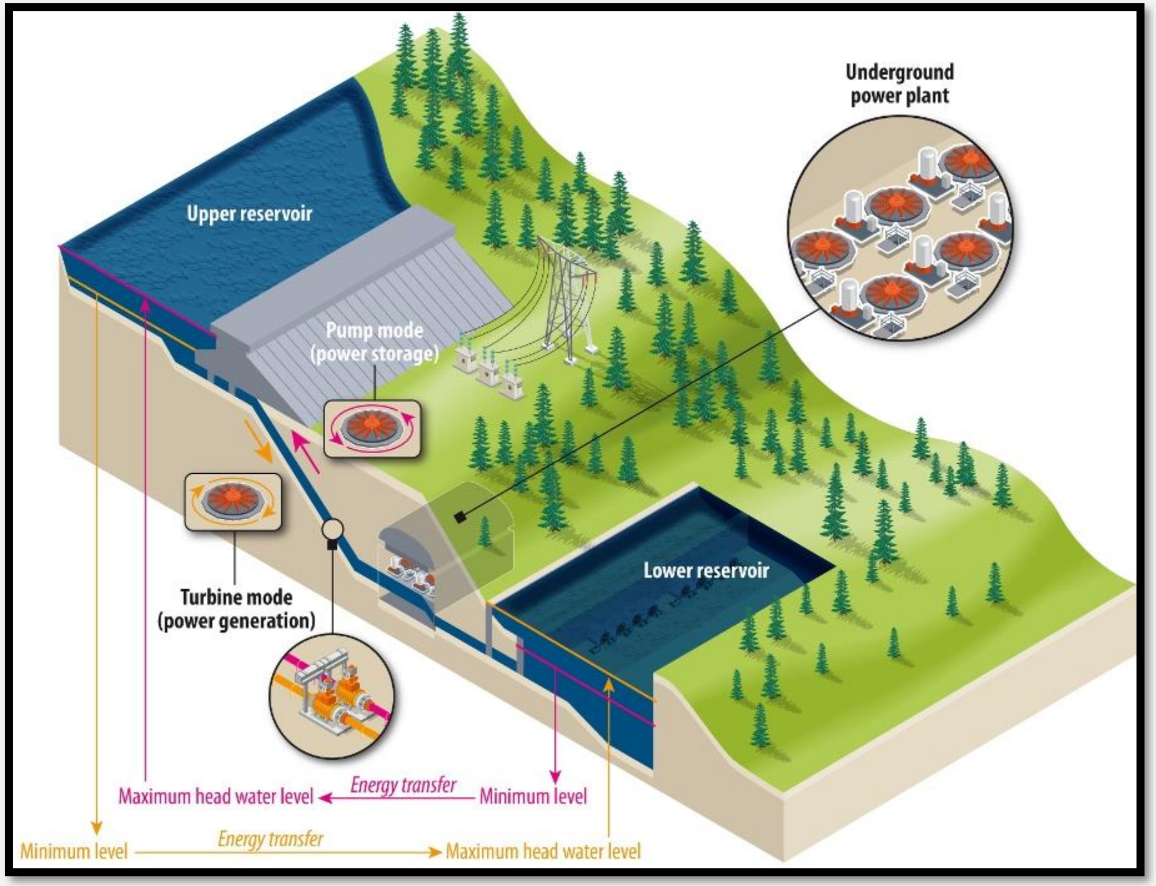
PHS facilities are divided in:

- Pure (or off-stream) PHS
- Reversible pump-turbine sets

The energy related to the storage of a volume V of water can be computed as

$$\boldsymbol{E_P} = \frac{\rho g h V}{3600 \eta_P}; \; \boldsymbol{E_G} = \frac{\rho V g h \eta_G}{3600}$$

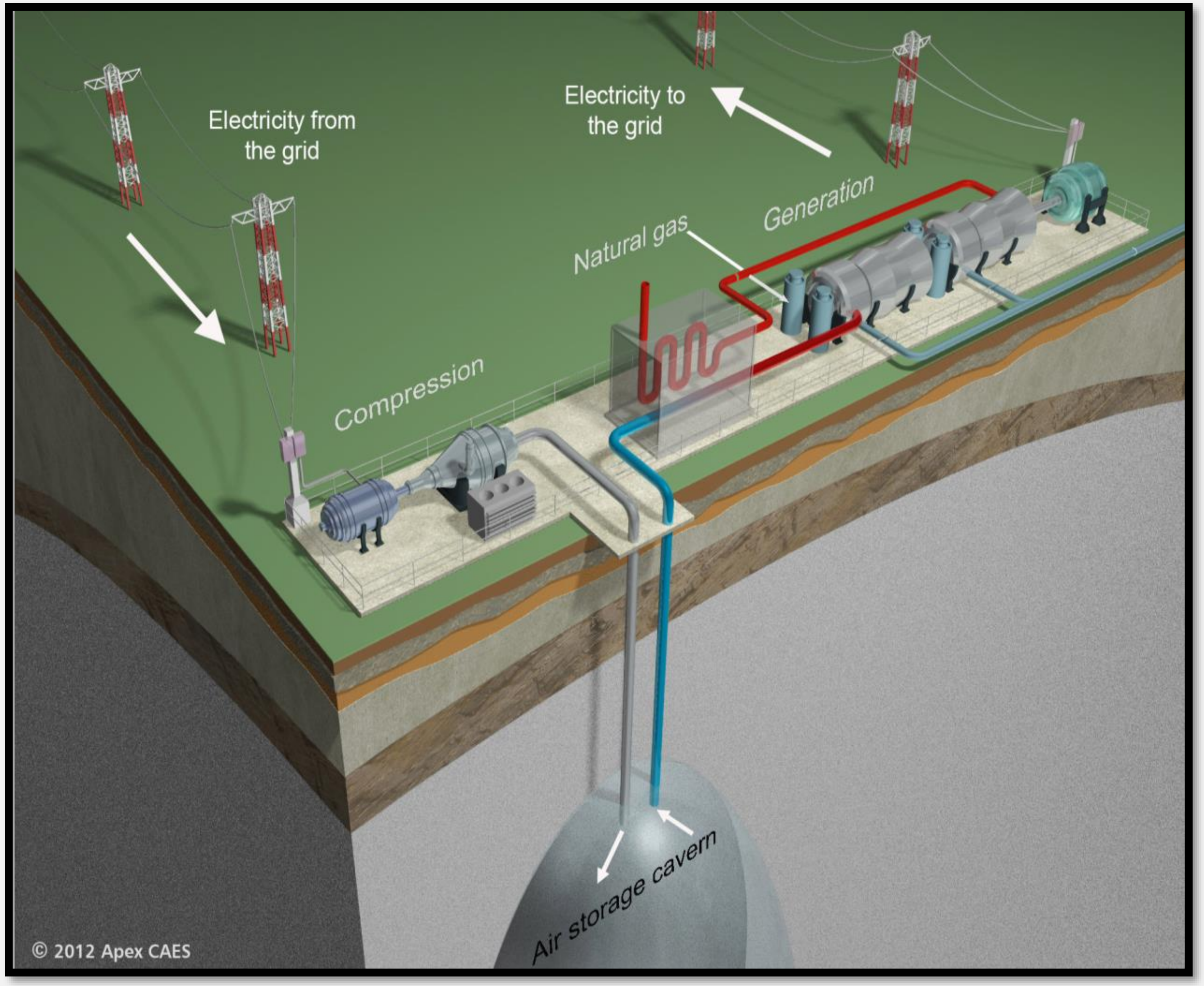
Typically, the overall efficiency $\boldsymbol{\eta} = {}^{E_G}/_{E_P}$ is within *70-80%* [7]



COMPRESSED AIR ENERGY STORAGE (CAES)

CAES systems:

- **Ordinary CAES** system
- CAES system with **recuperator**: this system applies regenerative cycle technology to CAES. The heat content of the exhaust gases is recovered with a HX to preheat air entering the combustor.
- **Advanced adiabatic** CAES system: heat is extracted and stored separately before the compressed air enters the cavern in order to avoid the efficiency loss due to the air cooling down. [8]



The compression power, is given by

$$P_C = \frac{\gamma}{\gamma - 1} p_1 \cdot \dot{V} \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma}{\gamma-1}} - 1 \right]$$

PHS advantages

- large *capacities*
- *low* operation and maintenance *cost*
- high *reliability*

Disadvantages

- They require *suitable terrain*
- *Construction* takes many years
- *Environmental impact* is a serious concern [9]

CAES advantages

- High *power* capacity
- Large *energy*-storage capacity
- Long *storage period*
- Low capital *cost*

Disadvantages

- Reliance on *favourable geography*
- Low *energy density*
- *Not carbon neutral* in most cases [5]

The potential impacts of PHS and CAES projects are site-specific and must be evaluated on a case-by-case basis

HYDROGEN STORAGE

The process is divided in **three steps**:

- Electrolysis plant:
  - Water is split into $\mathrm{H_2}$ and $\mathrm{O_2}$ in an electrolysis cell by supplying direct current to the electrodes
  - $\mathrm{H_2O} + w_{el} \rightarrow \mathrm{H_2} + \mathrm{O_2}$
  - Fuel cells, also denoted Proton Exchange Membranes (PEM), have simpler process layout, since there is no circulating liquid electrolyte
- Hydrogen storage:
  - The gas is compressed and stored in **pressurised storage tanks**: $\mathrm{H_2}$ can be stored as *compressed gas*, as *cryogenic liquid*, in solids (metal hydrides, carbon materials) and liquid *carriers* (methanol, ammonia)
  - **Compressed gas** storage is most relevant for large-scale stationary storage systems. Compression of $\mathrm{H_2}$ is normally achieved by use of piston compressors or centrifugal compressors
  - A future option could be within **bedrock** consisting of porous material
- Hydrogen-fuelled power generation:
  - The reverse reaction of water electrolysis (combustion) takes place:

    $$\mathrm{H_2} + \mathrm{O_2} \rightarrow \mathrm{H_2O} + q$$

    q which is then fed to a conventional power plant
  - In fuel cells, chemical energy is converted to electrical energy [12]

Advantages

- In comparison with other energy storage systems, H_2 offers great **flexibility in sizing** because of the modularity of electrolysers, fuel cells and storage tanks
- H_2 engines are cheap and reliable
- H_2 has **good combustion properties** with high flame velocity and adiabatic temperature

Disadvantages

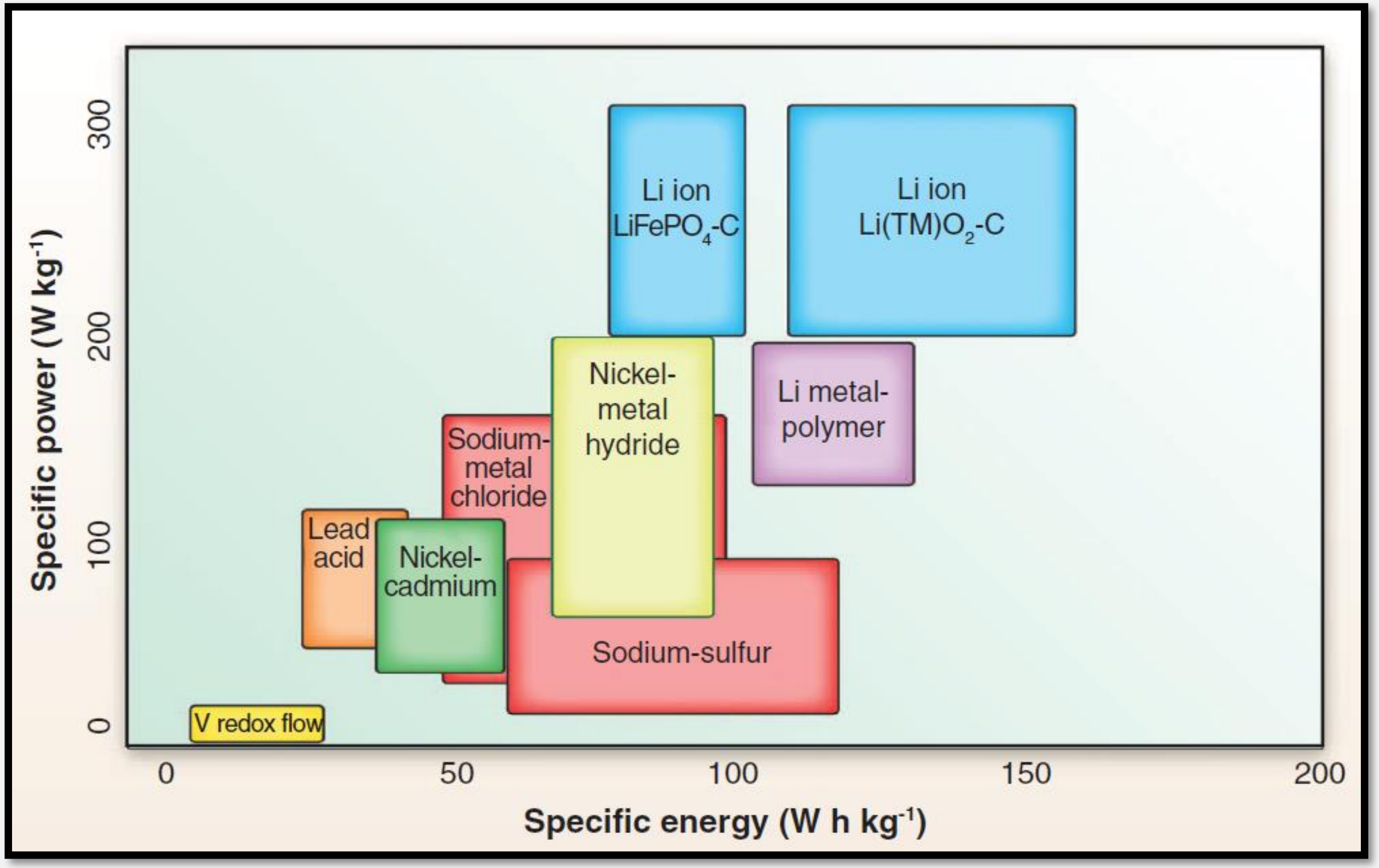
- **Low** round-trip storage **efficiency** (electricity-H_2-electricity)
- Low *reliability* and *lifetime* of fuel cells
- Limited capability of electrolysers to operate with fluctuating power input
- **High cost** of system components like catalysts and polymer membrane
- Intermittent operation may cause impurity of H_2 in O_2 and viceversa
- The alkaline electrolyte is very corrosive, the electrode will corrode if the production is stopped [11]

MYRTE Hydrogen Storage plant in Ajaccio, France

BATTERIES

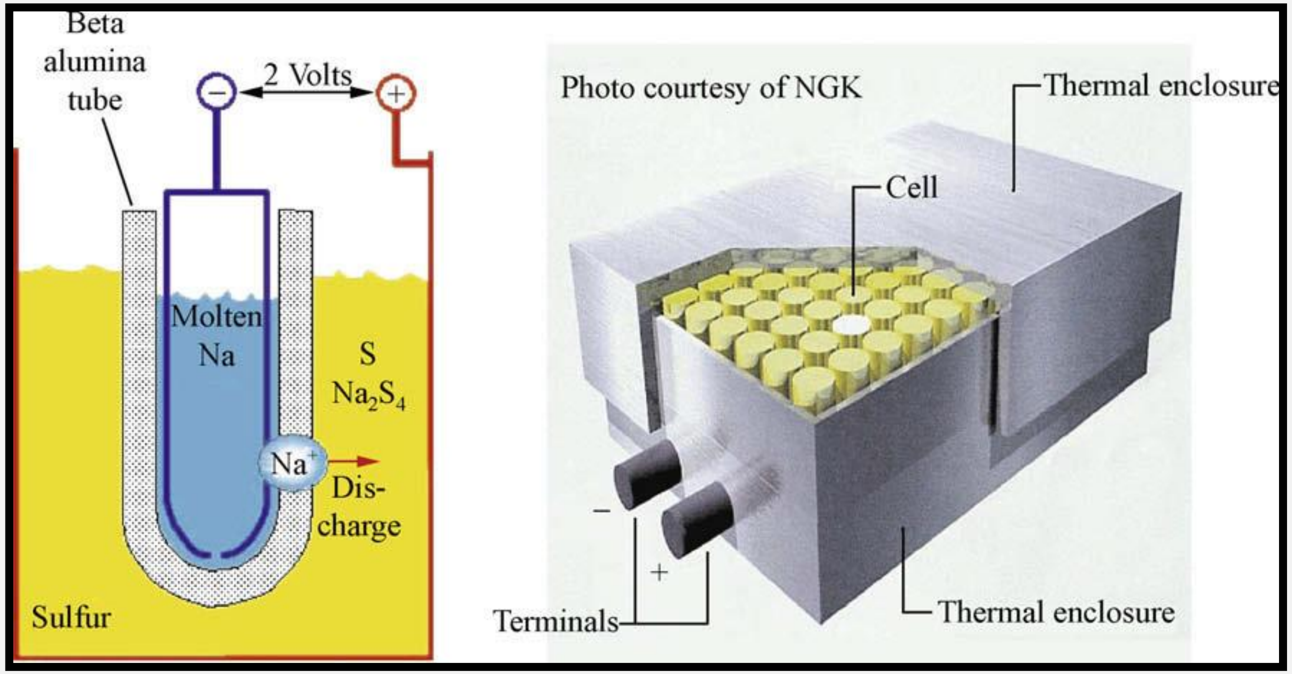
Available battery technologies:

- Lead acid (LA)
- Nickel Cadmium (NiCd)
- Sodium Sulphur (NaS)
- Sodium Nickel Chloride (ZEBRA)
- Lithium ion (LiB)
- Flow battery: vanadium redox (VRB)



Most of these technologies are currently **being investigated** for grid storage applications.
Today NaS is the only commercially established one [5].

SODIUM-SULFUR BATTERY



Reaction

$$2Na + 4S \rightleftharpoons Na_2S_4$$

NaS batteries are characterized by **high energy** ($150 \div 240$ Wh/kg) and **power densities** ($150 \div 230$ W/kg).
The efficiency is almost 90% and the **pulse power** capability is significant

NaS cells **have to be kept at** $300 \div 350$°C (at this temperature the β-alumina electrolyte is permeable and conductive for the Na^+ ion). This represents the **major drawback**: the heat source requirement reduces battery efficiency. The challenge is to *lower the operating temperature* in the next years, in order to make this battery more and more competitive.
Another important issue is **safety**: the *corrosivity* of the sulfur and its compounds and the high temperatures of the cells are potentially dangerous. An accident occurred on September 21, 2011 in Tsukuba, Japan, where a NaS battery storage plant caught on fire [13].

THERMAL ENERGY STORAGE (TES)

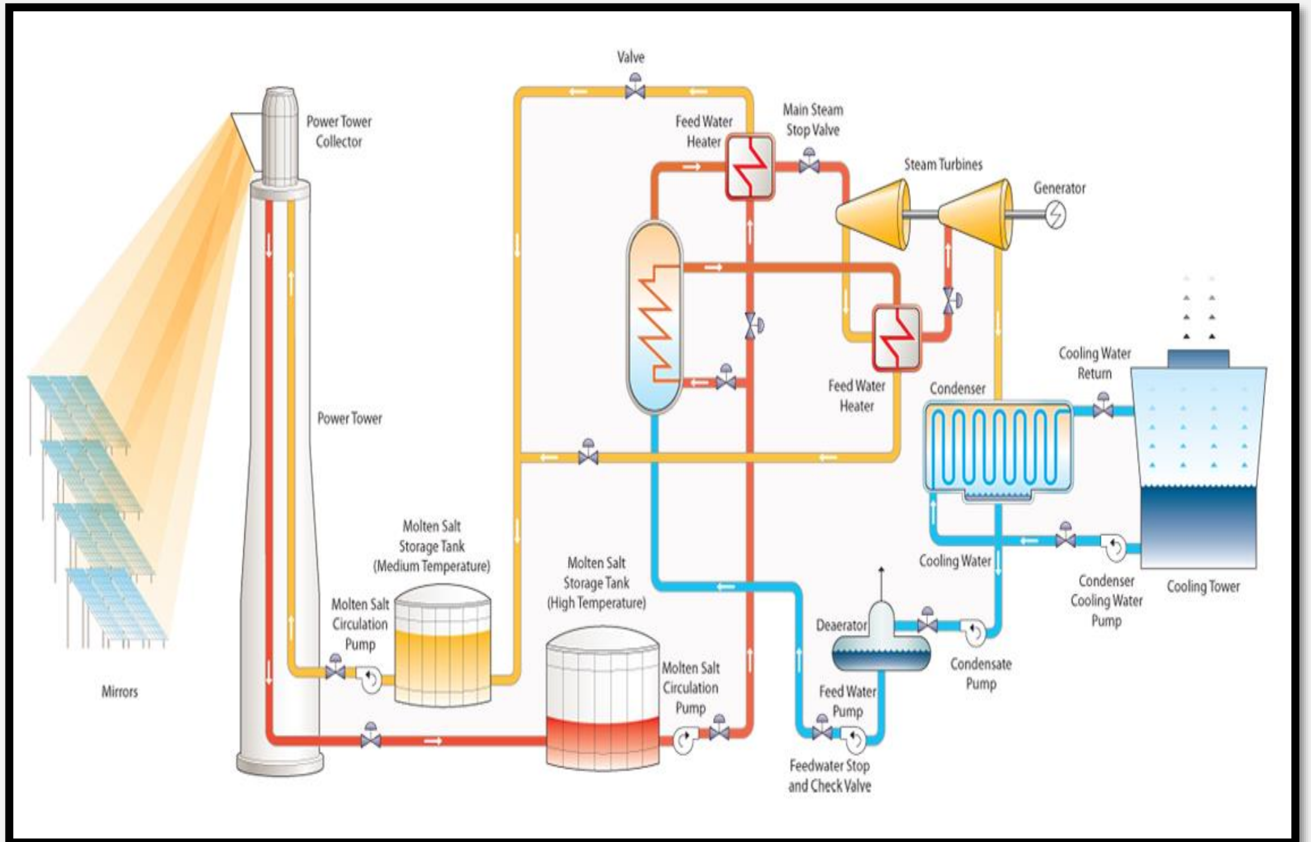
Mainly adopted in **large-scale CSP** plants, to allow work as a base-load generation technology.

Heat can be stored by means of:

- Sensible heat in *solids or liquids*
- *Phase-change* materials
- *Thermochemical* reactions

There are other, non-solar ways to store thermal power that exploit an excess of electricity during off-peak generation:

- **Pumped Heat Energy Storage** (PHES): electricity is used to drive a *heat pump* which is reversed to become a heat engine when needed.
- **Cryogenic Energy Storage** (CES): excess of electricity is used to generate a liquid fluid (air or N_2) at very low temperature that is later exploited by a heat engine.



In PHES systems, **concrete** can be used as a solid storage material from which power can be estracted using synthetic oil as carrier.
The most used liquid material is **molten salt** (KNO_3-$NaNO_3$ with $Ca(NO_3)_2$ or $LiNO_3$ mixture) due to its relatively *low cost* and *high operative temperature* ($500 \div 600°C$), compatible with classical steam turbines.
Phase-change materials exploit the latent heat released during the liquid-solid transformation. Constant temperature during charge/discharge, *high storage density* and temperature flexibility.
Thermochemical reactions are mainly used for long-term storage; high storage density and low heat losses. High amount of energy required, **solar fuels** can be produced via endothermic reversible reactions [10]:

Advantages

- They *reduce the mismatch* between solar insolation and demand through buffering
- *Low thermal losses* (no more than 3%)
- *Increased* annual solar-to-electricity *efficiency* → LCOE reduced by about 10%
- Less turbine start-up energy use

Disadvantages

- Requirement for *large solar fields*
- High *capital costs*
- *Increased operation losses* in the system

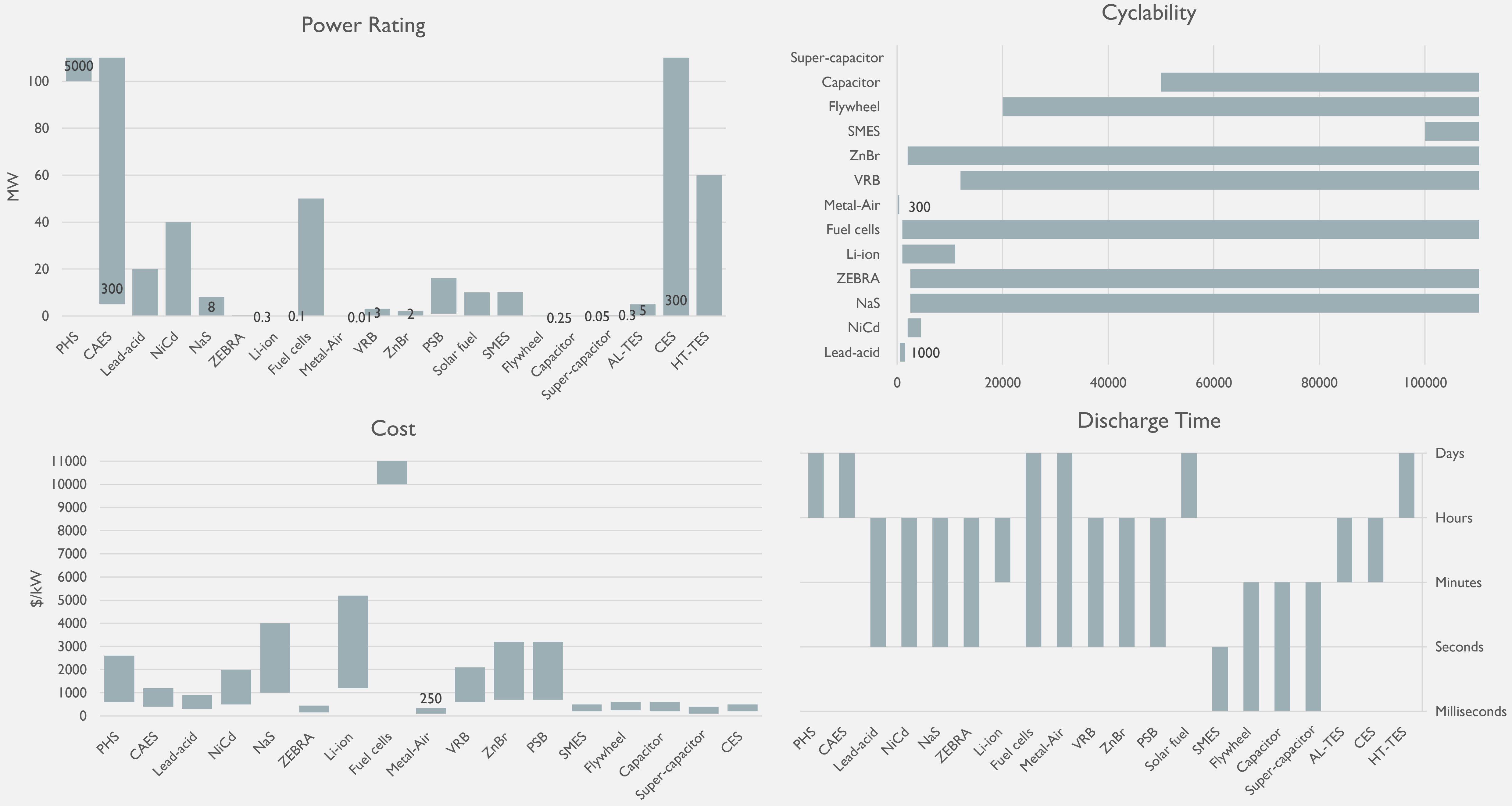
Methane reforming

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2$$

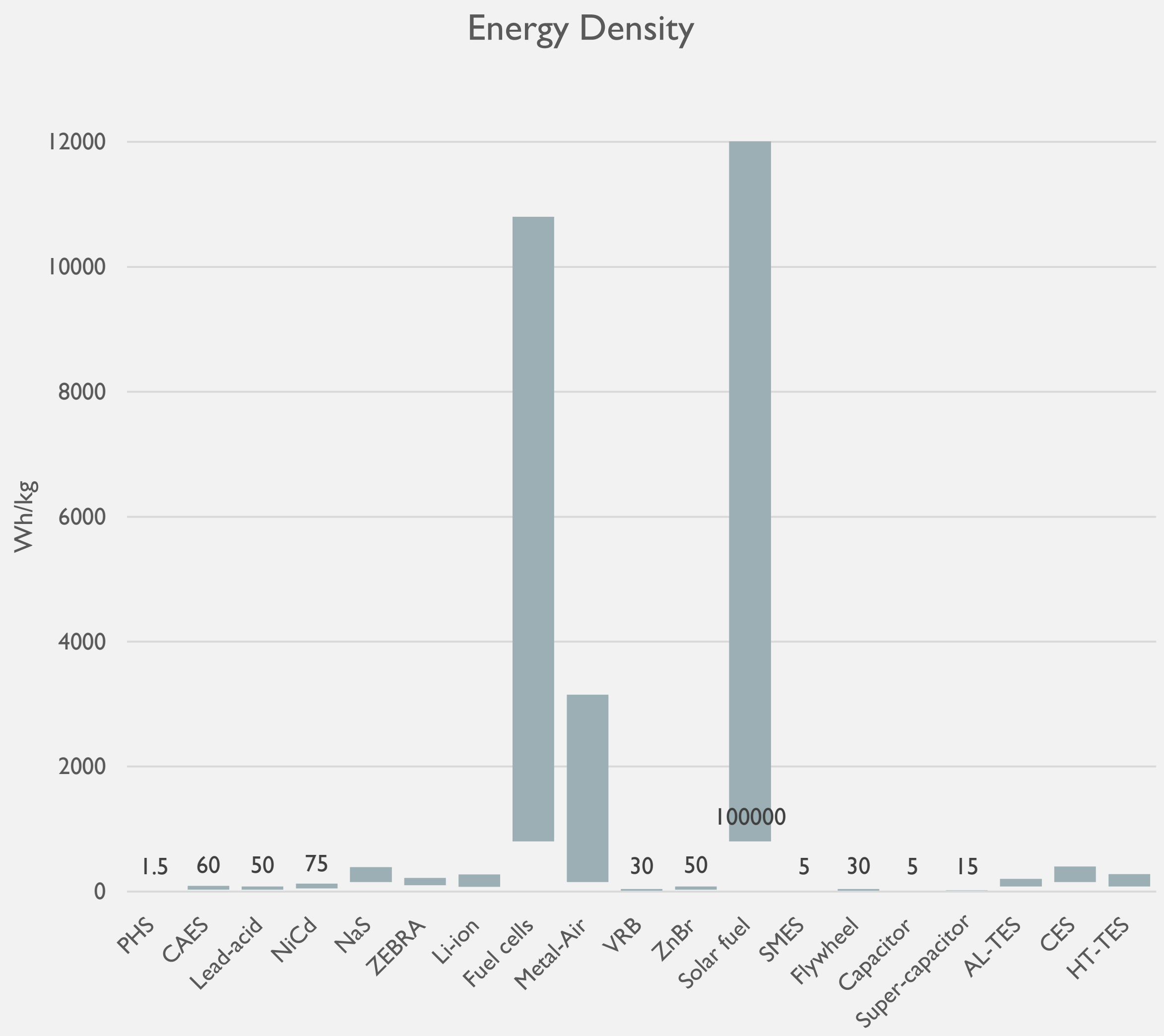
Ammonia synthesis/dissociation

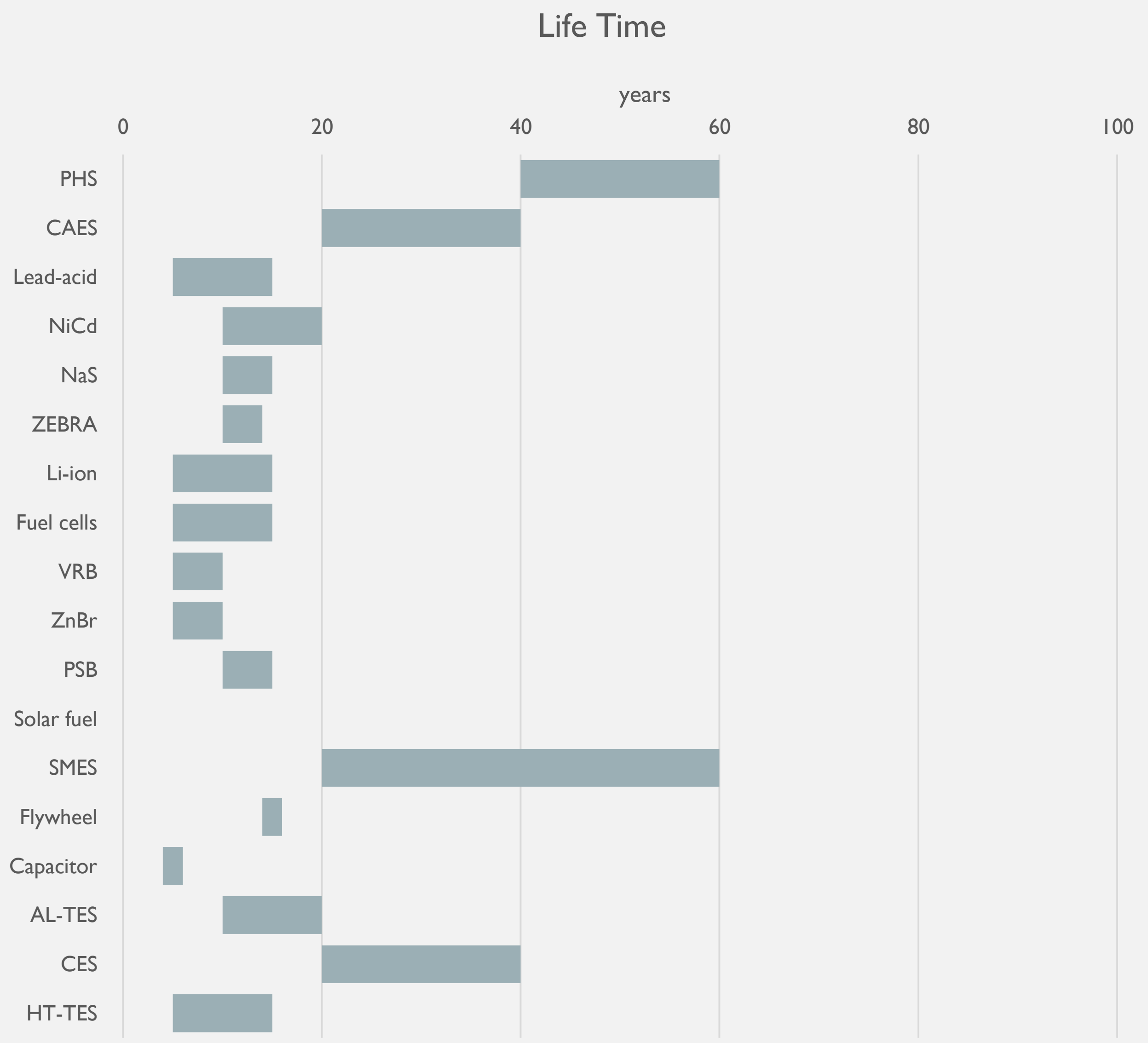
$$3H_2 + N_2 \rightleftharpoons 2NH_3$$

Cryogen ensure relatively *high energy density* ($100 \div 200$ Wh/kg) with a rather low efficiency (40-50%).
PHES is a *very low cost* solution for plants in the range of $2 \div 5$ MW



Graph data [6], information [5]





Other technologies are undesirable:

- ❑ PHS and CAES are site-specific and have low energy density
- ❑ Lead-acid batteries have low cycle life and require regular maintenance
- ❑ Hydrogen storage is difficult to implement and is costly

CONCLUSIONS

Although EES is **expensive**, large-scale VRES integration would be a nearly impossible challenge without it.

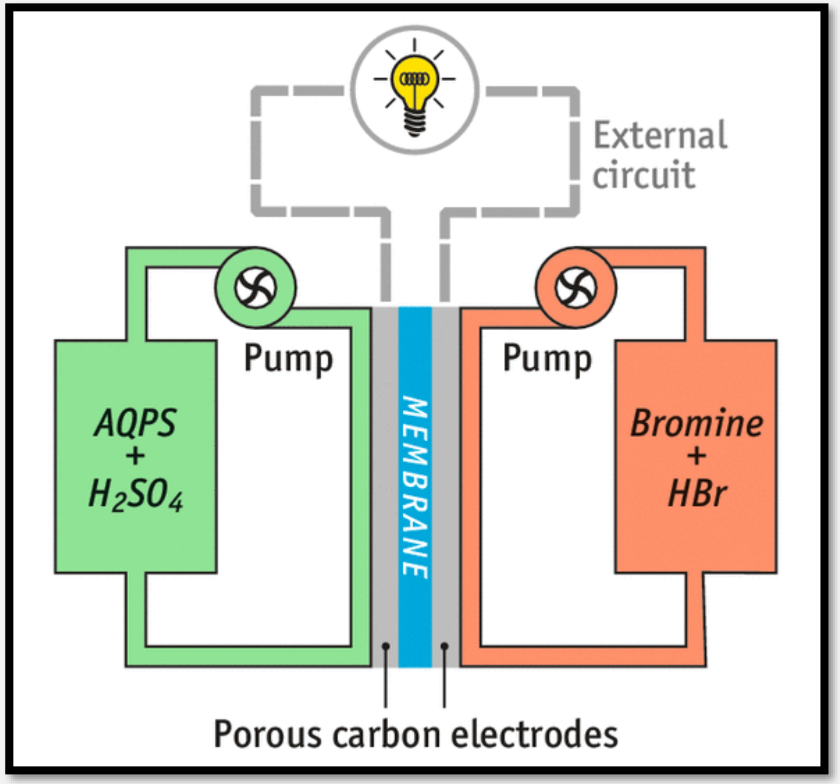
As load growth clogs the grid and VRES penetration increases, strategic use of EES may be **more viable** than the construction of new transmission and generation capacity [5].

WHAT'S NEXT?

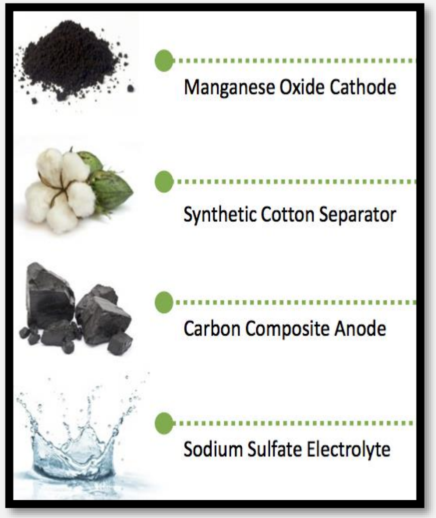
Among the technologies that will step up on the scene in the next future, two are particularly promising:

❖ Harvard's **quinone-based flow battery**

- As any flow battery the quantity of energy that can be stored only depends on the tanks size
- Organic, uses safe and economic materials
- Cycling showed >99% storage *capacity retention* per cycle
- Estimated price of 27 $/kWh (Vanadium costs ~81$/kWh)
- Available in 2 to 5 years [14]



Quinone flow battery (*Nature*)



❖ **Aqueous Electrolyte Polyionic batteries**

- Stationary, *long duration* energy storage applications
- Made from *abundant*, *non toxic* sustainable materials using consolidated and cheap manufacturing processes
- Same performance as Lead batteries with double the lifetime
- Safety and cost-effectiveness make it a real alternative to Li-ion for cheap energy storage [15]

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