EPFL

Energy storage

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EPFL – PLANAIR

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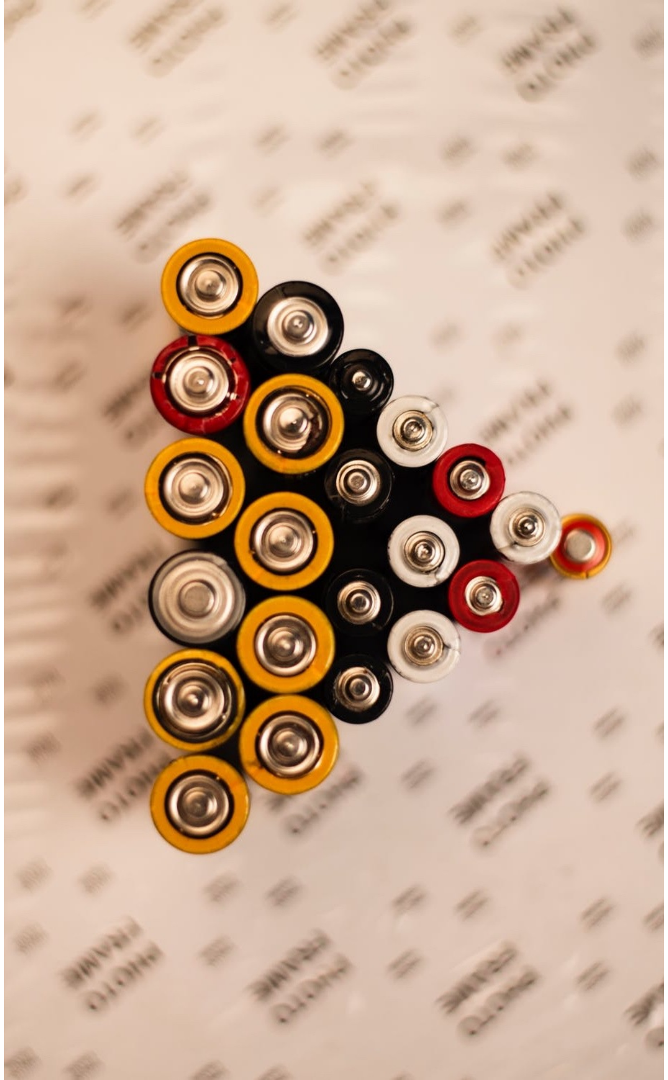
Goals

- **Classify** energy storage technologies by type, with their characteristics
- **Derive** their efficiencies (charge, discharge and round-trip)
- **Explain** the importance of energy storage in the future energy system



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Introduction

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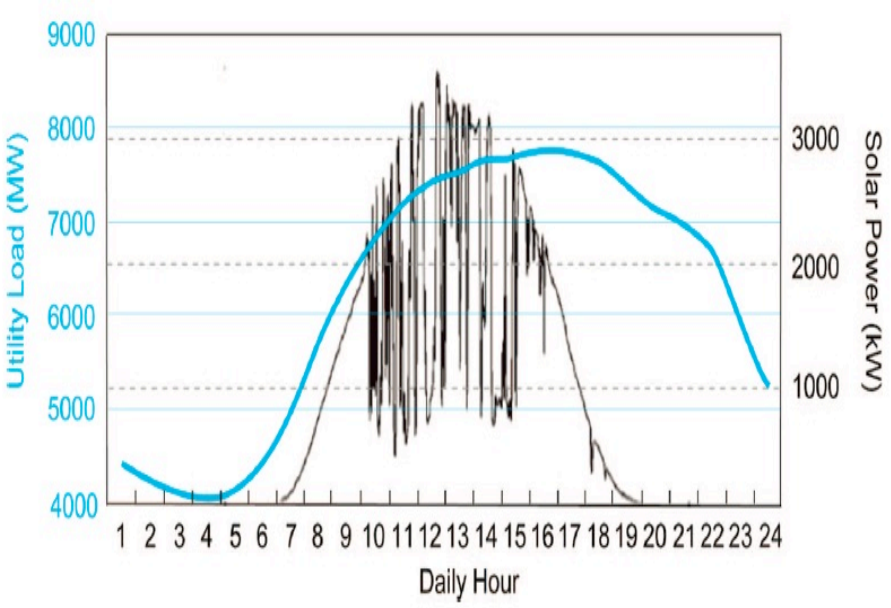
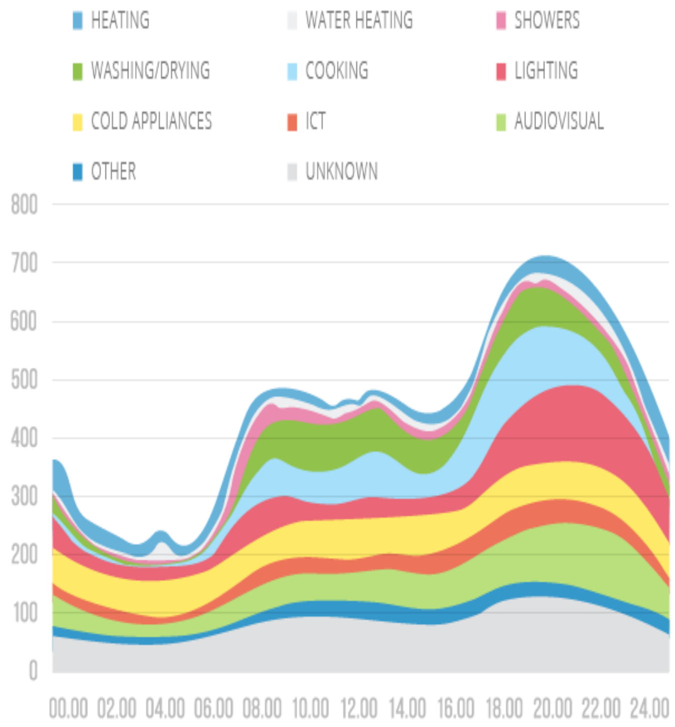
Introduction

Some renewable energies are variable, not all (biomass, geothermal) !

Solar and **wind** energy are **variable… and subject to fast variations!**

- c_p (solar): 10-20%
- c_p (wind): 20-40%





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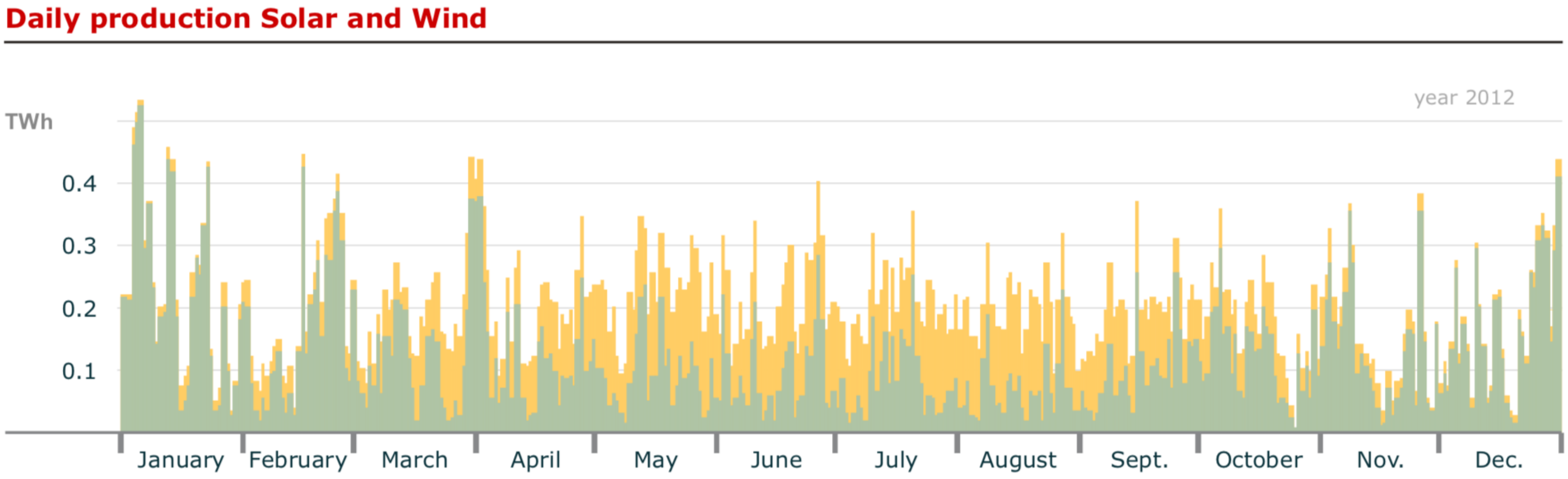
Introduction

- Luckily:
  - Complementarity of sun & wind
  - Demand: efficiency & demand-side management
  - Variability ≠ Uncertainty → forecasts



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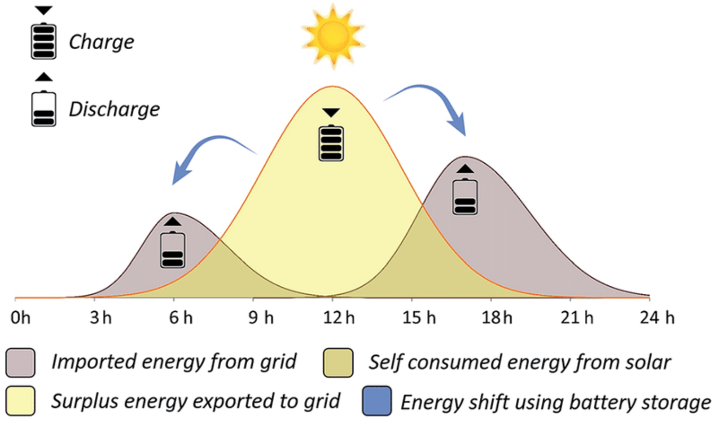
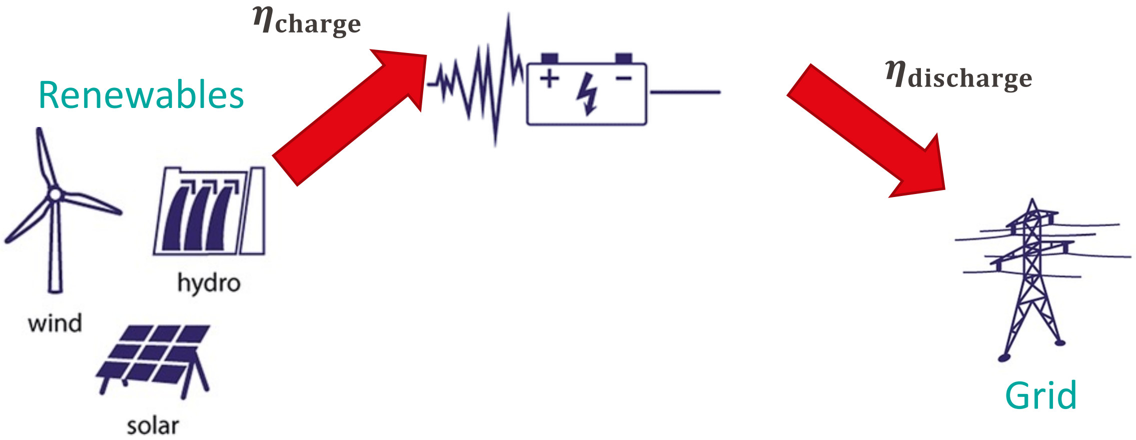
Introduction

"Decoupling of energy supply and demand"

- Efficient use of resources
- **Variable renewables**
- Self consumption/production
- Grid stability & peaks





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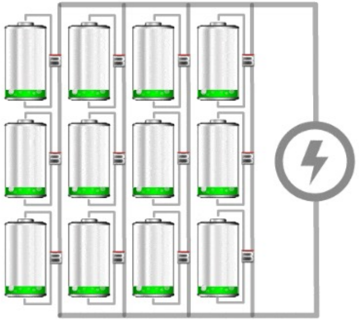
Introduction

- Charging efficiency = $\dfrac{\text{stored energy}}{\text{energy put into the storage}} = \eta_{\text{charge}}$

- Discharging efficiency = $\dfrac{\text{energy retrieved from the storage}}{\text{stored energy}} = \eta_{\text{discharge}}$

- Round-trip efficiency = $\dfrac{\text{energy retrieved from the storage}}{\text{energy put into the storage}} = \eta_{\text{charge}} \times \eta_{\text{discharge}}$



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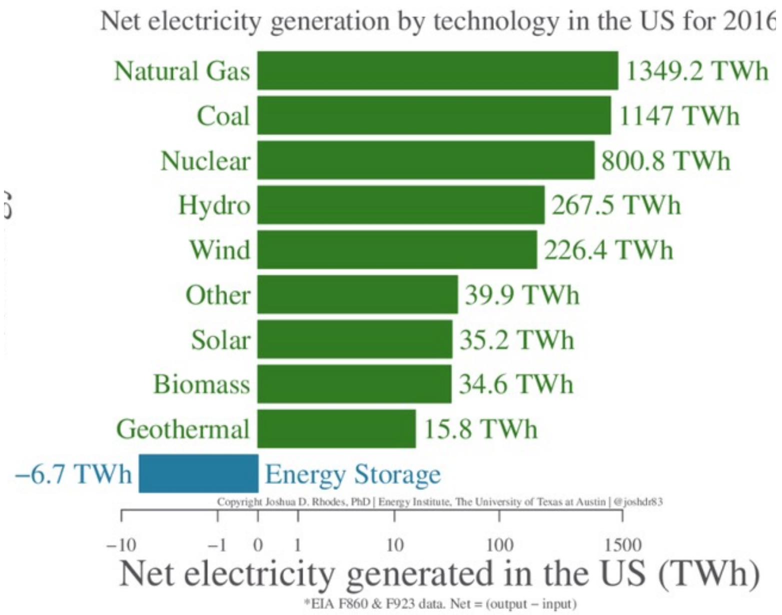
Introduction

- Storage **CONSUMES** electricity (**0.3%** of all electricity generated in the US)
- Charging and discharging losses
- Self-discharge losses (ex : batteries, thermal accumulators)



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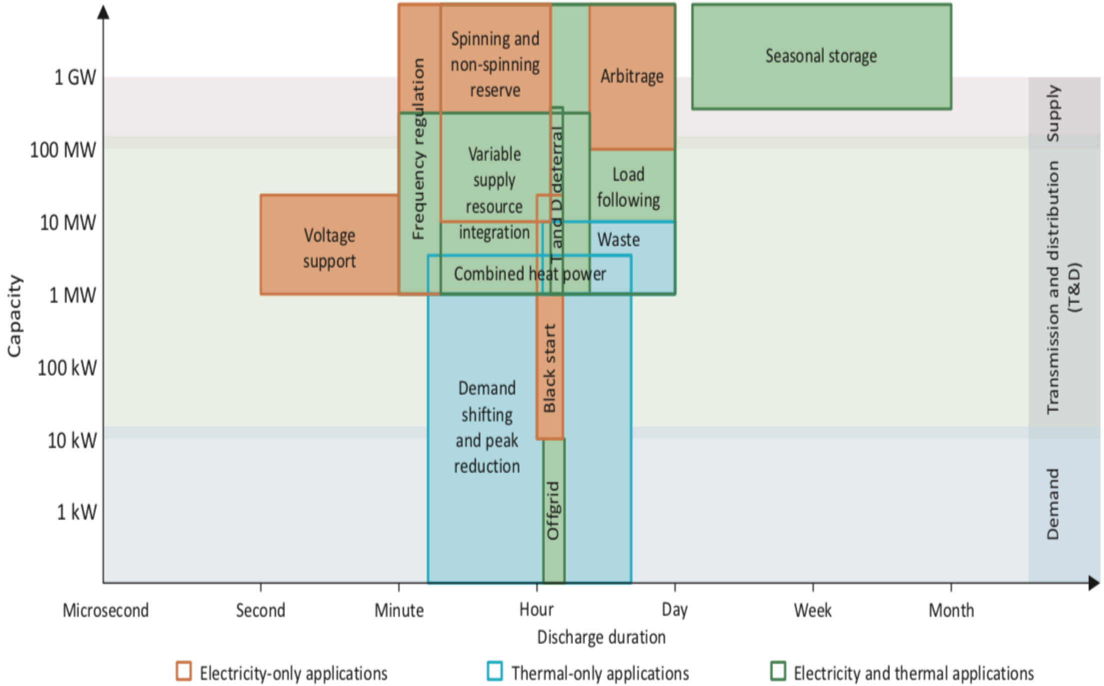
Introduction

- **Response** & **discharge time :** storage can be used for storing energy over minutes, hours, weeks and months



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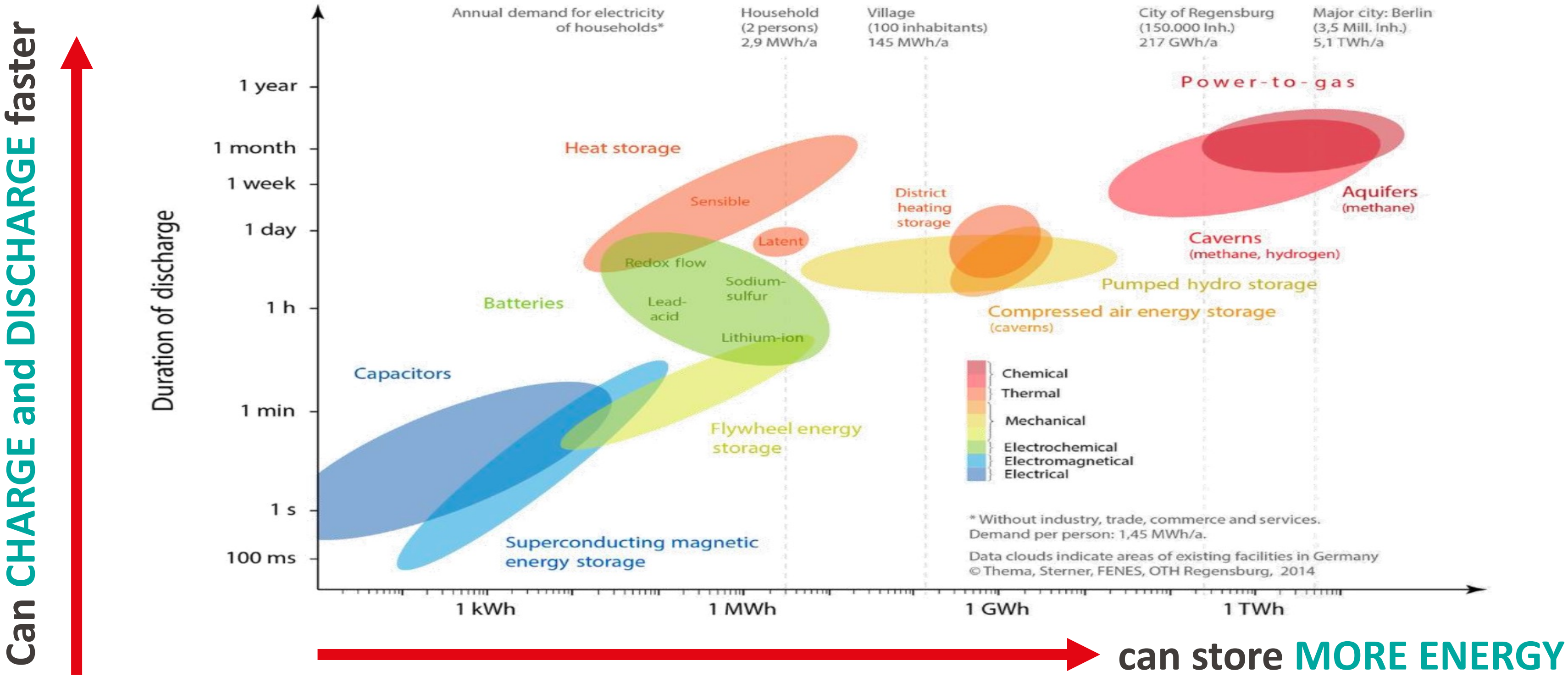
Introduction

- **Power density** = how fast energy can be stored and discharged, expressed in W/kg
- **Energy density** = how much energy can be stored, in J/m^3 or in J/kg



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Storage technologies

Mechanical

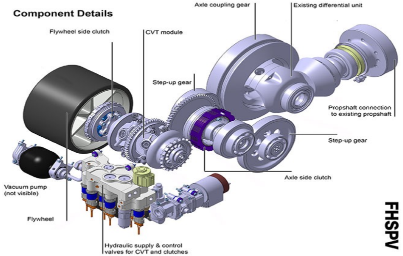
Thermal

Electrochemical

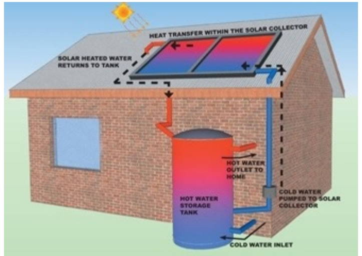
Chemical

Classification

- **Mechanical** (potential/kinetic)

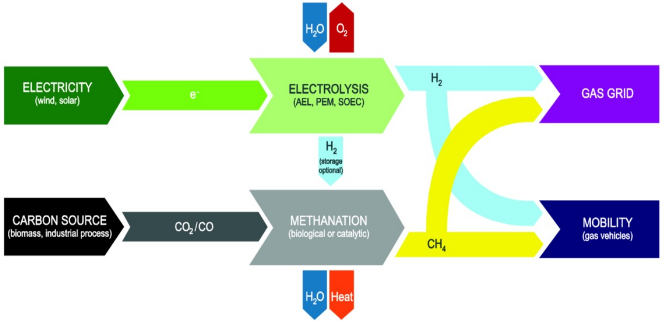


- **Thermal** (sensible/latent)



- **Electrochemical**

- **Chemical**



ME-409 ENERGY CONVERSION AND RENEWABLE ENERGY

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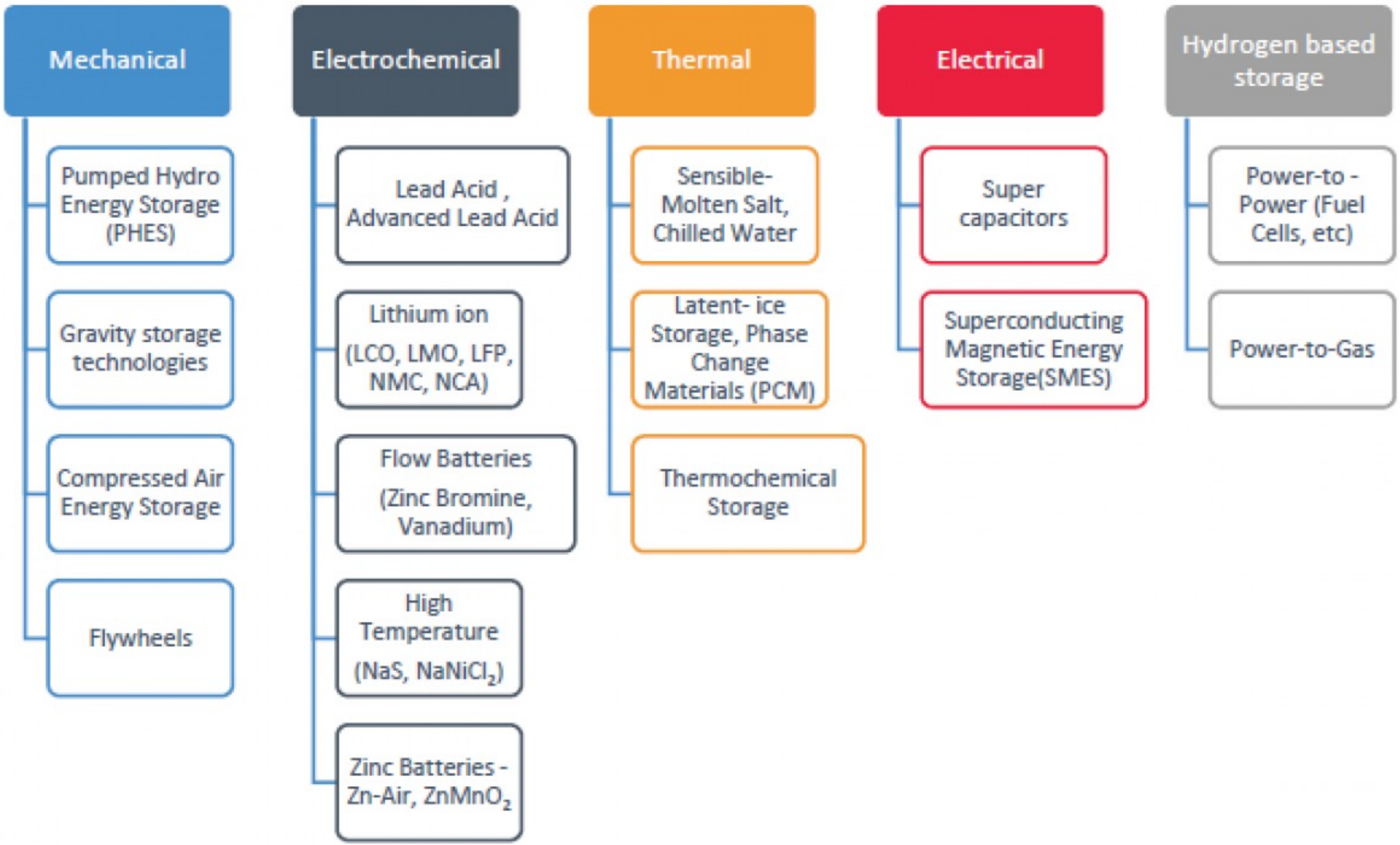
Classification



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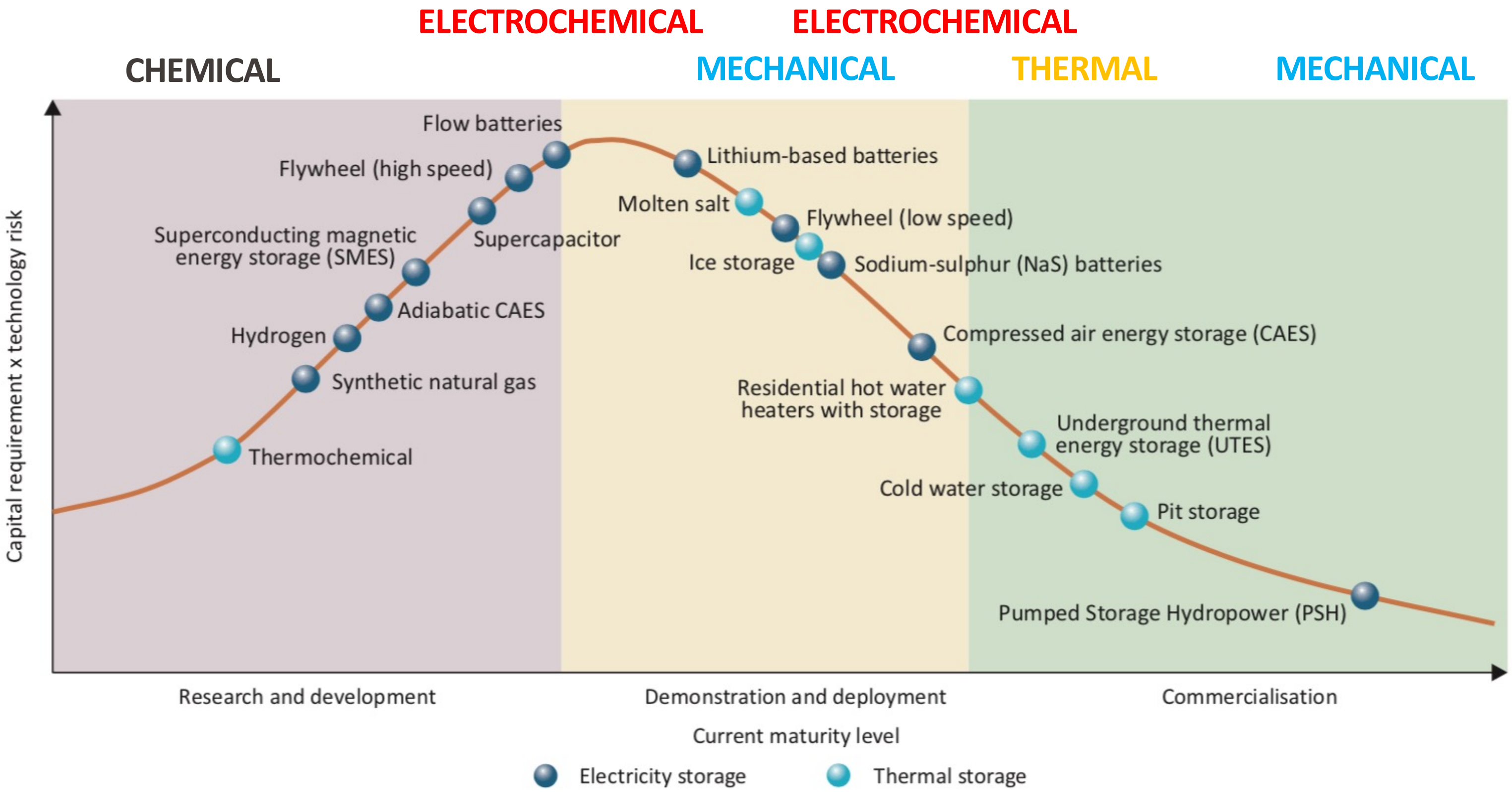
Classification



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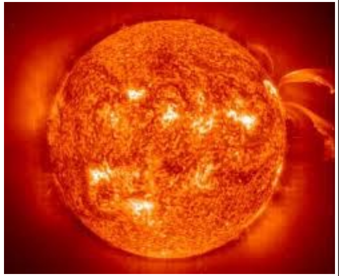
Classification

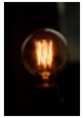
HEAT



POWER

HEAT

POWER



FUELS

CHEMICALS

RESOURCES

STORAGE

DEMANDS

Mechanical storage

Pumped hydro

Compressed air

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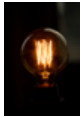
The concept

MECHANICAL STORAGE

(potential, kinetic)

POWER



POWER

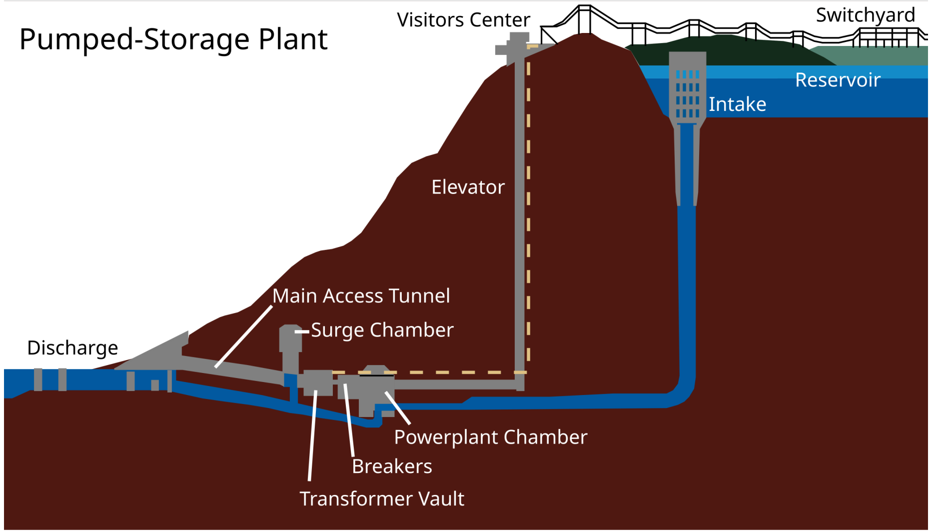
RESOURCES

STORAGE

DEMANDS

Mechanical
- Pumped hydro

- **Mechanical storage –** widespread technology (90% of all electricity storage)
- **Round-trip efficiency** : 70 to 85%, one of the most efficient so far !
- Low energy density – 0.5-5 **kWh/m³** of water! ⬄ 200 **m³** of water to store 1 MWh !
- Low power density



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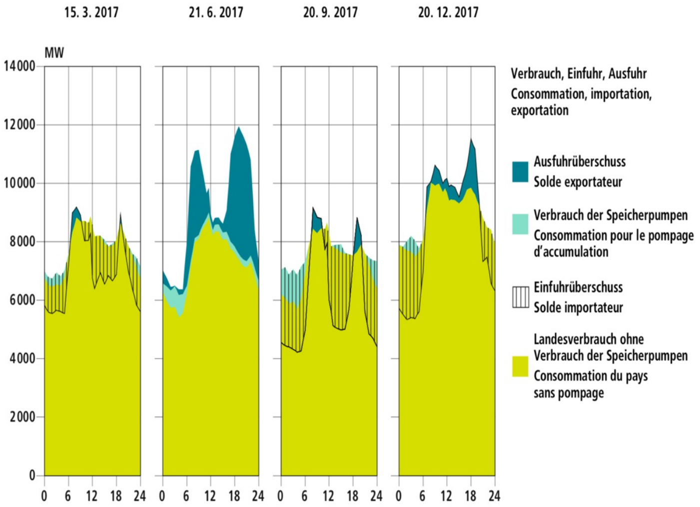
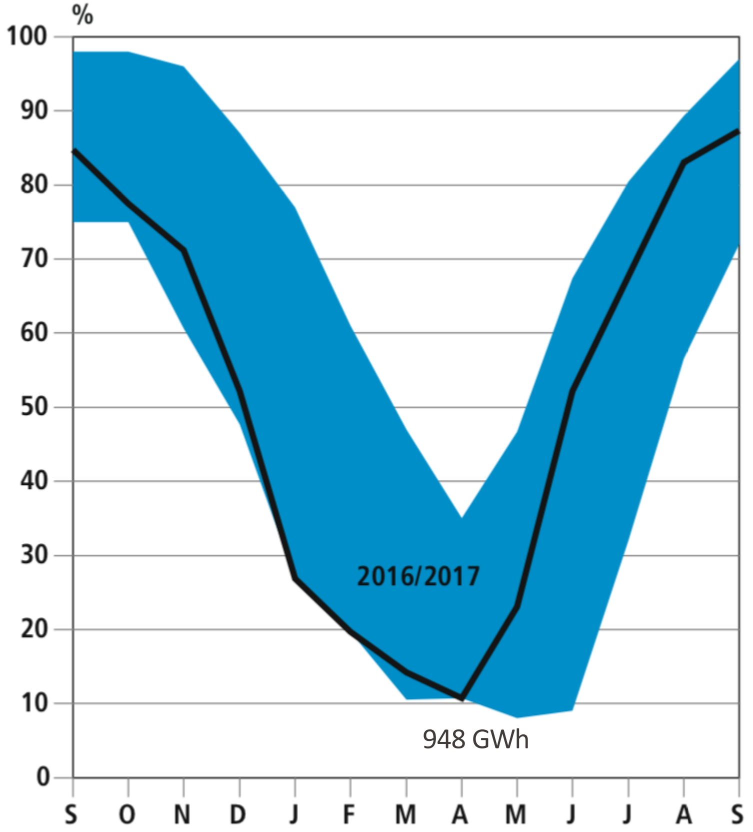
Mechanical

- Pumped hydro

- Day/night dynamics + seasonal
- 4 TWh$_e$/y consumed (2017-2021)
- 3+ GW$_e$ installed capacity (2017-2021)





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Mechanical
- Pumped hydro

New plant in Nant-de-Drance (VS):

- Upper basin: Vieux Emosson lake, 2225m
- Lower basin: Emosson lake, 1930m
- 6*150 MW_e Francis turbines
- 80% roundtrip efficiency

www.energy-storage.news/20gwh-pumped-hydro-energy-storage-plant-starting-operations-in-switzerland/

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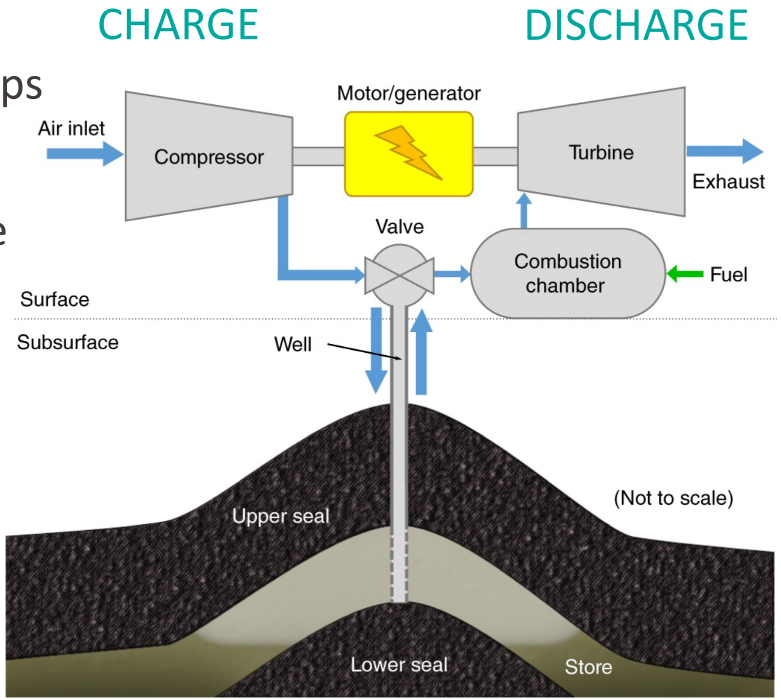
Mechanical

- Compressed air energy storage

Concept = Similar to a gas turbine in 2 steps

- Air compression
- Fuel combustion to increase the turbine inlet temperature

$$W_{max} = p_2 V_2 \ln\left(\frac{p_2}{p_1}\right) + (p_2 - p_1)V_2$$



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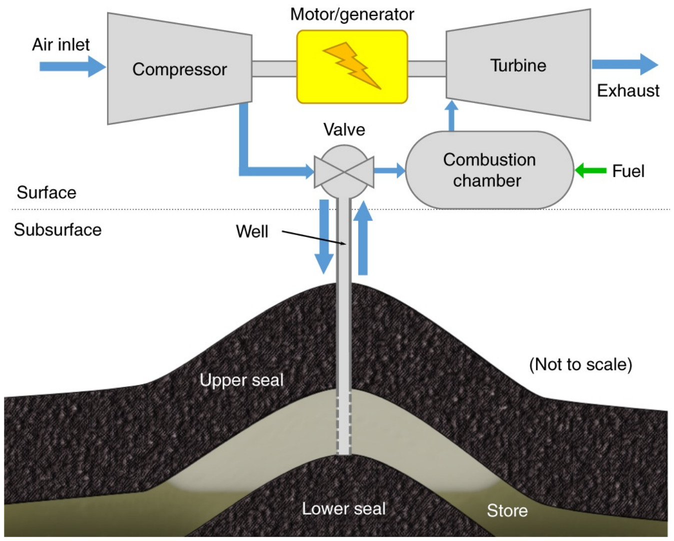
Mechanical

- Compressed air energy storage

- **Mechanical storage** – well-known technology
- **Round-trip efficiency** : 27% to 70%
- Geographical limitations (caverns), not widespread
- Challenges: turbomachinery design, thermal insulation, temperature levels



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Mechanical
- Compressed air energy storage

- Real-world applications:
  - 50-80 bar
  - 200-300 m^3 per stored Mwh_e

  ⇔ 200 **m^3** of air to store 1 MWh !
  - Roundtrip efficiency: 27-70%

- Caverns:
  - Salt domes, depleted gas fields
  - Old tunnels and army bunker

- Pilot adiabatic CAES project in Ticino
  - 120m long, 5m diameter tunnel
  - 1 MWh stored, **RT Efficiency – about** 70%

Huntorf (Germany): since 1978, 321 MW_{el}

McIntosh (USA): since 1982, 110 MW_{el}

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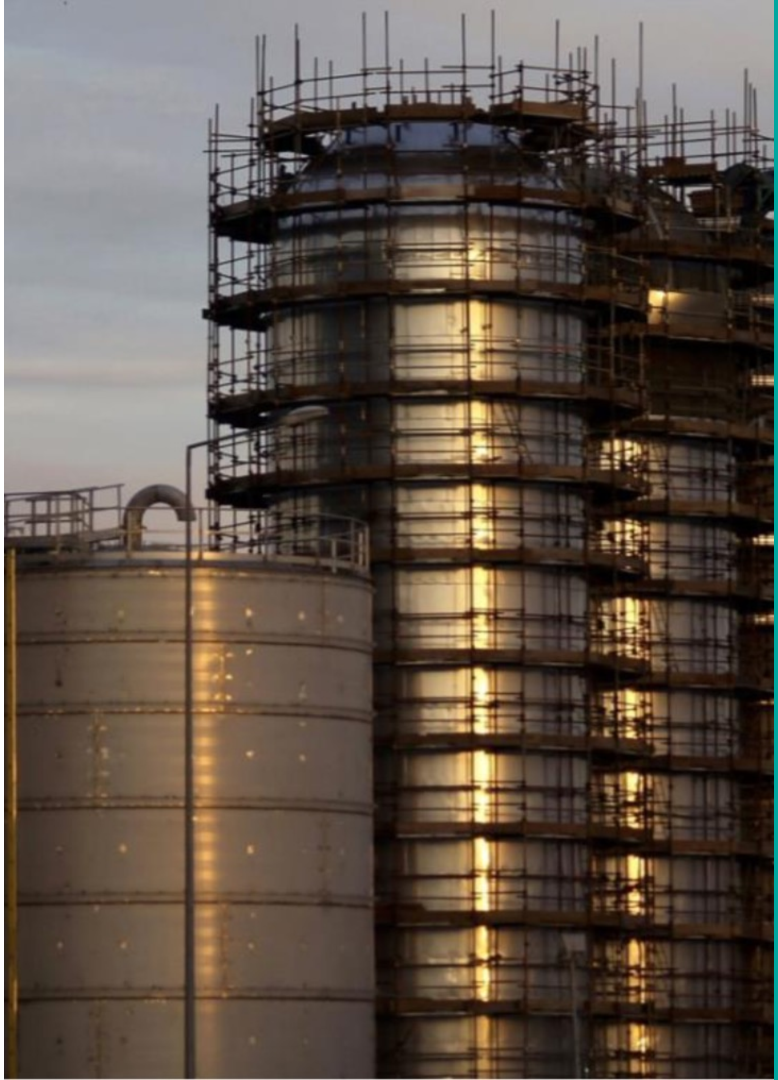


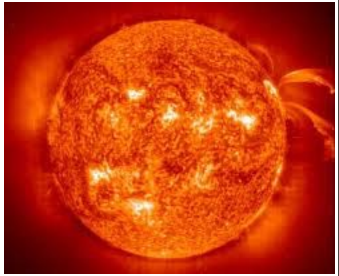
Thermal storage

Sensible

Latent

The concept

HEAT

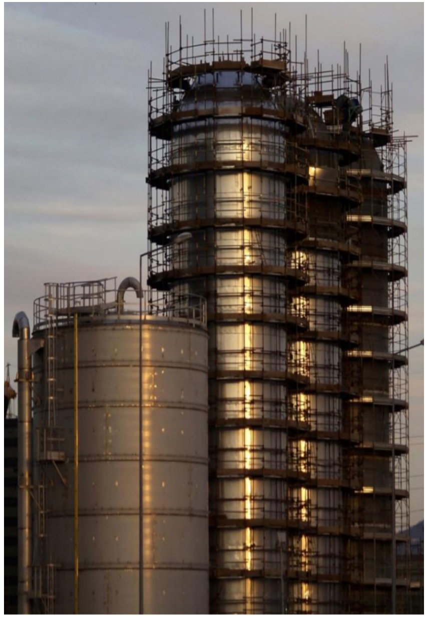


POWER

RESOURCES

THERMAL STORAGE

(sensible, latent)



STORAGE

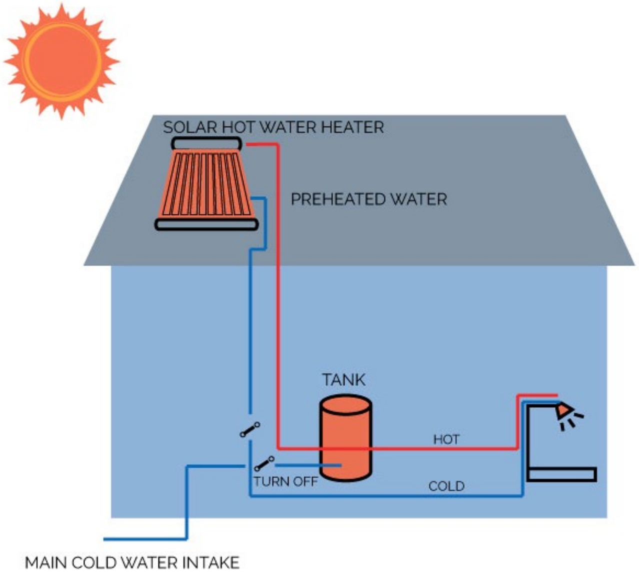
HEAT

DEMANDS

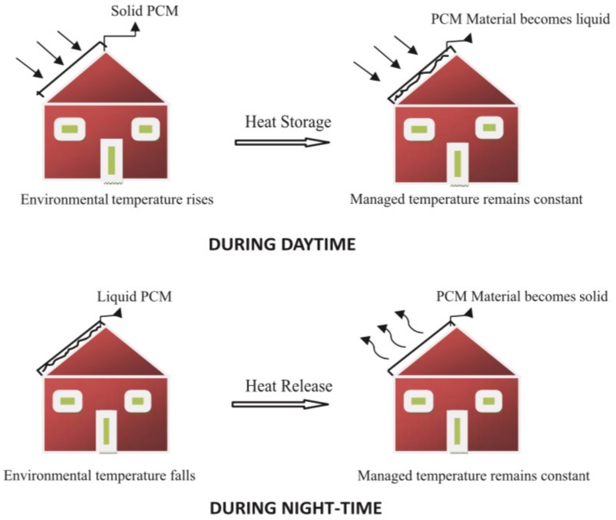
Thermal

- Sensible vs Latent

- Sensible $Q = mc_p \boldsymbol{\Delta T}$
- Concept = we increase/decrease its temperature



- Latent $Q = m\boldsymbol{\Delta h_{phase\ change}}$
- Concept = **Phase-changing materials**



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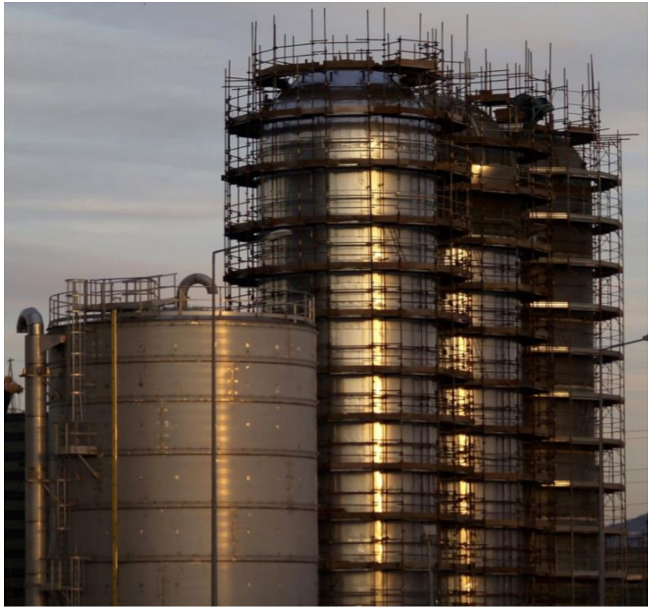
Thermal

- Sensible heat storage

- **Thermal storage** – well-known and widespread technology
- **Round-trip efficiency** : up to 80-90%
- Inexpensive, safe, possibly very cheap
- Synergies with solar, heat pump

- Challenges: thermal insulation,
- Limited energy density

- **Exemple of Torino : 5‘000 m^3** capacity, 5000 buildings, 515 km piping, pumps: 340 to 700 kg/s



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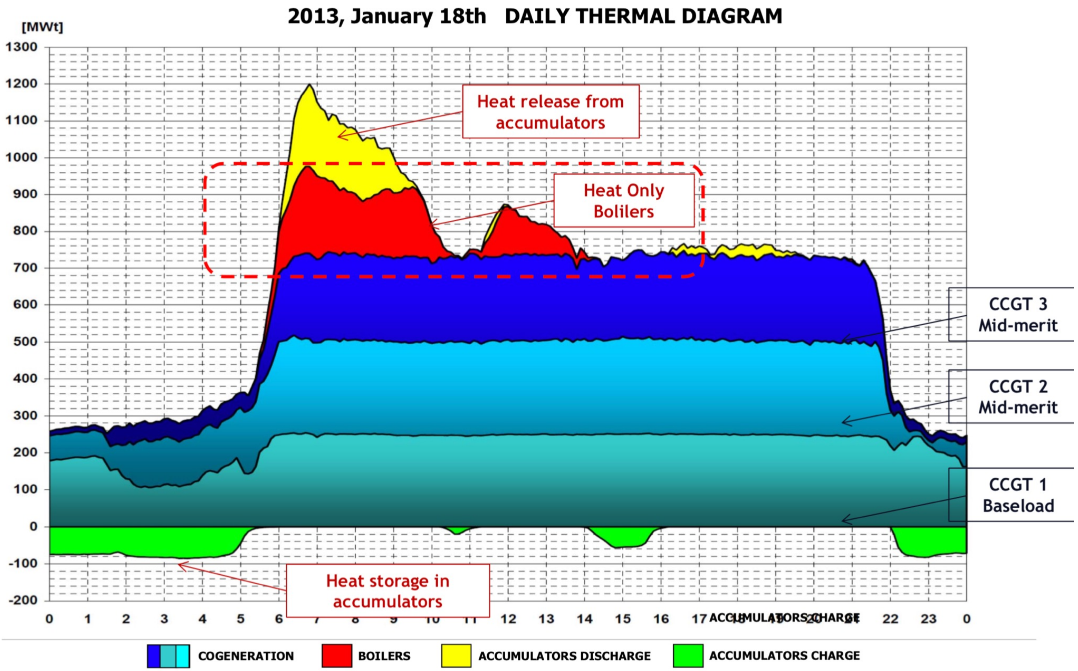
Thermal storage
- Sensible, the case of Torino (IT)

- Without **heat storage**



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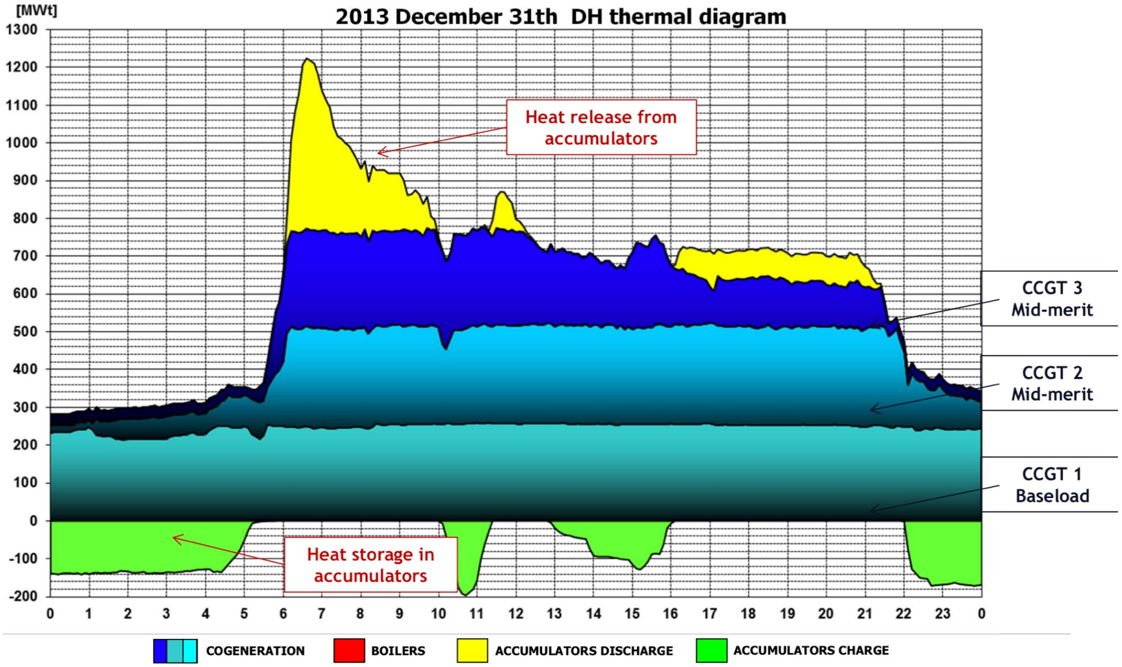
Thermal storage
- Sensible, the case of Torino (IT)

- **WITH heat storage**
- Higher flexibility, allows for less use of gas heaters and boilers



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Thermal

- Latent heat storage

- **Thermal storage** – usually solid-liquid change
- **Round-trip efficiency** : up to 80-90%
- Very versatile (different materials)
- Higher energy density than sensible

- Challenges: thermal insulation, efficiency dependent on fluid, cost

- **Exemple of** Crescent Dunes power plant, Nevada (USA), and molten salt storage (565°C, 10 hours)

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Electrochemical storage

Batteries

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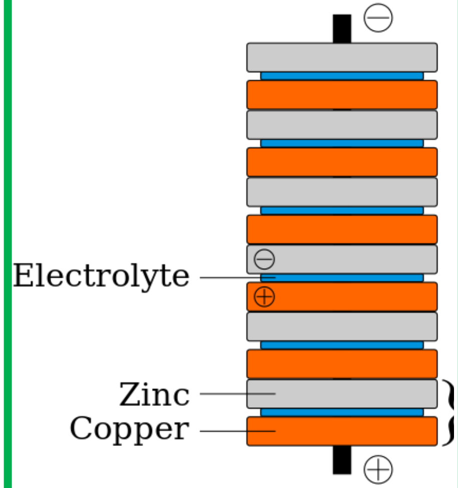
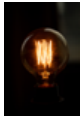
The concept

ELECTROCHEMICAL STORAGE (electrons)



POWER



POWER

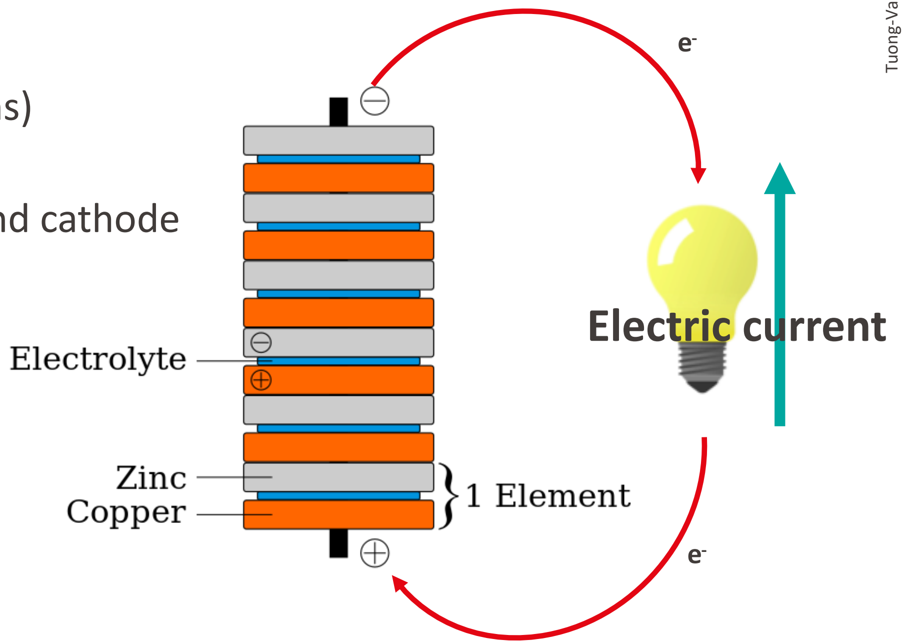
RESOURCES

STORAGE

DEMANDS

Electrochemical

- Concept = chemical reactions to enable the flow of electrons
- Basic principle:
  - Cathode gets reduced (gains electrons)
  - Anode gets oxidized (loses electrons)
  - Flows of electrons between anode and cathode



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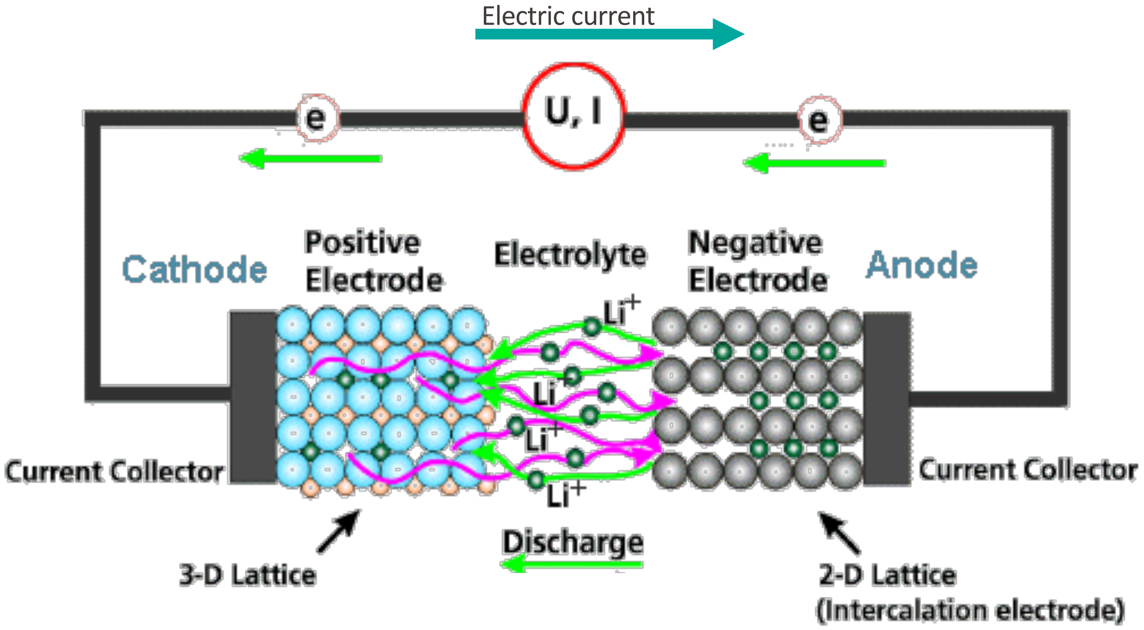
Electrochemical

- Cathode: lithium; Anode: graphite
- **Discharge** → **generating** current
  - Outside: electrons from **anode** (-) to **cathode (+)**
  - Inside: Li+ (cations) from **anode to cathode (+) through electrolyte**



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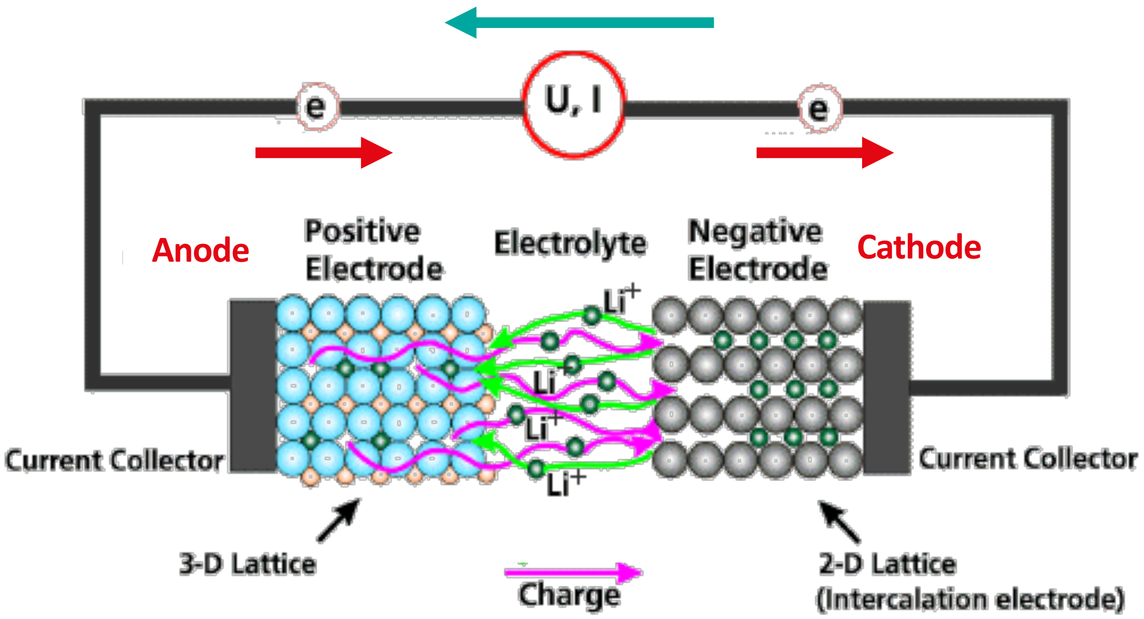
Electrochemical

- Cathode: lithium; Anode: graphite
- **Charge** → **imposing** current
  - Outside: electrons from **anode (+) to cathode (-)**
  - Inside: Li+ (cations) from **anode (+) to cathode (-) through electrolyte**



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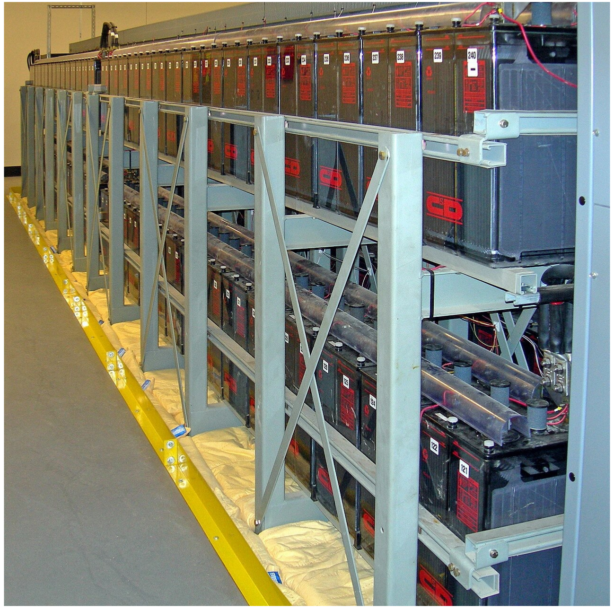
Electrochemical

- **Electrochemical storage –** mature
- Well-suited for small- and large-scale applications
- **Round-trip efficiency** : 75-90%
- Fast response time

- Challenges: low energy density, self-discharge issues, materials



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Electrochemical

Low energy density!
150 Wh/kg = 0.54 MJ/kg

Table 2. Summary of Battery Technologies[a]

battery	anode	cathode	voltage (V)	energy density $Wh \cdot kg^{-1b}$	cycle life
lead−acid	$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$	$PbO_2 + 4\,H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$	2.1	35	800
nickel−alkaline	$M + 2OH^- \rightarrow M(OH)_2 + 2e^-$	$2NiO(OH) + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^-$			
	M = Cd		1.3	35	700−2000
	M = Zn		1.6	70−120	500
	M = Fe		1.4	30−50	3000
	or				
	$2MH + OH^- \rightarrow 2\,M + H_2O + 2e^-$		1.2	75	600−1000
	or				
	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$		1.2	60	6000
lithium-ion	$LiC_6 \rightarrow Li^+ + e^-$	$MO_x + Li^+ + e^- \rightarrow LiMO_x$ (M = Co, Ni, Mn, V)	2.5−4.5	150	1200
high T-sodium	$2Na \rightarrow 2Na^+ + 2e^-$	$2Na^+ + 2e^- + xS \rightarrow Na_2S_x$	2.1	170	1800
		or			
		$2Na^+ + 2e^- + NiCl_2 \rightarrow Ni + 2NaCl$	2.6	115	
liquid flow	$Zn \rightarrow 2Zn^{2+} + 2e^-$	$Br_2 + 2e^- \rightarrow 2Br^-$	1.3		1000
	or	or			
	$V^{2+} \rightarrow V^{3+} + e^-$	$VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O$	1.6	29	
metal−air	$Zn \rightarrow 2Zn^{2+} + 2e^-$	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	1.2	300	0

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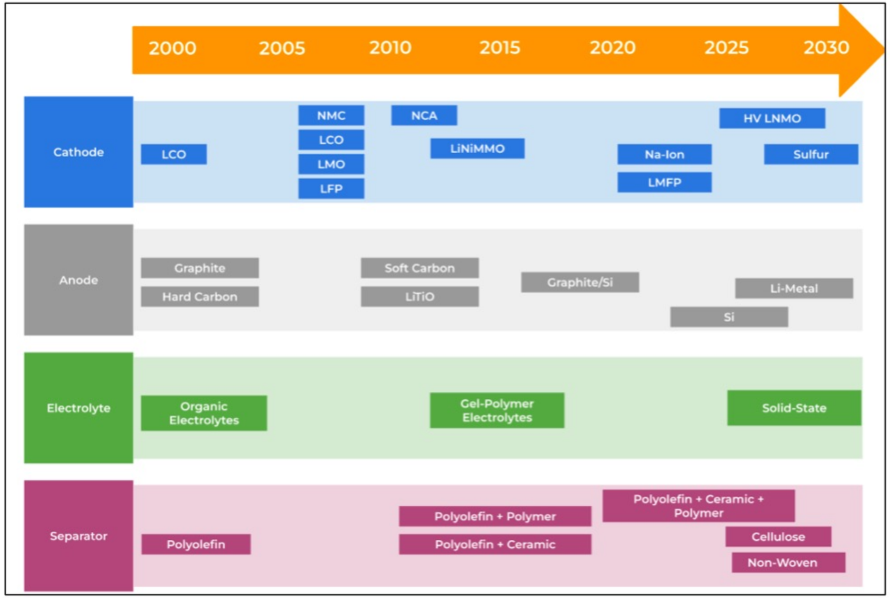
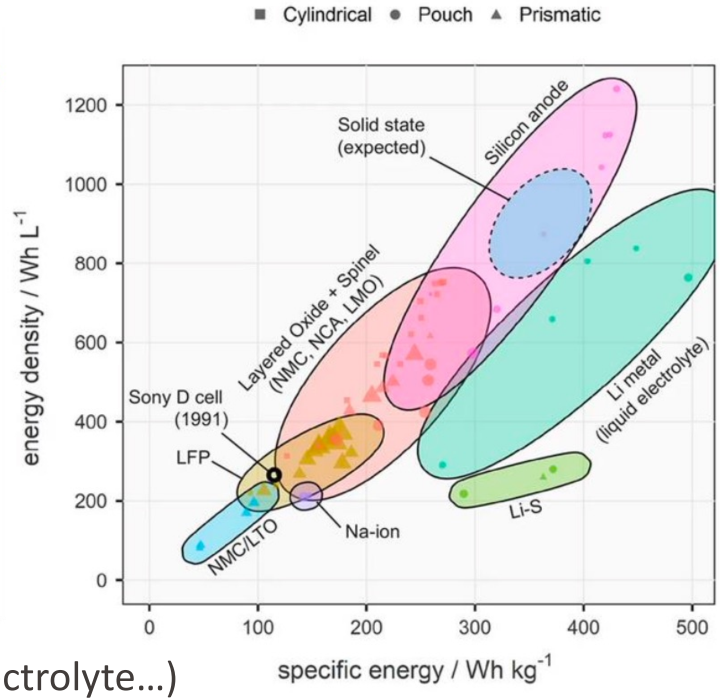
Electrochemical





- Change of materials (cathode, anode, electrolyte…)
- Towards greater energy densities

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Electrochemical

Key facts:

- Efficiencies: 75-95%
- Cost: 300-3500 USD/kW
- Short-term storage

Main types:

- Lead-acid (oldest, 0.15 USD/Wh)
- Lithium-ion
- Sodium-sulphur (NaS)

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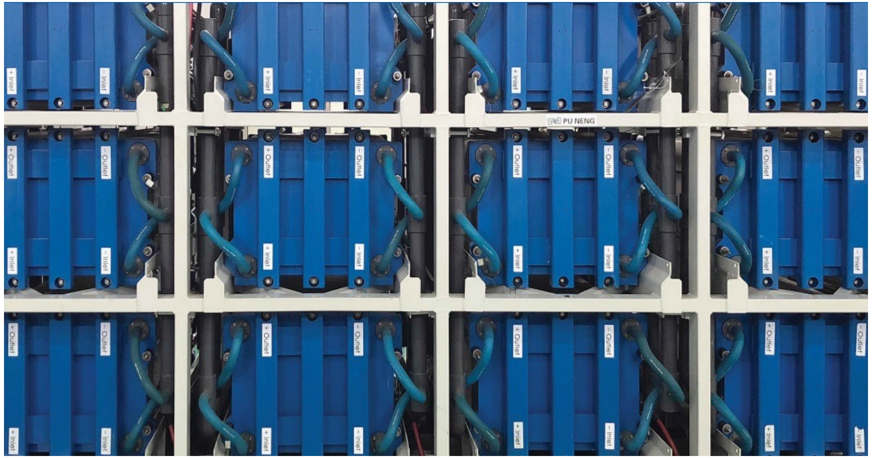
Electrochemical



New facts:

- Commissioning of a 100 MW/400 MWh vanadium redox flow battery (2022)

Source : www.energy-storage.news/first-phase-of-800mwh-world-biggest-flow-battery-commissioned-in-china/

For batteries :

- Impact of Russia's invasion of Ukraine (see: www.iea.org/reports/grid-scale-storage)
- Sensible metals : nickel, cobalt and graphite (Russia accounts for 20% of mined supply of nickel, large shares of Co and C !)

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Chemical storage

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EPFL

The concept

POWER

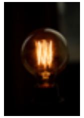
RESOURCES

CHEMICAL STORAGE (fuel)

STORAGE

HEAT

POWER



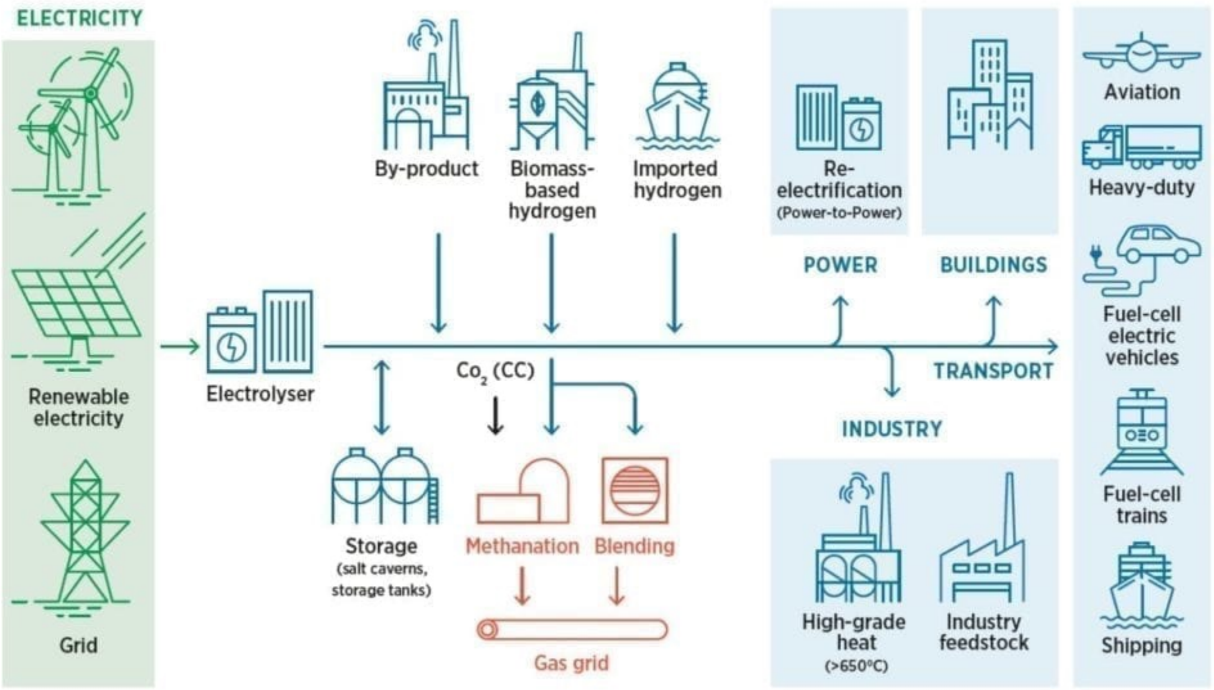
MOBILITY

INDUSTRY

DEMANDS

Chemical

- Concept = chemical reactions driven by electricity to generate a chemical fuel
- Basic principle: electrolysis + storage + reconversion



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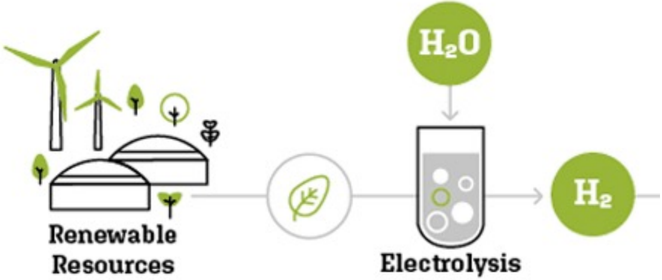
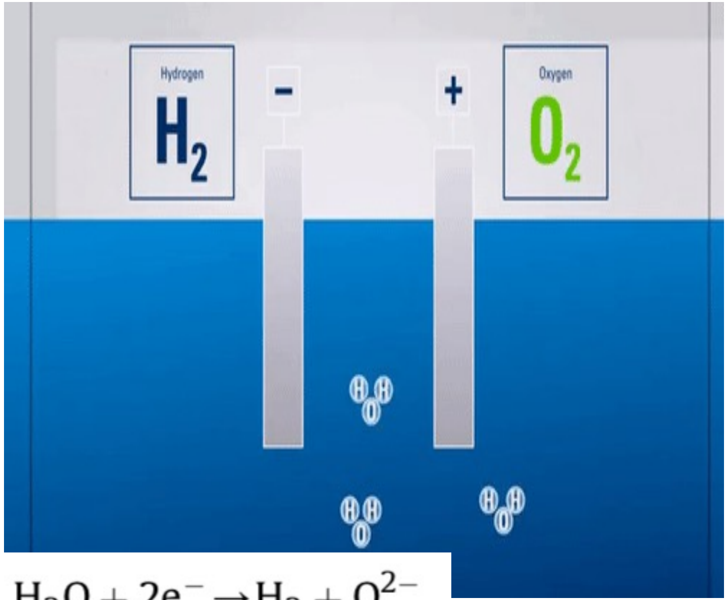
Chemical (power-to-X)

- **Charging:** Step 1 – **water electrolysis**



Excess electricity

Hydrogen (H_2)



$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

$$O^{2-} \rightarrow \tfrac{1}{2}O_2 + 2e^-$$

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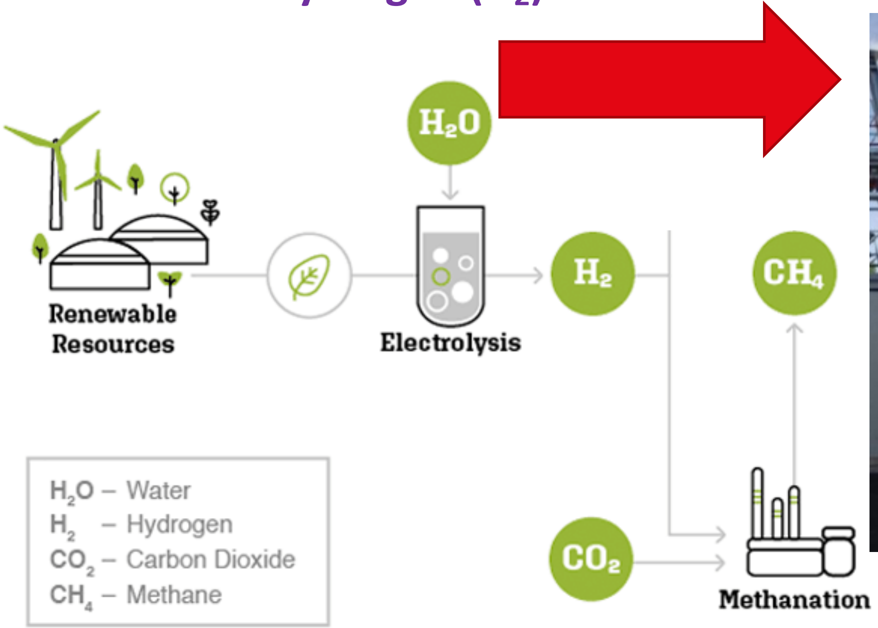
Chemical (power-to-X)

- **Charging:** Step 2 – **methanation**

Hydrogen (H_2) Methane (CH_4)



$$\mathrm{CO} + 3\,\mathrm{H_2} \longrightarrow \mathrm{CH_4} + \mathrm{H_2O} \quad \text{-206 kJ/mol}$$
$$\mathrm{CO_2} + 4\,\mathrm{H_2} \longrightarrow \mathrm{CH_4} + 2\,\mathrm{H_2O} \quad \text{-164 kJ/mol}$$

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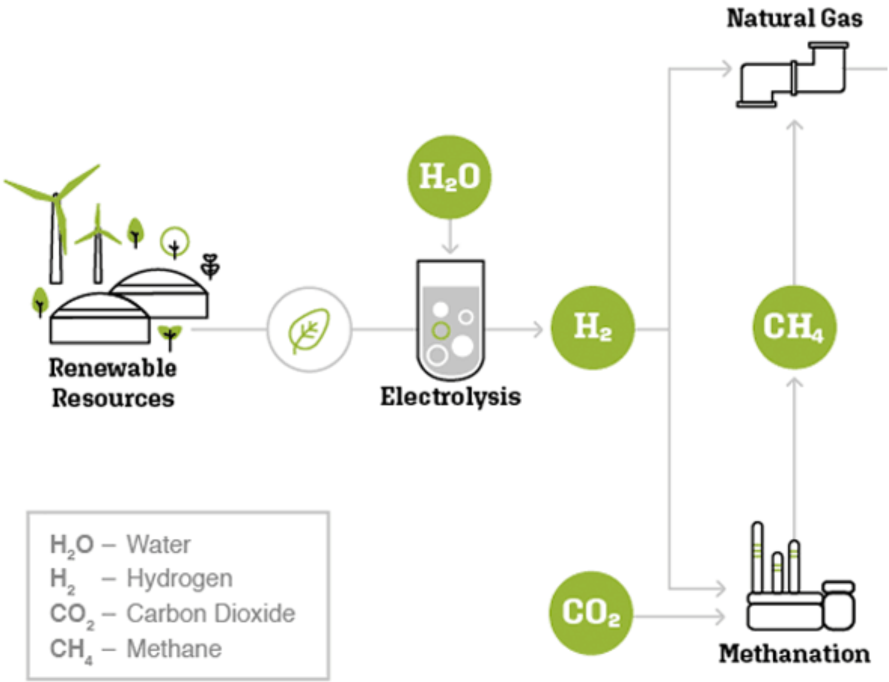
Chemical (power-to-X)

- **Charging:** Step 3 – **injection & transport**



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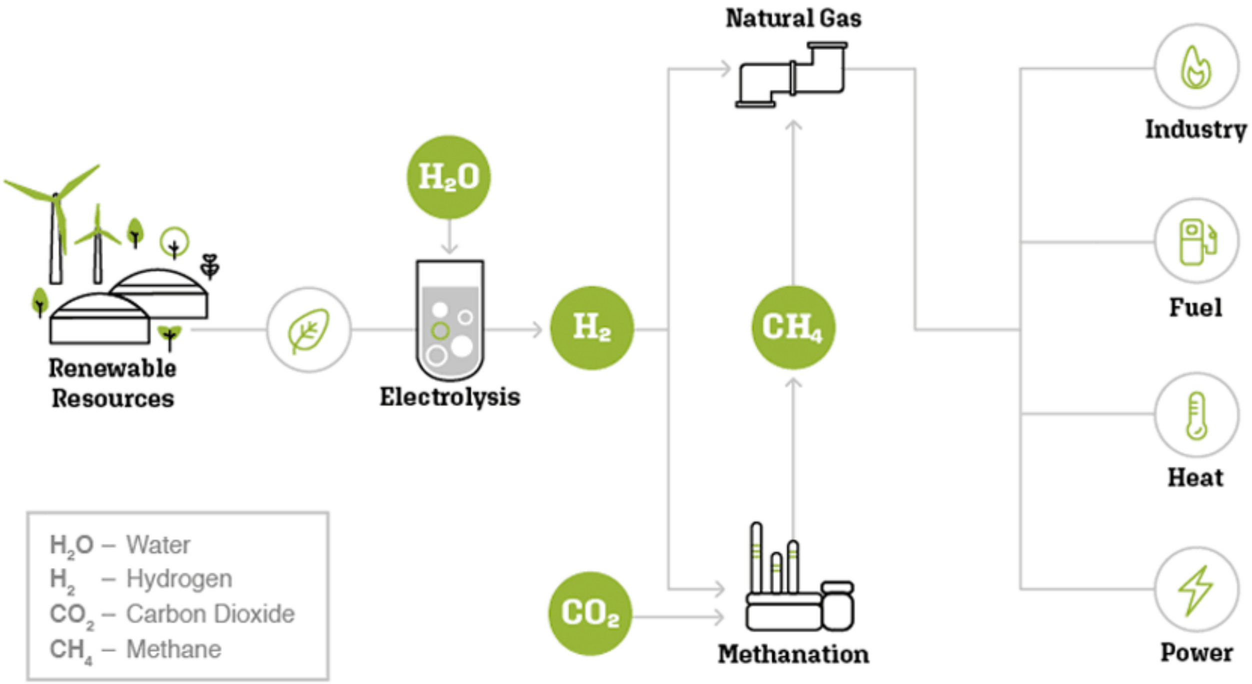
Chemical (power-to-X)

- **Discharging:** Step 4 – **use**



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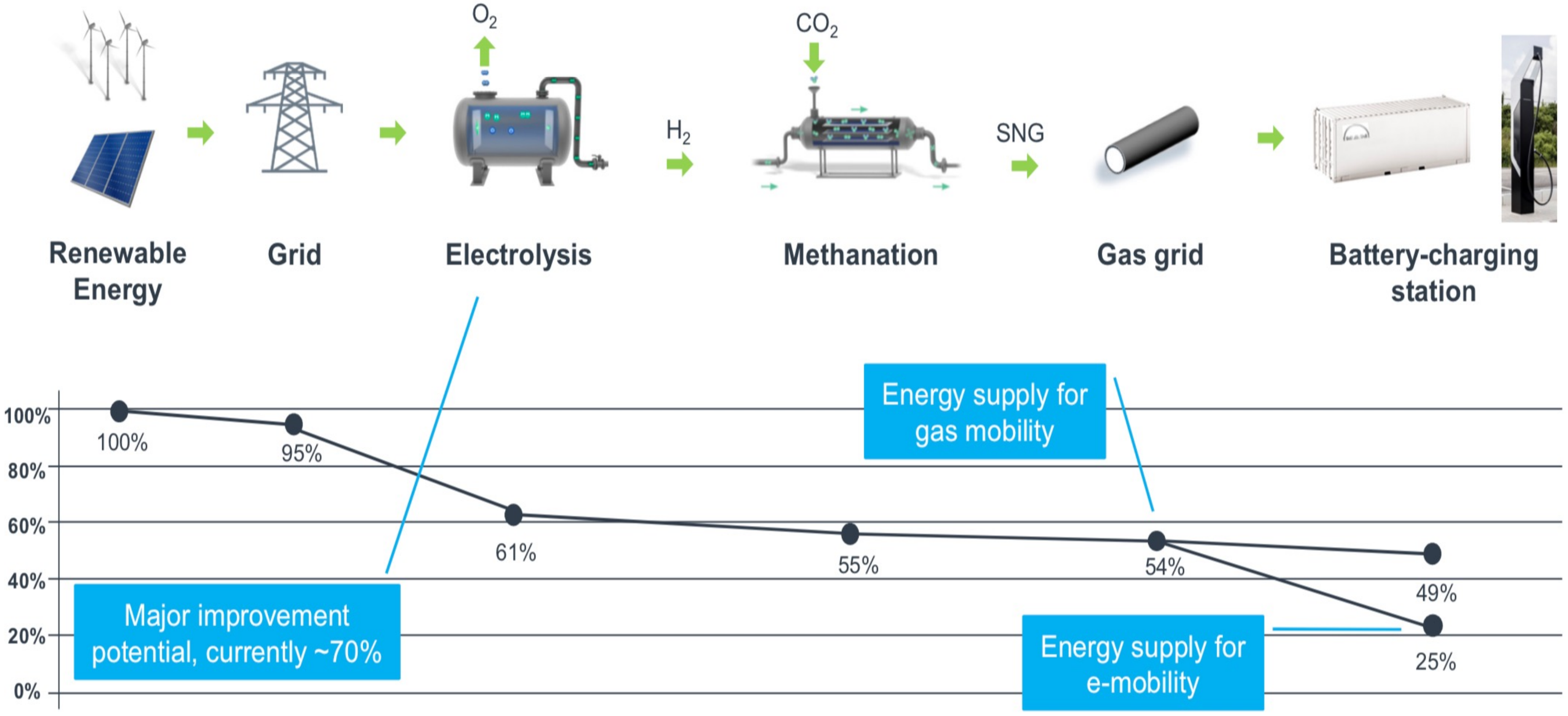
Chemical (power-to-X)

- **Overall process**



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Chemical

- Latent heat storage

- **Chemical storage – chemical reactions**
- **Round-trip efficiency** : up to 30-50 %
- Versatile in applications (mobility, power, heating)

- Challenges: low efficiency, hydrogen storage, investment cost, maturity of technologies

- **Exemple of power-to-gas demonstration plants (Solothurn)**

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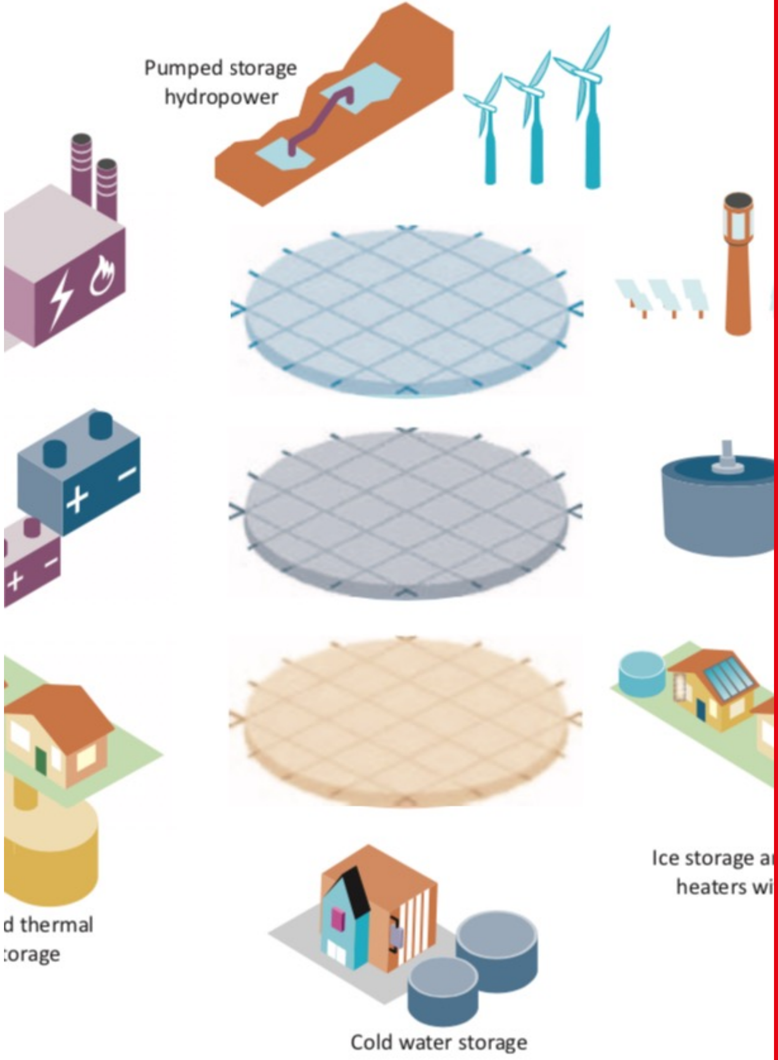

Storage in the energy system

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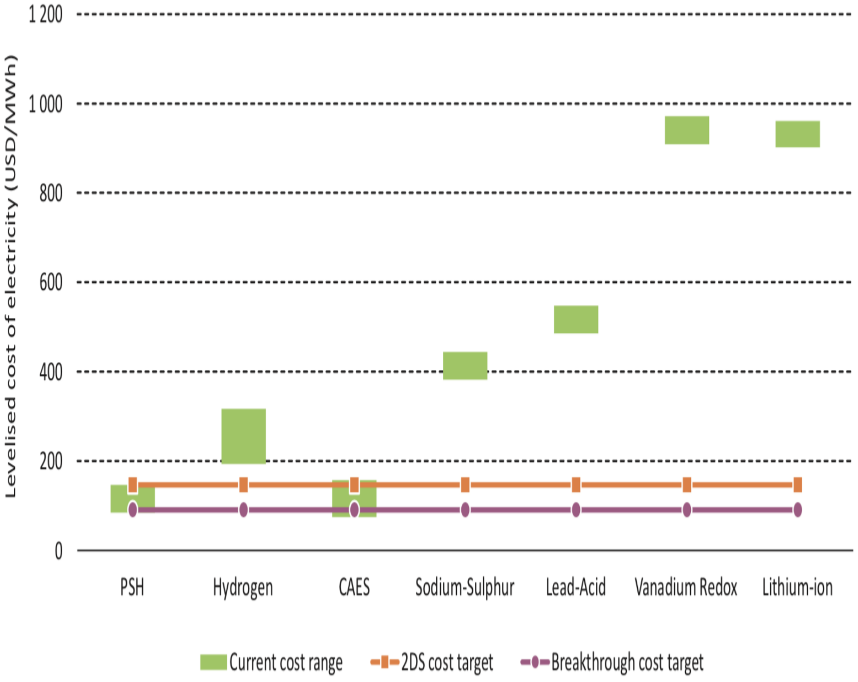
Roadmap for storage



- IEA 2DS scenario: stochastic renewables to produce 27-44% of electricity in 2050 → +310 GW storage
- IEA 2DS scenario: cost targets
- Few storage units are available at large-scale with a decent price! (hydropower and compressed air)
- Still a challenge for advanced batteries and hydrogen

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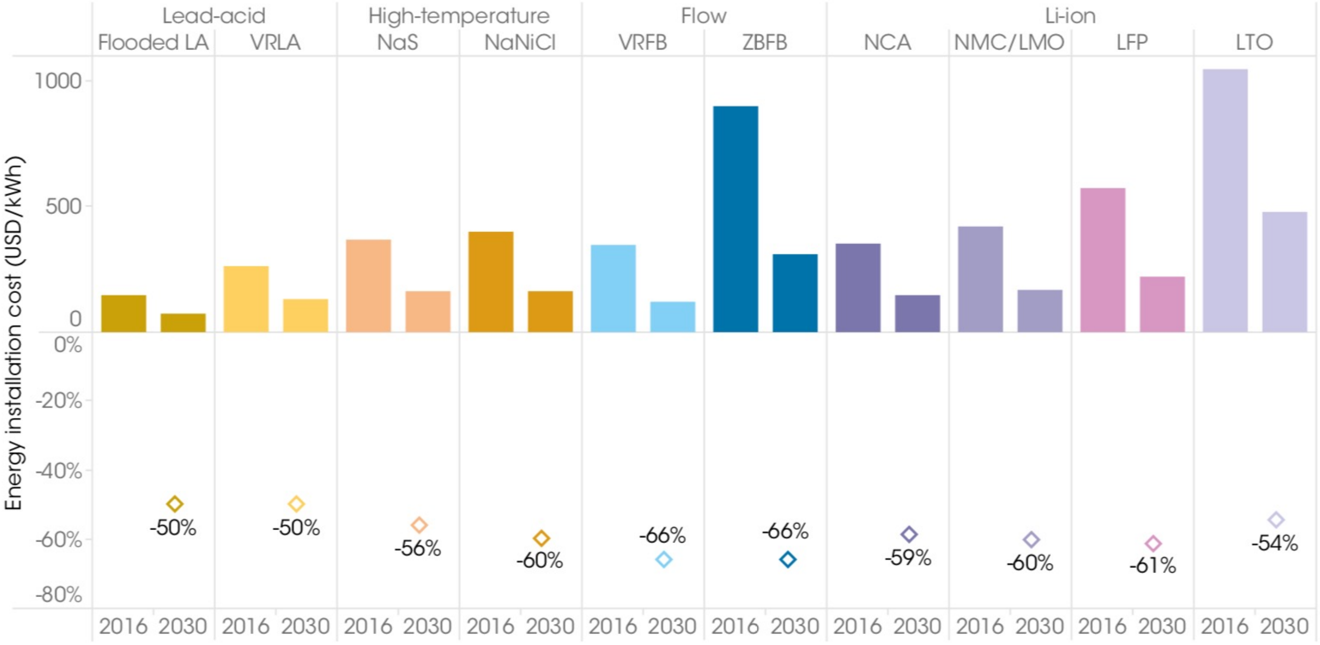
Roadmap for storage

- IRENA: potential for cost reduction of batteries

Figure ES6: Battery electricity storage system installed energy cost reduction potential, 2016-2030



Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

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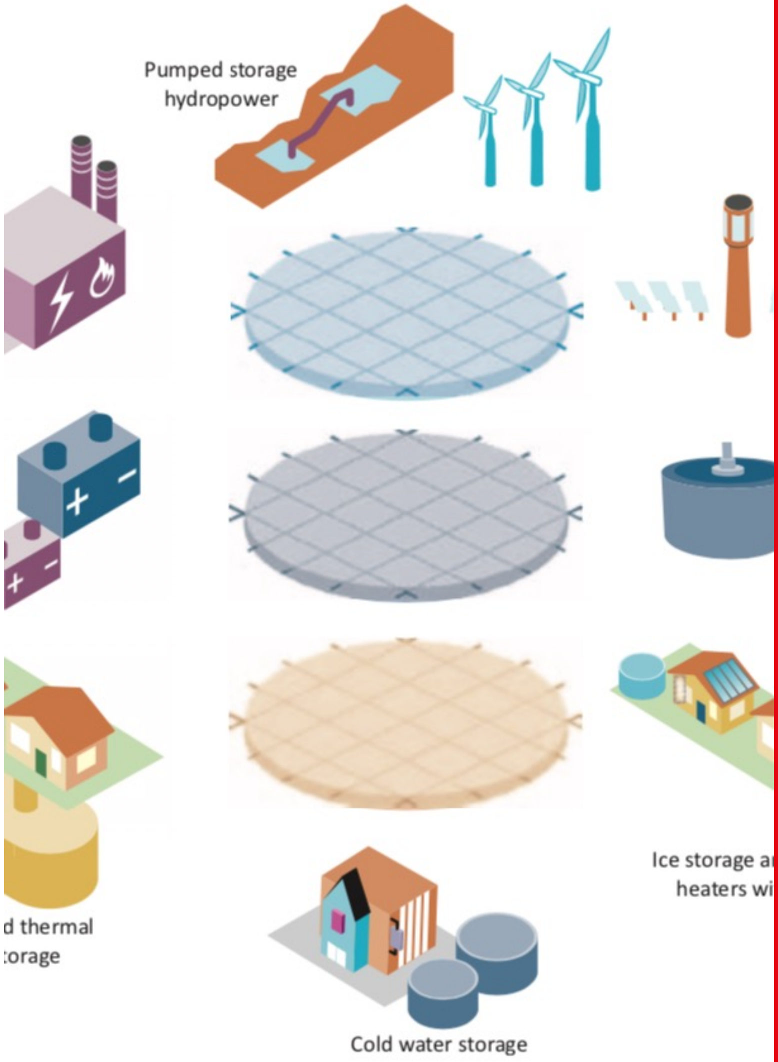

Take-home message

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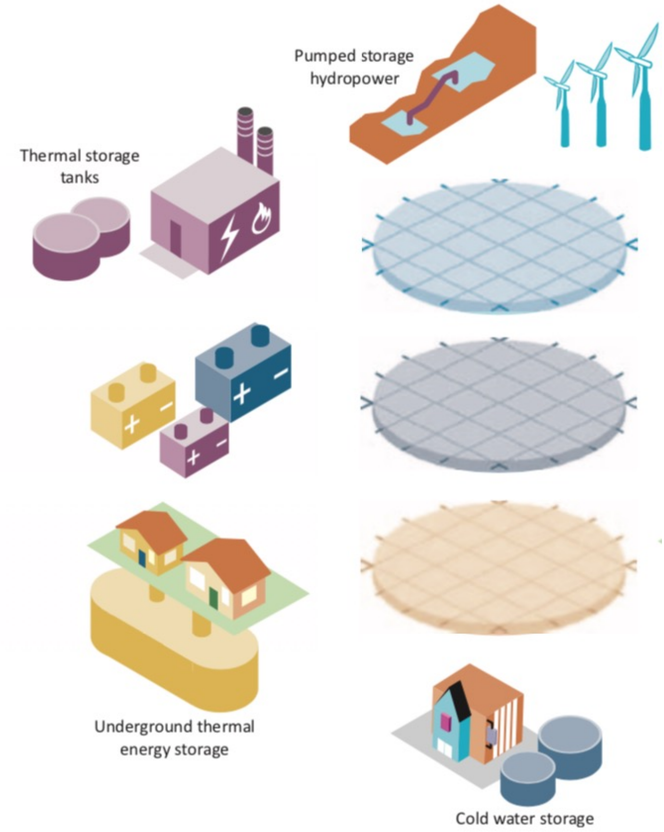
Take-home message

- Variable renewables → storage is key!
- Different classifications
- **Mechanical (potential)**
  - PHES: eff=85%, 1000 m^3/MWh
  - CAES: eff = 70%, ~200 m^3/MWh
- **Thermal energy storage (TES)**
  - Sensible, latent, thermochemical
  - Eff = up to 90%
- **Electrochemical**
  - Short-term, eff = 75-95%, e = 0.1-1 MJ/kg
- **Chemical**
  - Storing excess electricity in fuels
  - Eff = 25-50%



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Questions?

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