Renewable Energy

- Outline:
  - Why energy storage
  - Overview over approaches
  - Energy storage:
    - Pumped hydro energy storage
    - Compressed air energy storage
    - Flywheels
    - Thermal energy storage
    - Chemical energy storage

Learning outcomes of todays lecture

- Energy storage:
  - Why is energy storage vital for a future energy economy
  - What storage options are useful for what energy and power densities and what time-scales?
  - General working principle of storage technologies:
    - Pumped hydro energy storage
    - Compressed air energy storage
    - Flywheels
    - Thermal energy storage (sensible, latent, thermochemical)
    - Chemical energy storage (fuels, batteries, flow batteries, capacitors)

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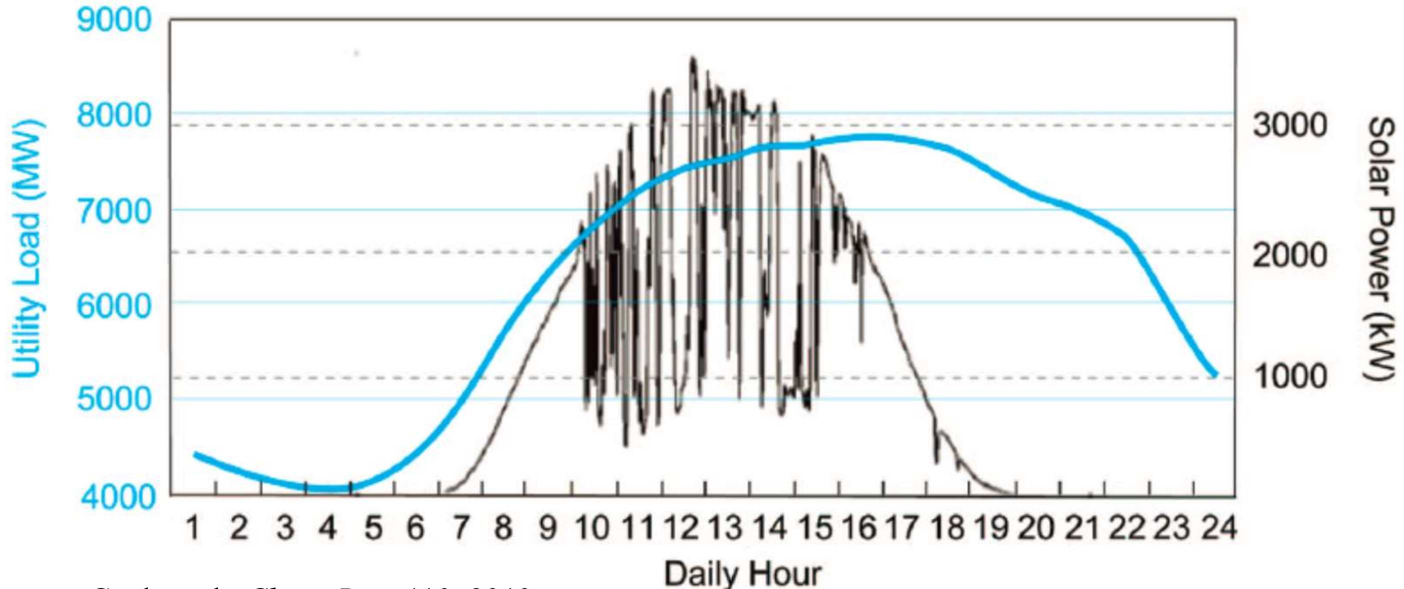
Why energy storage

- Energy storage:
  – Bridging periods between when/where energy is available and when/where it is in demand



Cook et al., *Chem. Rev.*, 110, **2010**.

  – Energy intermittency characteristic for renewable energy sources
    - Capacity factor for conventional electricity generation 90%
    - Capacity factor for wind 25 %
    - Capacity factor for solar PV 15 %

Why energy storage

- Energy storage can have different aims:
  - Geographical distances between supply and demand
  - Timely differences between production and demand, fluctuations
  - Bridging seasonal differences and imbalances
  - Leveling daily load cycles, ‘peak shaving’
  - Improving stability, power quality, and reliability of supply

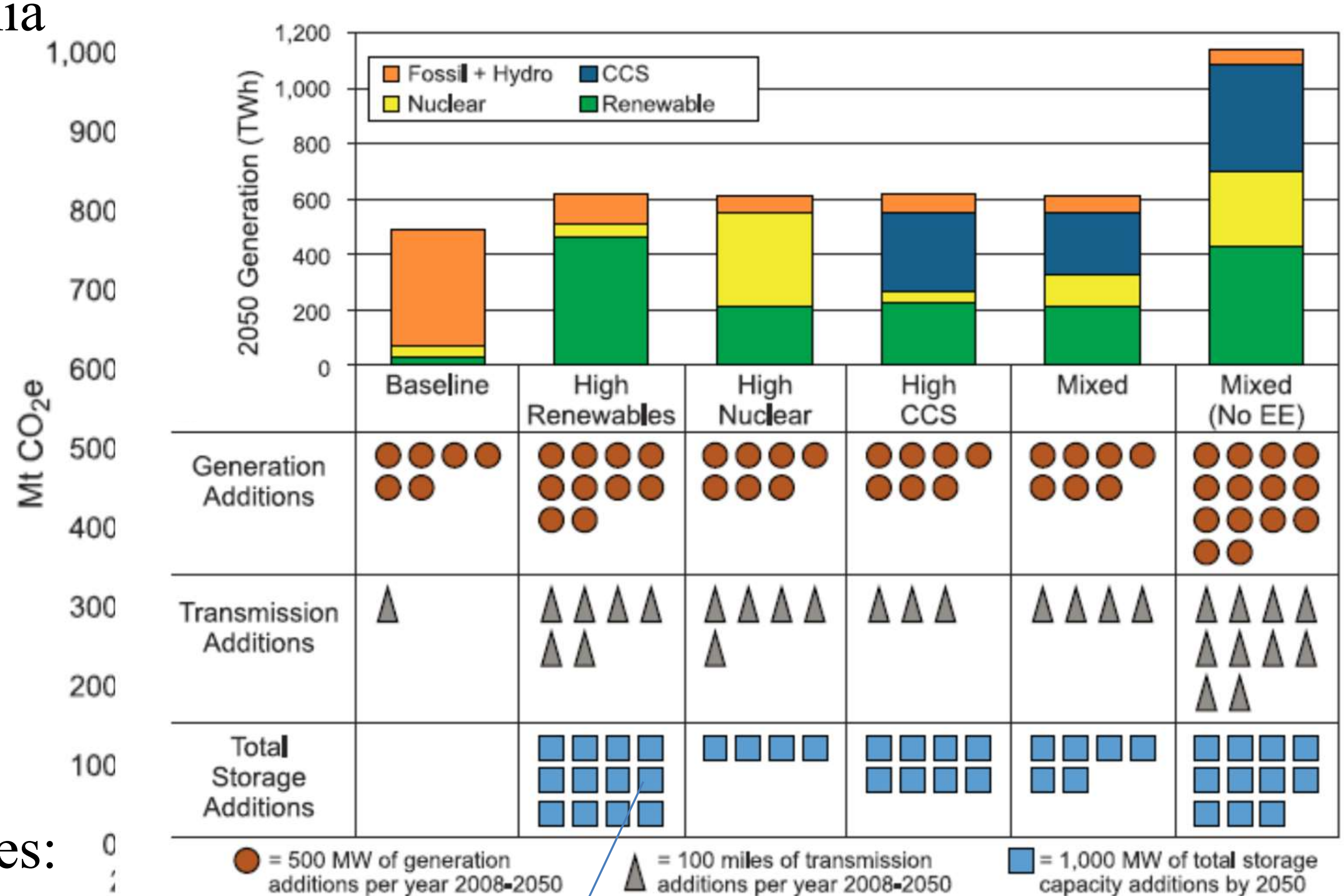
Why energy storage

- Energy storage:

Advantages	**Disadvantages**
Increased operational performance, reliability, flexibility	Loss of efficiency
Decreased mismatch between periods of energy supply and demand	Increased initial costs
Enhanced opportunities for renewable energy resources through more flexible energy systems	Sometimes difficult match between range of performance of energy system and storage
Potential to decrease the use of fossil fuels	
Improved opportunities for distributed generation	
Improved economics over lifetime of energy system, sometimes including lower initial energy system costs and maintenance costs	
Increased system efficiency (decreases utilization of energy sources)	
Reduced space requirements	
Decreased environmental impact	
Enhanced energy sustainability	

How much storage

- Study for California



Williams et al., Science, 2012

10x current capacity

- The key approaches:
  - Efficiency
  - Decarbonization
  - Electrification

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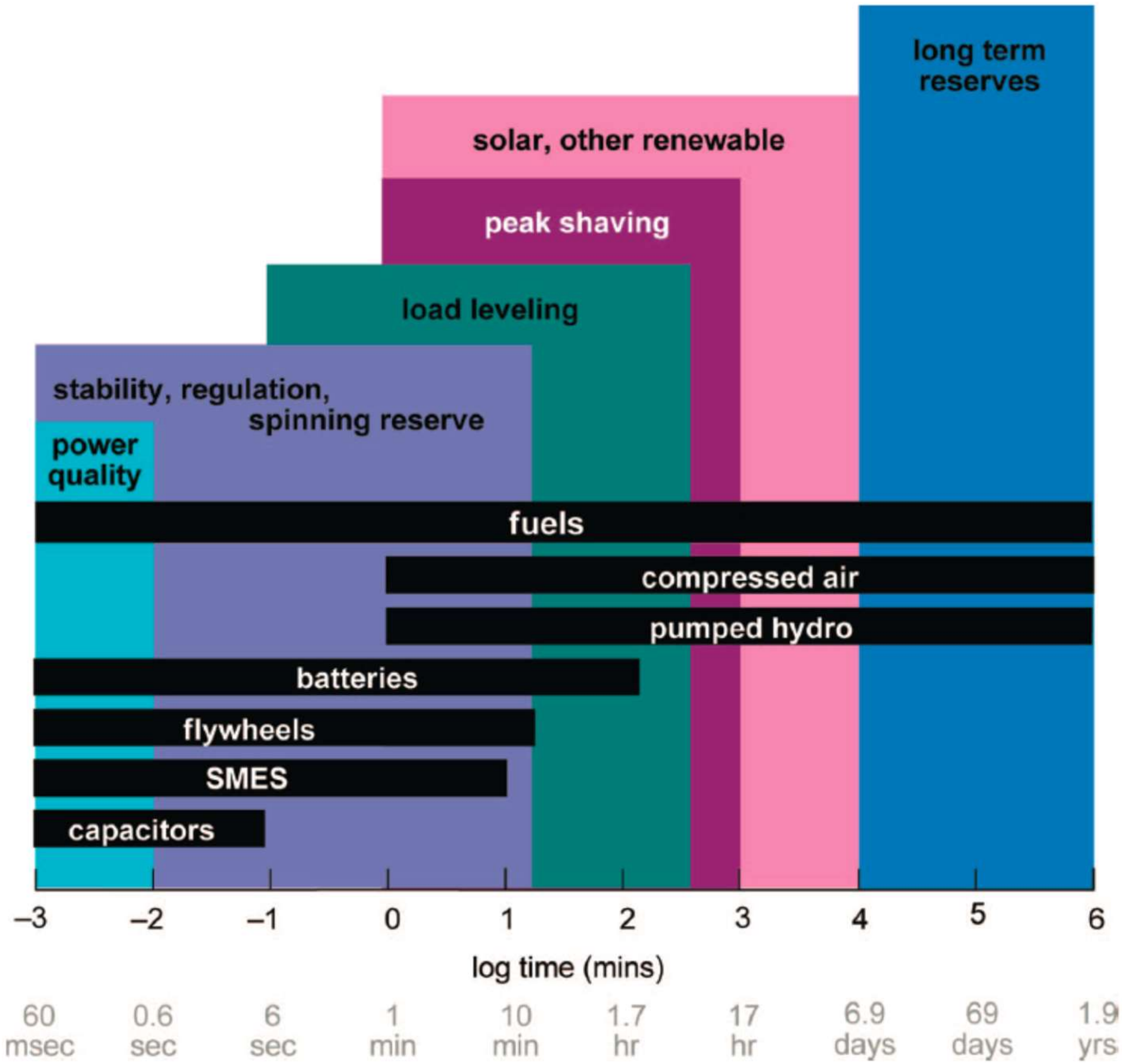
Overview

- Types of energy storage:
  - Potential energy: pumped hydro, compressed air storage
  - Kinetic energy: flywheel
  - Thermal (incl. thermochemical): water tanks, molten salt tanks
  - Chemical (incl. electrochemical): batteries, supercapacitors, superconductors, fuels
  - (Biological and organic)

Overview

- Energy storage, comparison:



Cook et al., *Chem. Rev.*, 110, **2010**.

Overview

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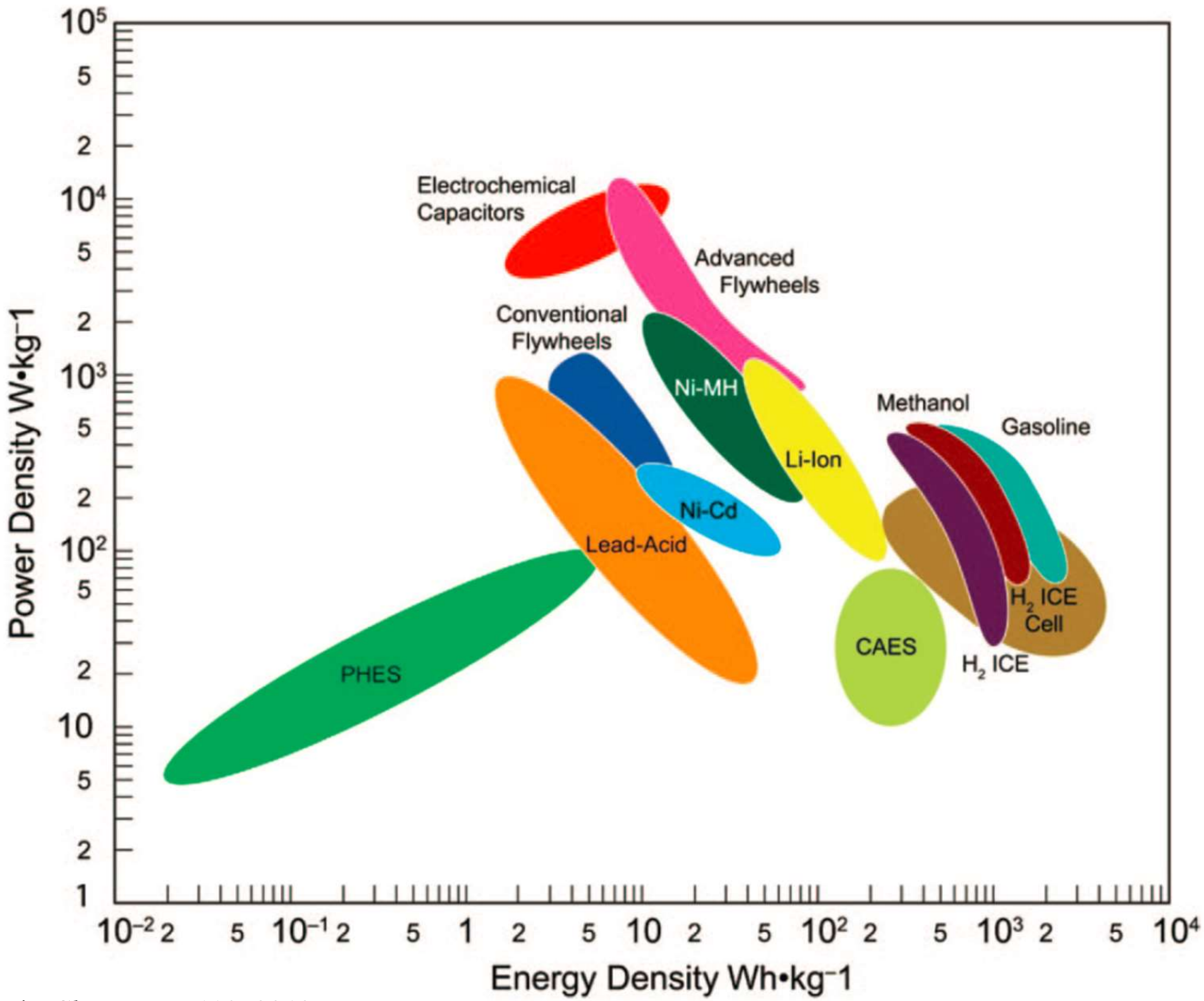

Cook et al., *Chem. Rev.*, 110, **2010**.

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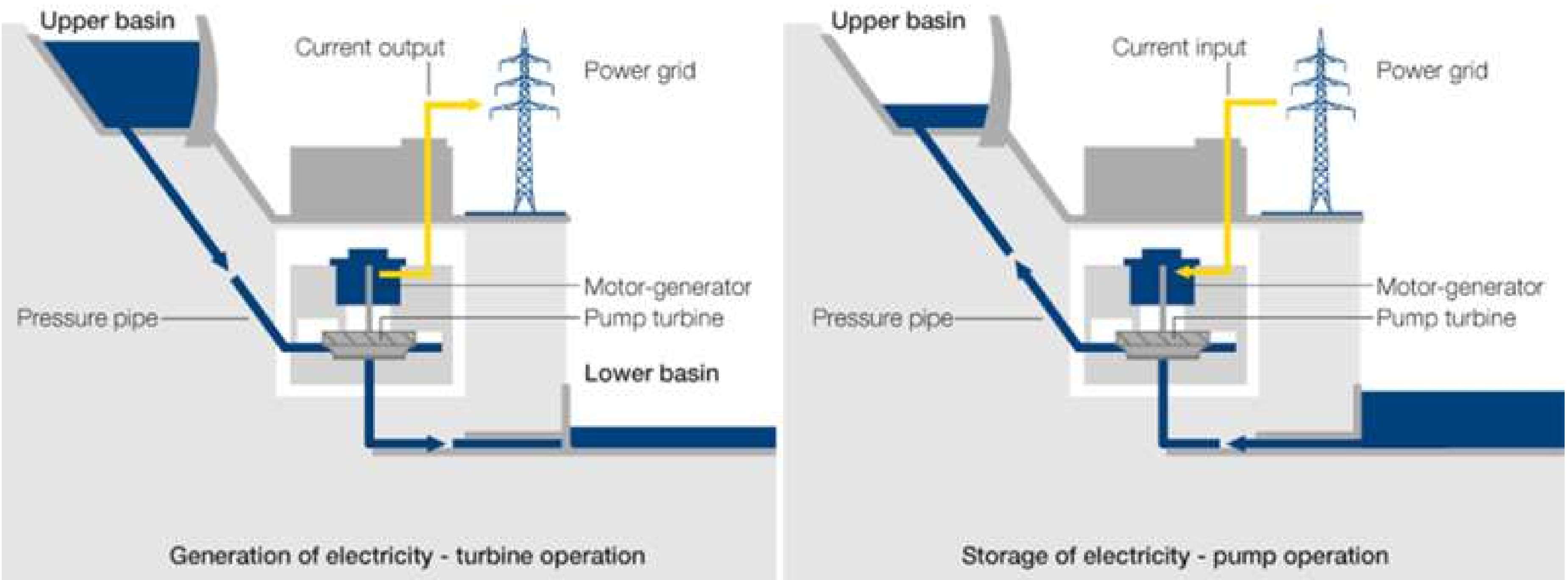
Energy storage

- Pumped hydro energy storage (PHES):
  - available surplus or off-peak generating capacity is used to pump water from a low elevation reservoir to a reservoir at higher elevation
  - potential energy is recovered



Energy storage

- Pumped hydro energy storage (PHES):
  - PHES facilities often use reversible pump turbines, where the water pump and the turbine are a single, bidirectional device
  - Overall process can have round trip efficiencies as high as 80%
  - But owing to the low energy density of a water column, large volumes of water are needed
  - Maximum energy density low (5-7 J/kg)
  - PHES requires approx. 50 km^2 per 100 MW
  - Practical plants with very large capacity (>1GW) to small scale (<100kW)
  - Large investments needed
  - Land-use issue associated with PHES can lead to public resistance
  - Underground PHES possible (but even higher prizes)

Energy storage

- Pumped hydro energy storage (PHES):
  - Energy stored in potential energy:

$$E_{pot} = mg\Delta h$$

  - Power:

$$P = \frac{\Delta E}{\Delta t} = \rho g \Delta h \dot{V}$$

← Volume flow rate [m^3/s]

  - Plus losses in turbine and pump (efficiencies 85 – 90%)
  - Evaporation
  - Friction, leakage

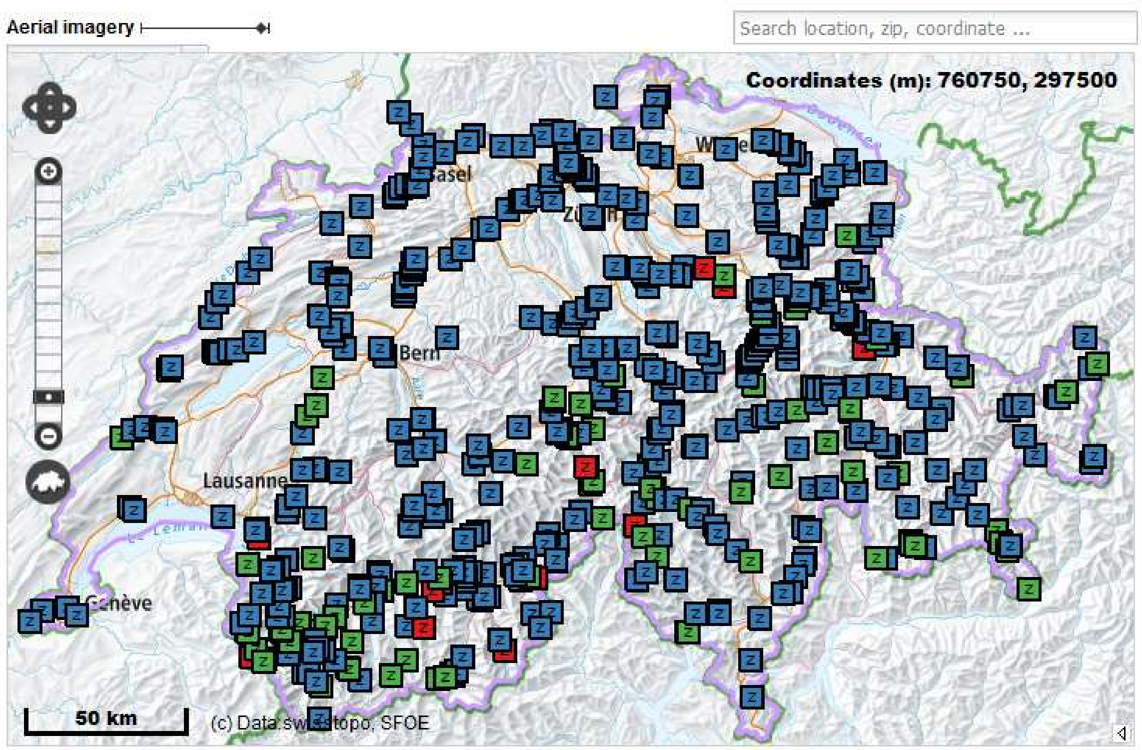
Energy storage

- Pumped hydro energy storage (PHES) - Switzerland:
  - Well suited:
    - Alpine landscape with steep mountains
    - Sound geological conditions, relatively watertight rock reducing leakage losses;
    - Inserted in the large European electric grid with dominant thermal power
  - Today 604 hydropower plants in Switzerland (power plants with a capacity of at least 300 kW)
  - Produce an average of around 36’175 GWh/y
  - The contributions are:
    - 47.4% run-of-river power plants
    - 48.2% storage power plants
    - 4.4% pumped storage power plants

Energy storage

- Pumped hydro energy storage (PHES) - Switzerland:
  - 2/3 of this energy is produced in the mountain cantons of Uri, Graubünden, Ticino and Valais, while Aargau and Bern also generate significant quantities

Map: Hydropower statistics

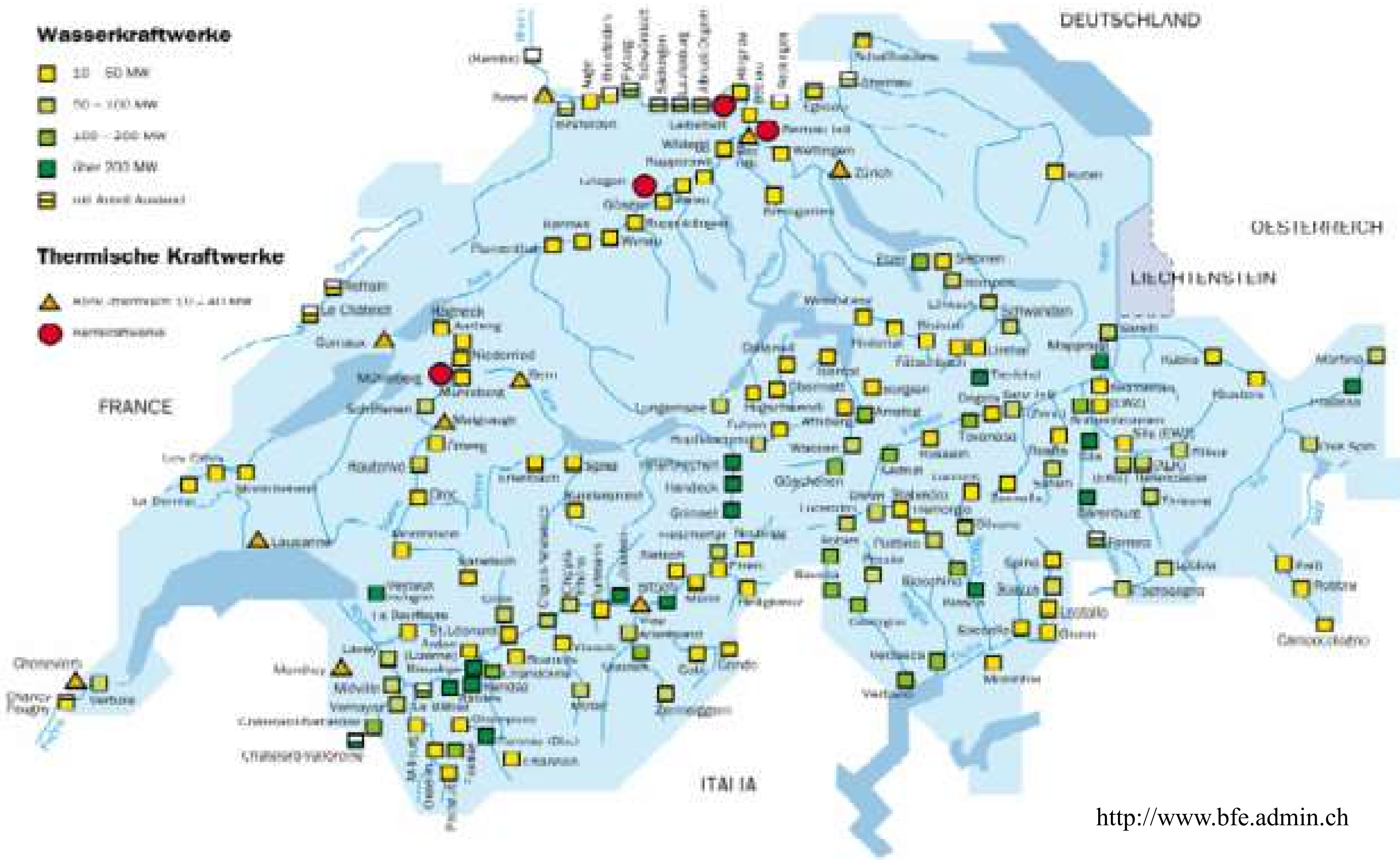


http://www.bfe.admin.ch/geoinformation/05061/05249/05391/index.html?lang=en

- Laufkraftwerk
- Reines Umwälzwerk
- Speicherkraftwerk
- Pumpspeicherkraftwerk

Energy storage

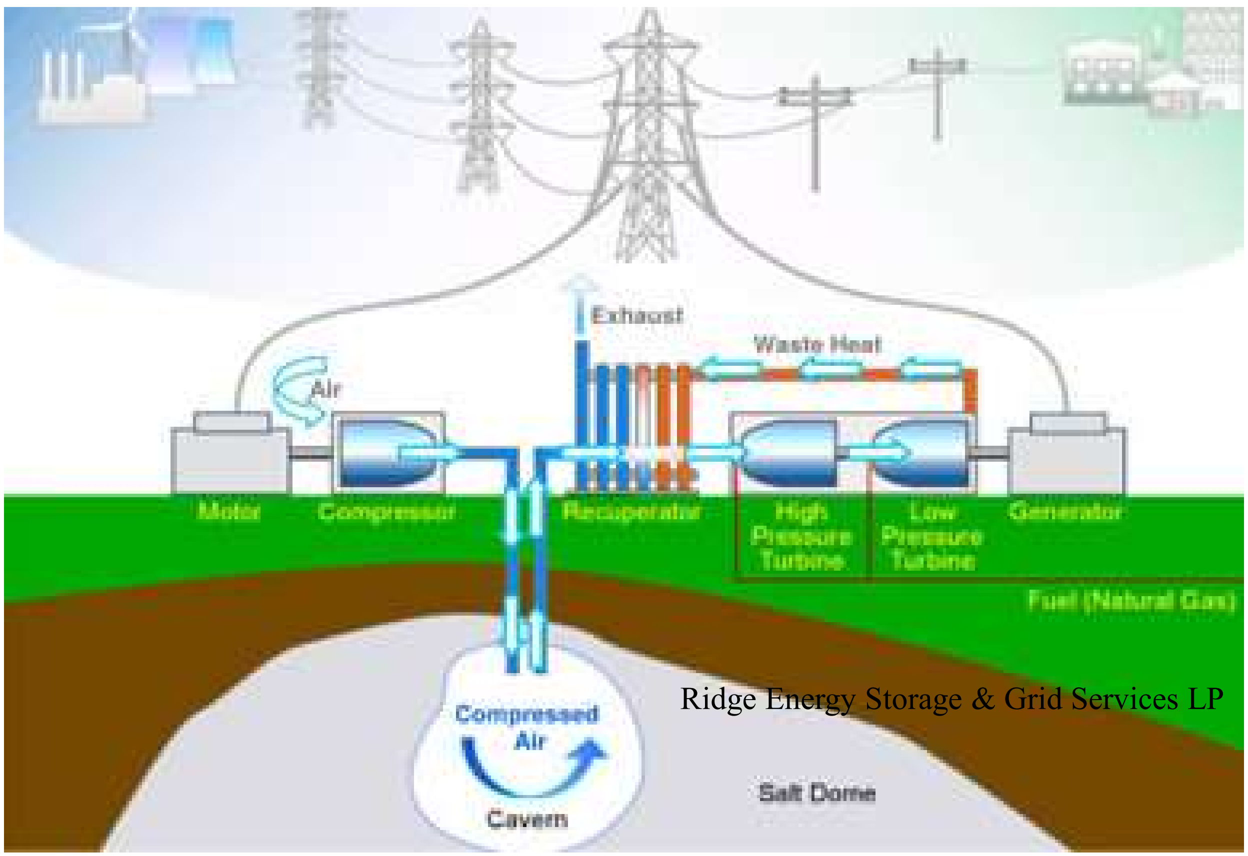
- Pumped hydro energy storage (PHES) - Switzerland:



http://www.bfe.admin.ch

Energy storage

- Compressed air storage:
  - Long been used to provide mechanical work
  - Recently interest in its use for electricity storage: uses electricity to compress air, to be used (possibly with the addition of fossil fuel) in down-stream high pressure turbine



Ridge Energy Storage & Grid Services LP

Energy storage

- Compressed air storage:
  - Different types dependent on heat management:
    - Isothermal: heat flows out and in during sufficiently slow cycling (compression and expansion), gas temperature remains constant
    - Adiabatic: the heat generated upon air compression is stored and returned to the air upon expansion (estimated efficiency up to 70%)
    - Diabatic: heat generated is removed from the system, lower efficiencies but simpler to engineer and cheaper
  - Operating pressures of 50-80 bar are typical
  - Volume of 200-300 m^3 is required per stored MWh

Energy storage

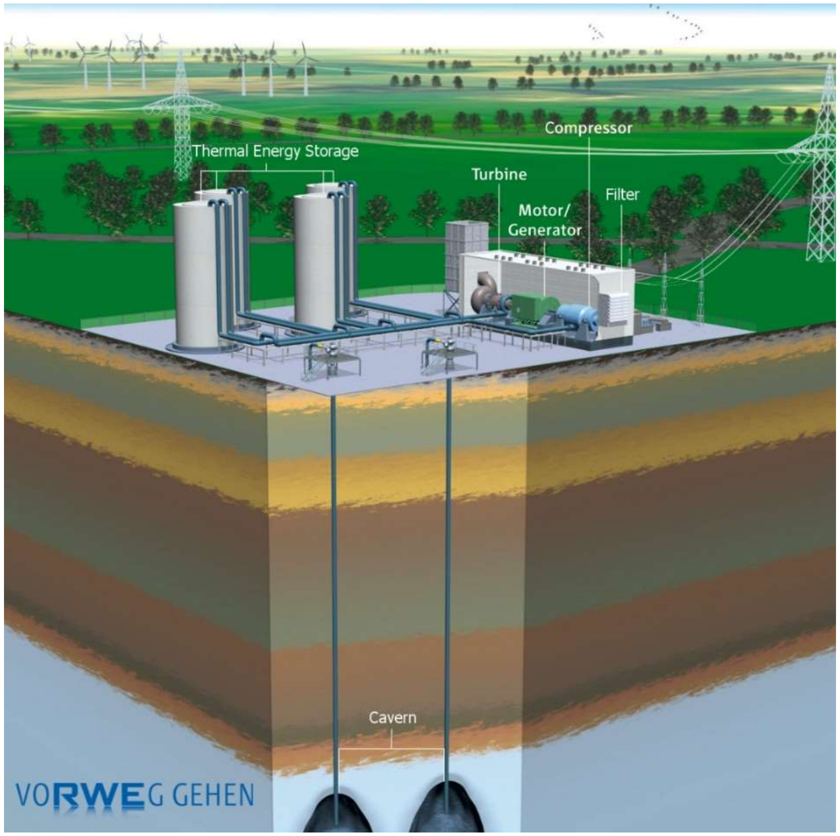
- Compressed air storage:
  - Work:

$$W = -\int_{V_1}^{V_2} p\,dV = \begin{cases} \text{isothermal } (pV = \text{const}):\ p_1 V_1 \ln\left(\dfrac{p_2}{p_1}\right) \\ \text{adiabatic } (pV^{\kappa} = \text{const}):\ \dfrac{p_1 V_1}{\kappa - 1}\left(\left(\dfrac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right) \end{cases}$$

  - Energy density of 114 kWh/kg can be achieved in isothermal and reversible case when compressing to 200 bar

Energy storage

- Compressed air storage:
  - Caverns used:
    - Salt domes
    - Depleted gas fields
    - Old tunnels and army bunker



Energy storage

- Compressed air storage, in operation
  - Diabatic CAES power plants

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

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

  - Cycle efficiencies around 40-55%
  - Heat from compression wasted, fossil fuels required

Compressed air energy storage

- Pilot project for Switzerland for advanced adiabatic CAES in Pollegio
- Tests in large-scale tunnel at high temperature and pressure (up to 33 bars)
  Heat storage capacity: 10’000 kWh_{th}

alacaes an airlight energy company

ETH zürich

PAUL SCHERRER INSTITUT PSI

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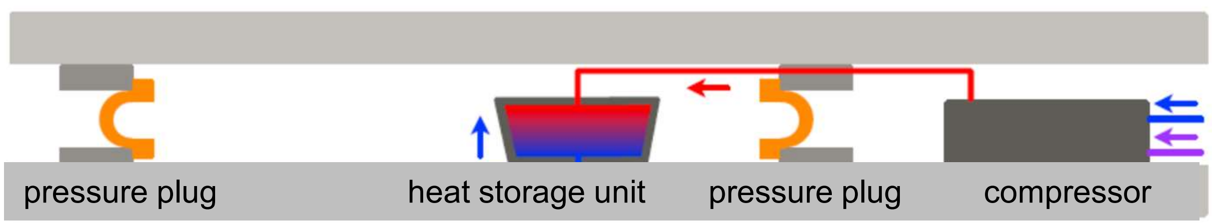
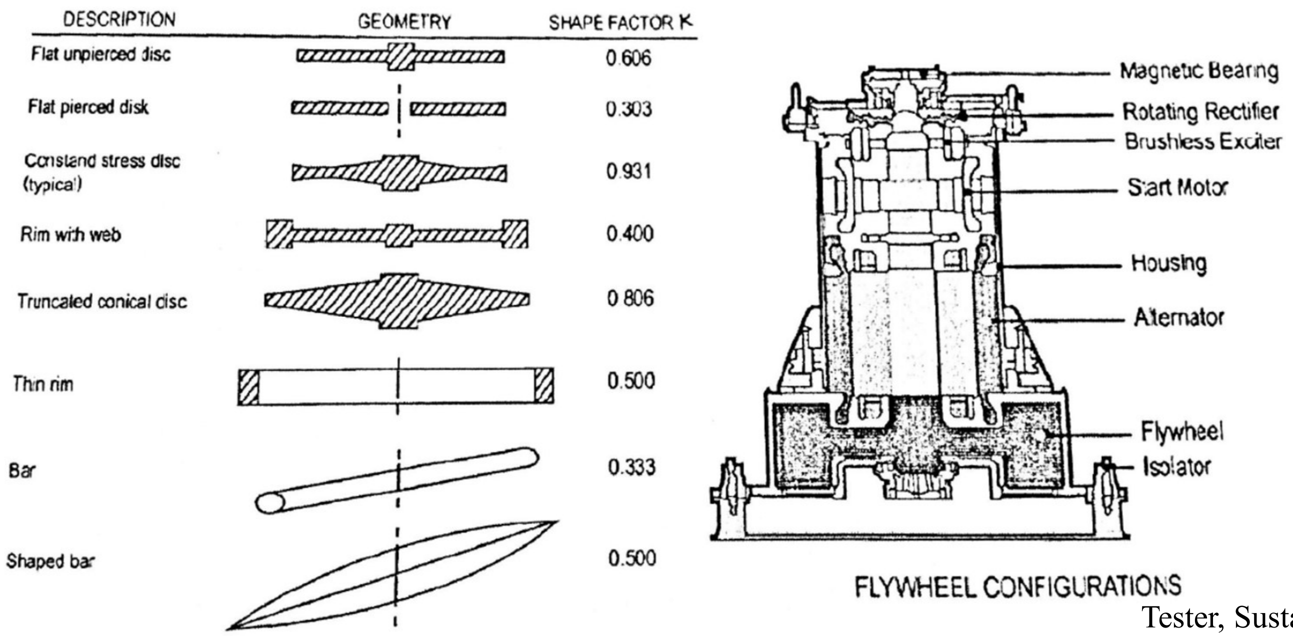


Energy storage

- Flywheels:
  - Store energy in a rotating mass (kinetic energy storage)
  - The rotor resides in an evacuated or helium filled container to reduce aerodynamic losses and rotor stresses

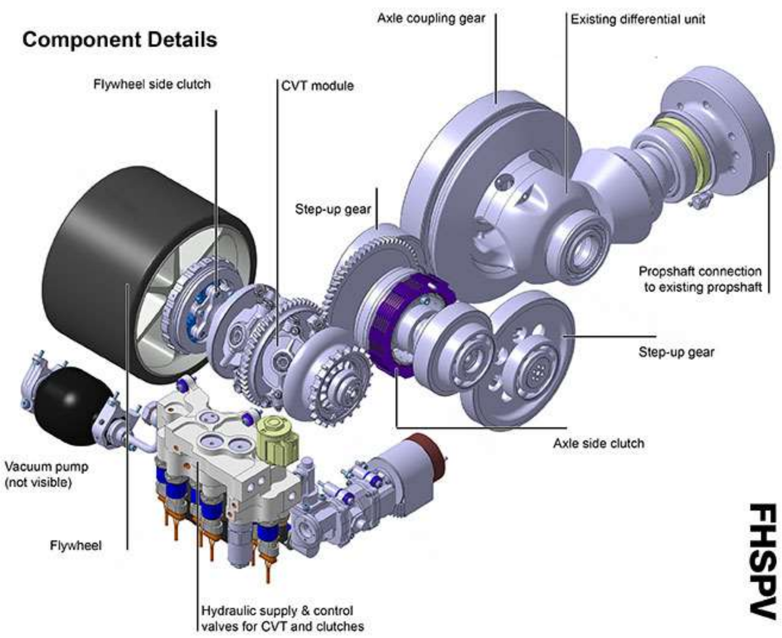


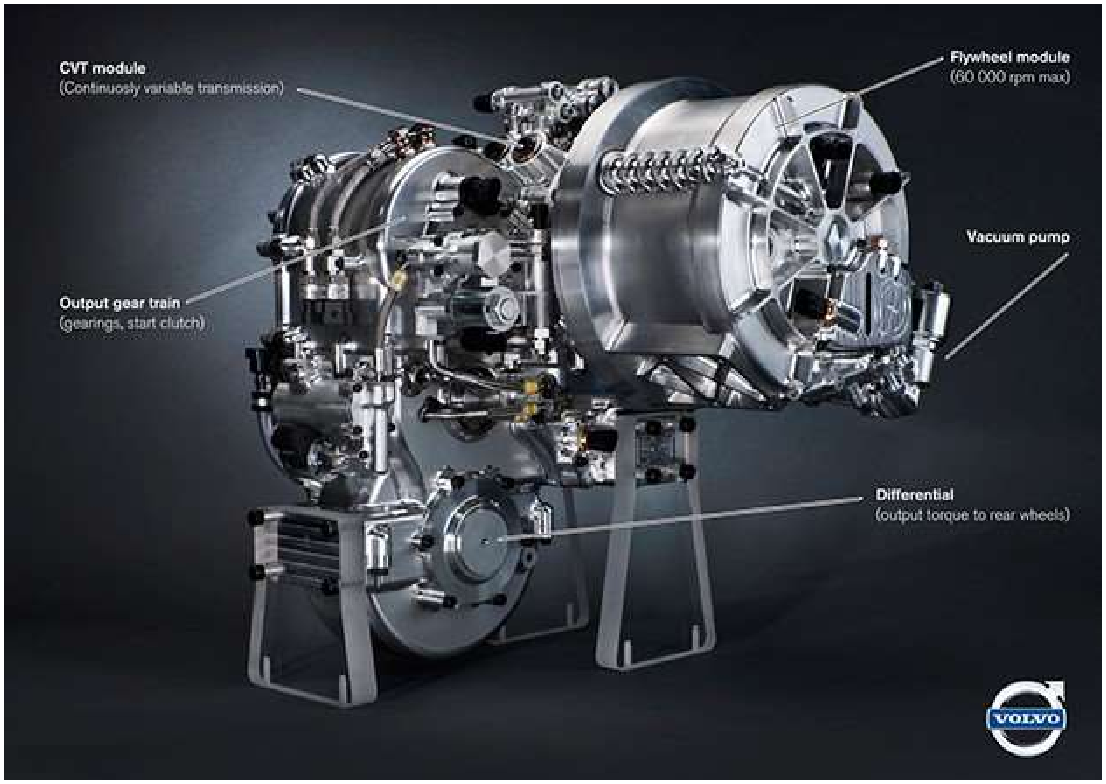
Tester, Sustainable Energy, 2012.

  - For electricity storage: the flywheel is outfitted with an electrical machine and power electronic interface (motor/generator, variable-speed power electronics converter, power controller)

Energy storage

- Flywheels:
  - Automotive:



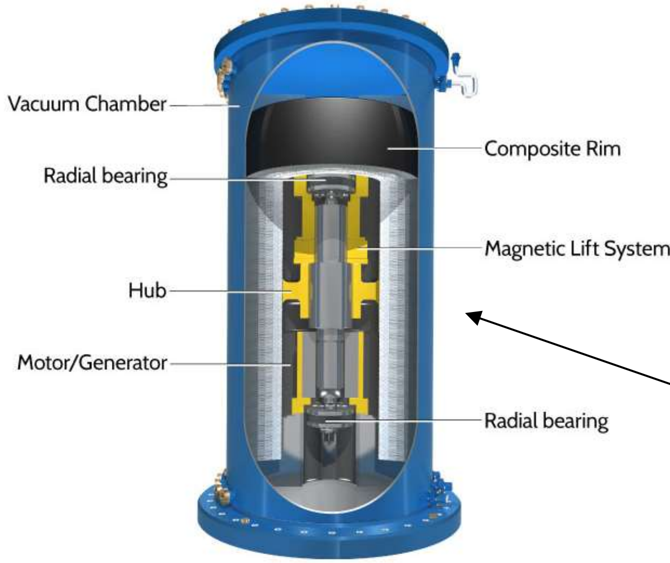


Energy storage

- Flywheels:
  - Beacon Power, 20 MW plant, commercial operation 2011
  - 200 flywheels
  - Provides frequency regulation service to the grid operator.
  - In this market, Beacon flywheels perform between 3,000 and 5,000 full depth-of-discharge cycles a year

Energy storage

- Flywheels:



beaconpower.com

Energy storage

- Flywheels:
  - Energy: $E_{rot} = \frac{1}{2} I \omega^2$

    Rotaitonal speed [rad/s]

    Moment of inertia [kgm^2]

  - Moment of inertia depends on mass and shape of rotor:

    Cylindrical rotor

$$I = \int_V \rho r^2 dV = \int_0^{2\pi} \int_0^{l} \int_0^{R} \rho r^2 r dr dl d\varphi$$

E.g. for solid cylinder: $I = \frac{1}{2} m R^2$

  - Flywheel energy storage thus increases with increasing mass of the rotor at increasing distance from the axis of rotation and increasing rotational velocity

Energy storage

- Flywheels:
  - The efficiency depends on the energy extraction over different rotational speeds and loss of energy owing to friction
  - The practical limitations depend on strength of materials:
    - Tensile stress in rim: $$\sigma_{max} = \rho m R^2 \omega^2$$
    - Max energy density: $$E = km \frac{\sigma_{max}}{\rho}$$ (Shape factor: k)
      - conventional (low speed, 6000 rev/min), made of metals (high σ_{max} but high ρ) → low energy density (~5Wh/kg) and moderate power density
      - advanced (high speed, 50 000 rev/min), reinforced polymer composites (lower ρ, higher σ_{max}) → higher energy density (~100Wh/kg))

Energy storage

- Flywheels:
  - Better bearings (magnetic bearings, superconducting magnetic bearings) to increase efficiency
  - Applications:
    - Because the rotor is fixed in a flywheel, energy may be stored by increasing the rotational velocity of the flywheel.
    - Stored energy from the flywheel may be released upon decreasing the rotational velocity of the flywheel.
    - speed of a flywheel can be adjusted quickly (0.1 s), therefore they can store and release energy at:
      - high rates (0.1 s-h)
      - for many cycles (100'000-2'000'000)
      - with long service lives (15-25 years)
      - at appreciable energy storage (0-1000 MW)

Energy storage

- Flywheels:
  - Self-discharge of flywheels can be significant, therefore application limited to short term:
    - Currently used for uninterruptible power supply systems, load following and peak power supply, telecommunications, power quality improvement, and rail support
    - Possible future use for renewable energies:
      - power smoothing, avoiding rapid voltage fluctuations, and flicker (continuous cycling)
      - power system stability (high power cycling and injection)
      - grid reinforcement (peak lopping, distributed storage)
      - bridging power until a diesel generator set in a hybrid stand-alone power system is started and ready to be brought online

Energy storage

- Flywheels in a car: exercise

A car (mass of 1000 kg, shape factor equals 0.6) has a pair of flywheels (carbon fiber reinforced plastic, density 1500 kg/m^3 and tensile stress 2000 N/mm^2) which recuperates energy from breaking, which is then reused during acceleration. Dimension a pair flywheel that stores the energy of a car moving at up to 120 km/h and determine its rotational speed. What is the maximum rotational speed the flywheel should be able to withstand?

Energy storage

- Thermal energy storage:
  - Useful as 40% of todays energy is thermal energy at temperature lower than 250°C
  - Often driven by daily to seasonal variations (e.g. residential heating using solar energy)
  - Three types of storage (and combinations thereof):
    - Sensible heat storage (temperature change, heat capacity)

$$E = mc_p \Delta T$$

    - Latent heat storage (phase change)

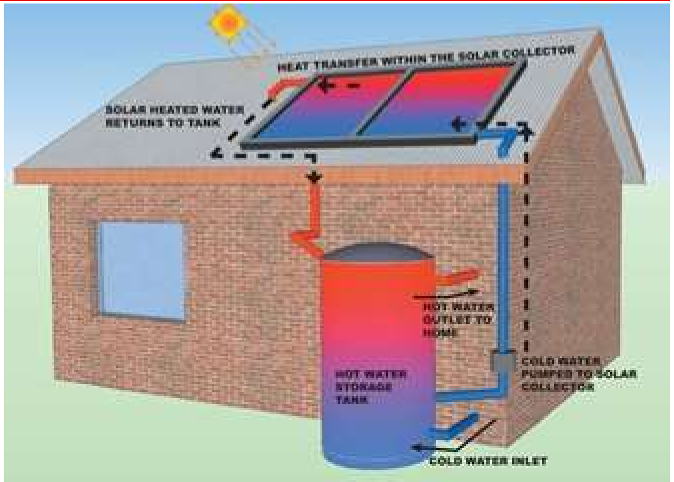
$$E = m\Delta h_{lat}$$

    - Thermochemical heat storage (reaction enthalpy)

$$\mathrm{C} + \mathrm{heat} \leftrightarrow \mathrm{A} + \mathrm{B}$$

Energy storage

- Thermal energy storage:
  - Example: sensible heat storage by large water tanks
    - Heat capacity of water 4 kJ/kg/K
    - Stored energy: $E_{sens} = mc_p \Delta T$



  - Heating energy demand of older 200 m^2 house with specific energy consumption of 100 kWh/m^2/year

    → requires 909 t (~ 909 m^3) of water to be heated by 20 K

  - But there is heat loss:

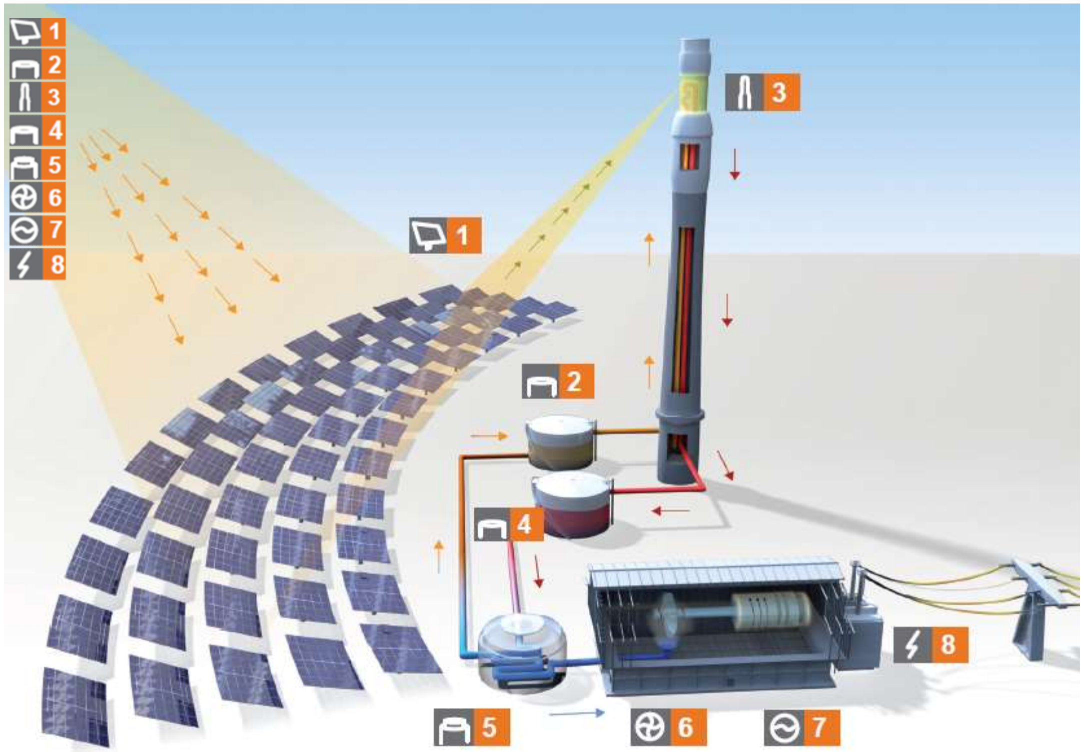
$$\rho c_p V \frac{dT}{dt} = \dot{Q}_{lost} \approx -kA \frac{(T - T_\infty)}{\Delta x}$$

Energy storage

- Thermal energy storage:
  - Large water tanks have problems with corrosion, fouling
  - Instead use packages of gravel, rock, or massive parts of buildings:
    - Heat capacity of granite 0.75 kJ/kg/K
    - Heat capacity of gravel, sand 0.71 kJ/kg/K
    - Heat capacity of gravel-water 1.32 kJ/kg/K
  - Or store heat in geothermal ground source or subsurface aquifier

Energy storage

- Thermal energy storage:
  - Example: high-temperature heat storage for CSP
  - Molten salts (sodium and potassium nitrates: $NaNO_3$ and KNO_3)
  - Direct heating, storage capacity of 15 h
  - Two tanks: cold-salts tank (290ºC) and hot-salts tank (565ºC)



Energy storage

- Thermal energy storage:
  - Latent heat storage:
    - Heat is stored upon phase change
    - Most convenient: solid-liquid (heat is stored during melting)
    - Advantage:
      - Possible larger specific energy density
      - Operates at constant temperature

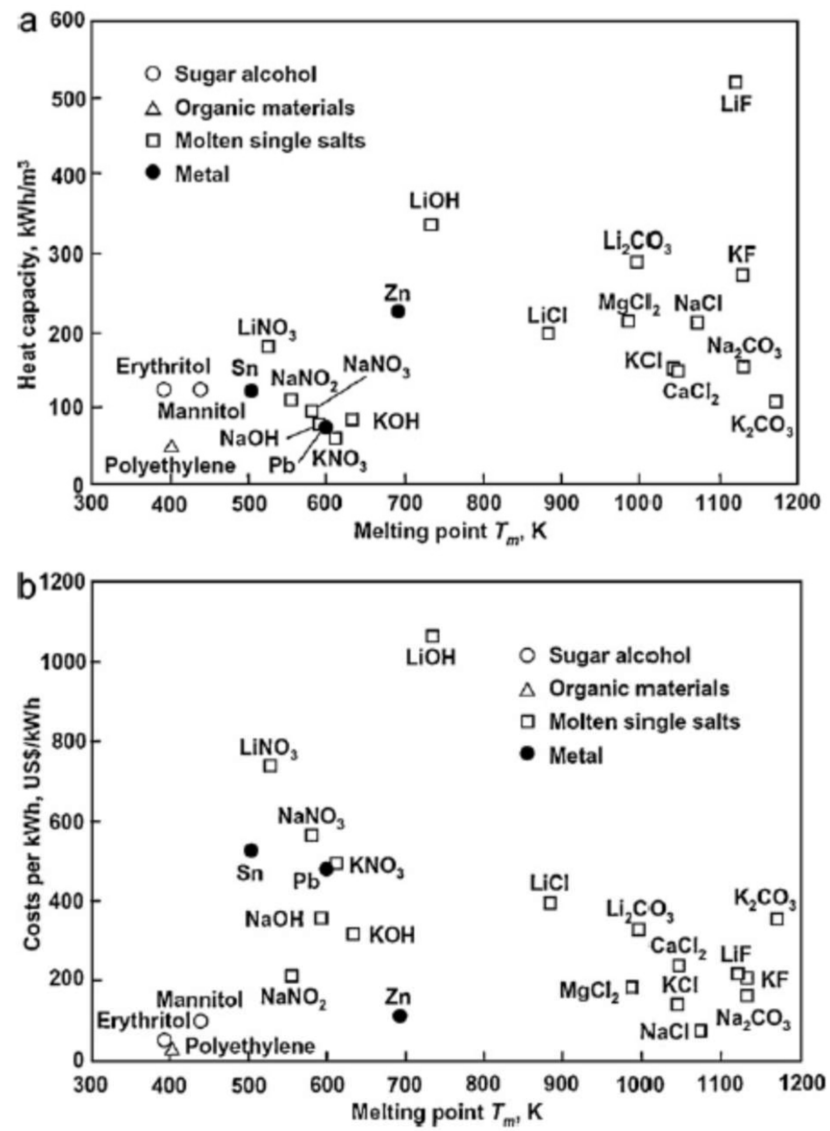
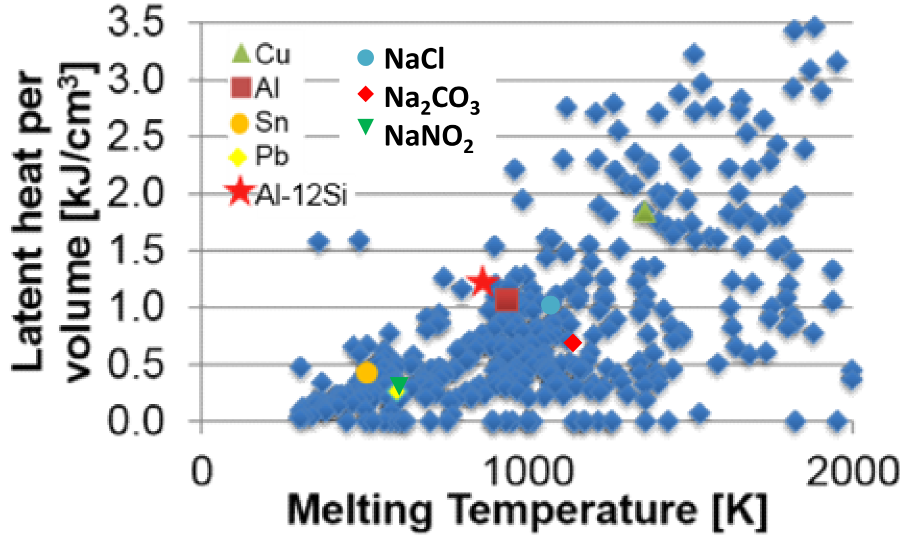


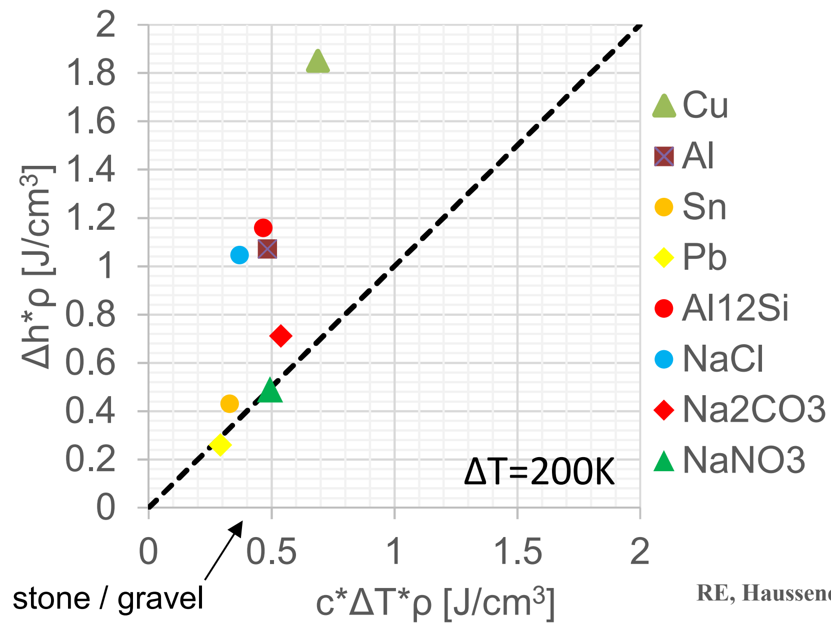
Fig. 1. Heat capacity (a) and media cost (b) of high melting point PCMs [29].

Energy storage

- Material properties – latent:



- Latent versus sensible:



Energy storage

- Thermal energy storage:
  - Thermochemical heat storage (reaction enthalpy)

$$C + \text{heat} \leftrightarrow A + B$$

Table 1. Promising Materials for Thermochemical Energy Storage [8, 16]

Thermochemical Material (C)	Solid Reactant (A)	Working Fluid (B)	Energy Storage Density of Thermochemical Material (GJ/m^3)	Charging Reaction Temperature (°C)
$MgSO_4 \cdot 7H_2O$	$MgSO_4$	$7H_2O$	2.8	122
$FeCO_3$	FeO	CO_2	2.6	180
$Ca(OH)_2$	CaO	H_2O	1.9	479
$Fe(OH)_2$	FeO	H_2O	2.2	150
$CaCO_3$	CaO	CO_2	3.3	837
$CaSO_4 \cdot 2H_2O$	$CaSO_4$	$2H_2O$	1.4	89

Abedin et al., A Critical Review of Thermochemical Energy Storage Systems, 2011

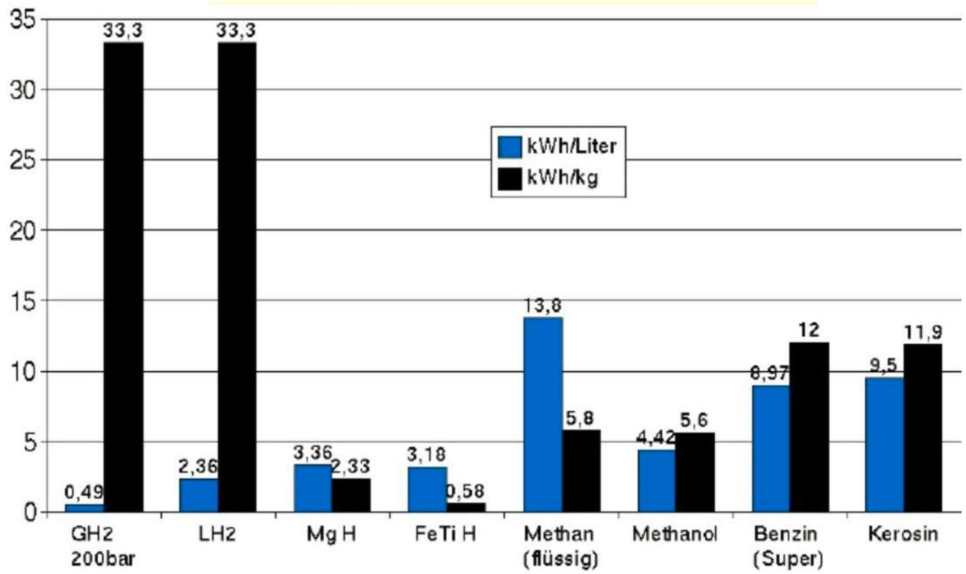
Energy storage

- Chemical energy storage:
  - Considerable amount of energy is contained in the chemical bonds that hold atoms in place in molecules
  - Breaking these bounds selectively such as during oxidation of fossil fuels as they are combusted can release a large amount of energy at high temperatures
  - Stored for millenia (fossil fuels) or years (biomass)

Energy storage

- Chemical energy storage:
  - Liquid and solid chemical energy carriers have generally high specific energy (e.g. wood 18MJ/kg, methanol 20 MJ/kg) and high volumetric energy density
  - Gases (hydrogen, methane) have high specific energy density (e.g. hydrogen 141 MJ/kg) but low volumetric energy density

    → pressurize, liquefy, metal-hydrides, etc.



  - See «Hydrogen as an energy carrier»-lecture

Energy storage

- Chemical energy storage:
  - Reversible chemical reactions to store energy:
    - Electrochemical: batteries

In a battery, electrons flow (in an external circuit) from one side of the device (the anode) to the other side of the device (a cathode). To maintain electroneutrality, cations must also flow in the same direction but along a separate path (within the electrolyte contained inside the battery cell) so that the battery does not short circuit. The flow of electrons and cations during battery discharge permits devices to be externally powered. Energy storage is achieved by reversing the electron and cation flow by applying an external energy source.

- Electrochemical devices can have high efficiency (not limited by Carnot)
- Depended on surface processes

Energy storage

- Chemical energy storage:
  - Reversible chemical reactions to store energy:
    - Electrochemical: batteries

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

[a] Data taken from refs 87 and 88. [b] Theoretical limiting energy densities: lead−acid, 252; nickel−alkaline, 240−300; lithium-ion, 400; high T-sodium 750−790; metal−air, Li 13000, Cd 4600, Mg 6800, Al 8100, Zn 1300, Fe 1200 (note: these quoted energy densities do not correct for the weight of the metal oxide product at the cathode; when this is included, the energy densities of all of these metal air batteries is greatly reduced).

Cook et al., *Chem. Rev.*, 110, **2010**.

Oxidation and Reduction

EMPA
Materials Science & Technology

Reduction

Likes to be reduced

$Hg^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Hg(\ell)$
$Ag^+(aq) + e^-$	$\longrightarrow$	$Ag(s)$
$Hg_2^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$2\,Hg(\ell)$
$Fe^{3+}(aq) + e^-$	$\longrightarrow$	$Fe^{2+}(aq)$
$I_2(s) + 2\,e^-$	$\longrightarrow$	$2\,I^-(aq)$
$O_2(g) + 2\,H_2O(\ell) + 4$	$\longrightarrow$	$4\,OH^-(aq)$
$Cu^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Cu(s)$
$Sn^{4+}(aq) + 2\,e^-$	$\longrightarrow$	$Sn^{2+}(aq)$
$2\,H_3O^+(aq) + 2\,e^-$	$\longrightarrow$	$H_2(g) + 2\,H_2O(\ell)$
$Sn^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Sn(s)$
$Ni^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Ni(s)$
$V^{3+}(aq) + e^-$	$\longrightarrow$	$V^{2+}(aq)$
$PbSO_4(s) + 2\,e^-$	$\longrightarrow$	$Pb(s) + SO_4^{2-}(aq)$
$Cd^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Cd(s)$
$Fe^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Fe(s)$
$Zn^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Zn(s)$
$2\,H_2O(\ell) + 2\,e^-$	$\longrightarrow$	$H_2(g) + 2\,OH^-(aq)$
$Al^{3+}(aq) + 3\,e^-$	$\longrightarrow$	$Al(s)$
$Mg^{2+}(aq) + 2\,e^-$	$\longrightarrow$	$Mg(s)$
$Na^+(aq) + e^-$	$\longrightarrow$	$Na(s)$
$K^+(aq) + e^-$	$\longrightarrow$	$K(s)$
$Li^+(aq) + e^-$	$\longrightarrow$	$Li(s)$

Likes to be oxidized

Oxidation

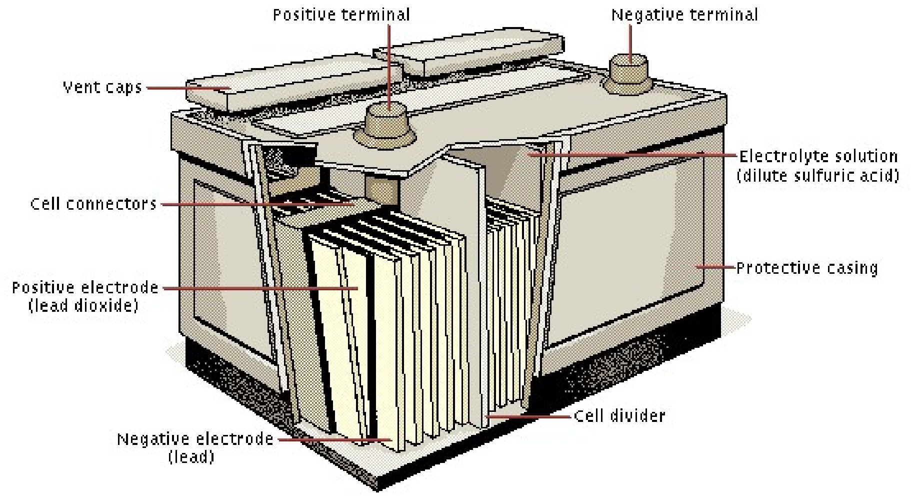
$Hg(\ell)$	$\longrightarrow$	$Hg^{2+}(aq) + 2\,e^-$
$Ag(s)$	$\longrightarrow$	$Ag^+(aq) + e^-$
$2\,Hg(\ell)$	$\longrightarrow$	$Hg_2^{2+}(aq) + 2\,e^-$
$Fe^{2+}(aq)$	$\longrightarrow$	$Fe^{3+}(aq) + e^-$
$2\,I^-(aq)$	$\longrightarrow$	$I_2(s) + 2\,e^-$
$4\,OH^-(aq)$	$\longrightarrow$	$O_2(g) + 2\,H_2O(\ell) + 4\,e^-$
$Cu(s)$	$\longrightarrow$	$Cu^{2+}(aq) + 2\,e^-$
$Sn^{2+}(aq)$	$\longrightarrow$	$Sn^{4+}(aq) + 2\,e^-$
$H_2(g) + 2\,H_2O(\ell)$	$\longrightarrow$	$2\,H_3O^+(aq) + 2\,e^-$
$Sn(s)$	$\longrightarrow$	$Sn^{2+}(aq) + 2\,e^-$
$Ni(s)$	$\longrightarrow$	$Ni^{2+}(aq) + 2\,e^-$
$V^{2+}(aq)$	$\longrightarrow$	$V^{3+}(aq) + e^-$
$Pb(s) + SO_4^{2-}(aq)$	$\longrightarrow$	$PbSO_4(s) + 2\,e^-$
$Cd(s)$	$\longrightarrow$	$Cd^{2+}(aq) + 2\,e^-$
$Fe(s)$	$\longrightarrow$	$Fe^{2+}(aq) + 2\,e^-$
$Zn(s)$	$\longrightarrow$	$Zn^{2+}(aq) + 2\,e^-$
$H_2(g) + 2\,OH^-(aq)$	$\longrightarrow$	$2\,H_2O(\ell) + 2\,e^-$
$Al(s)$	$\longrightarrow$	$Al^{3+}(aq) + 3\,e^-$
$Mg(s)$	$\longrightarrow$	$Mg^{2+}(aq) + 2\,e^-$
$Na(s)$	$\longrightarrow$	$Na^+(aq) + e^-$
$K(s)$	$\longrightarrow$	$K^+(aq) + e^-$
$Li(s)$	$\longrightarrow$	$Li^+(aq) + e^-$

Likes to be reduced

Noble metals: Do not like to be reduced. Stable in water

Energy storage

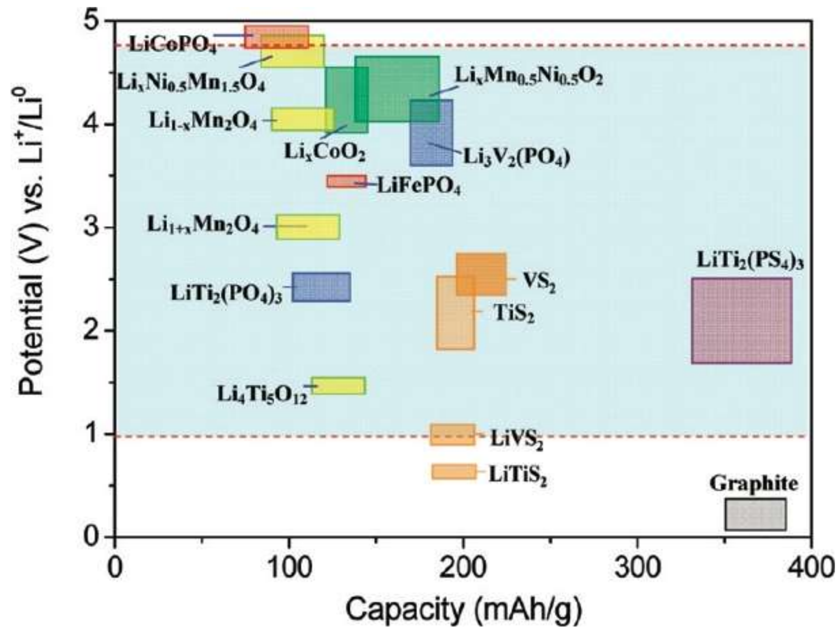
- Chemical energy storage:
  - E.g. lead-acid batteries: most common and oldest battery type (invented in 1859 by Planté)
    - Discharge/charge:

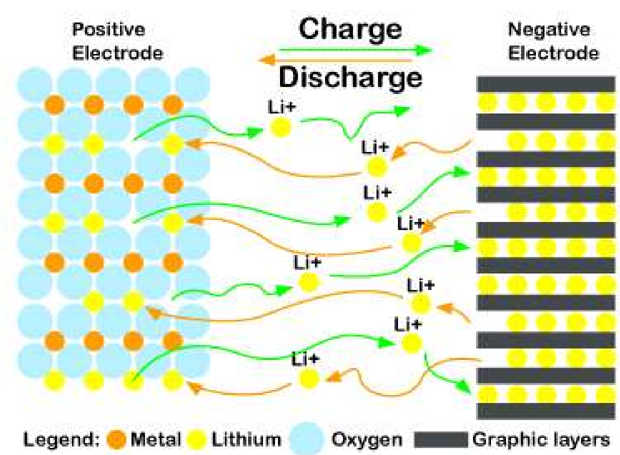


    - Maximum theoretical potential 2.1 V
    - Relatively inexpensive: $0.15/Wh
    - Low specific energy density (30-40 Wh/kg), due to high molecular weight of lead-acid

Energy storage

- Chemical energy storage:
  - E.g. Li-ion batteries:
    - Battery of choice in portable applications
    - Various material systems possible, most famous: Li_xCoO_2 with around 4.2 V
    - Discharge/charge:





- Specific energy density (100-265 Wh/kg)
- Prize: $0.4/Wh

Energy storage

- Comparison lead acid and Li ion batteries - Technical specifications

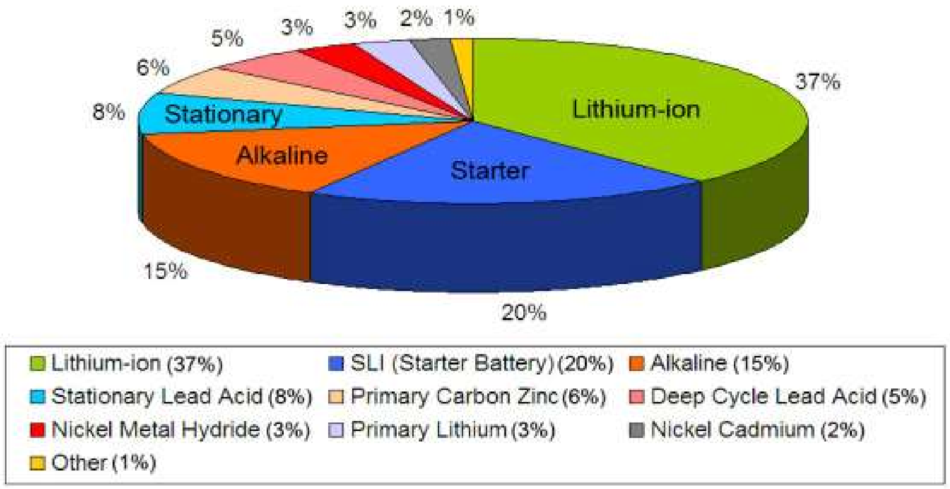
	Flooded lead acid	VRLA lead acid	Lithium-ion (LiNCM)
Energy Density (Wh/L)	80	100	250
Specific Energy (Wh/kg)	30	40	150
Regular Maintenance	Yes	No	No
Initial Cost ($/kWh)	65	120	600[1]
Cycle Life	1,200 @ 50%	1,000 @ 50% DoD	1,900 @ 80% DoD
Typical state of charge window	50%	50%	80%
Temperature sensitivity	Degrades significantly above 25°C	Degrades significantly above 25°C	Degrades significantly above 45°C
Efficiency	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 80% @4-hr rate 60% @1-hr rate	100% @20-hr rate 99% @4-hr rate 92% @1-hr rate
Voltage increments	2 V	2 V	3.7 V

http://www.batterypoweronline.com/main/wp-content/uploads/2012/07/Lead-acid-white-paper.pdf

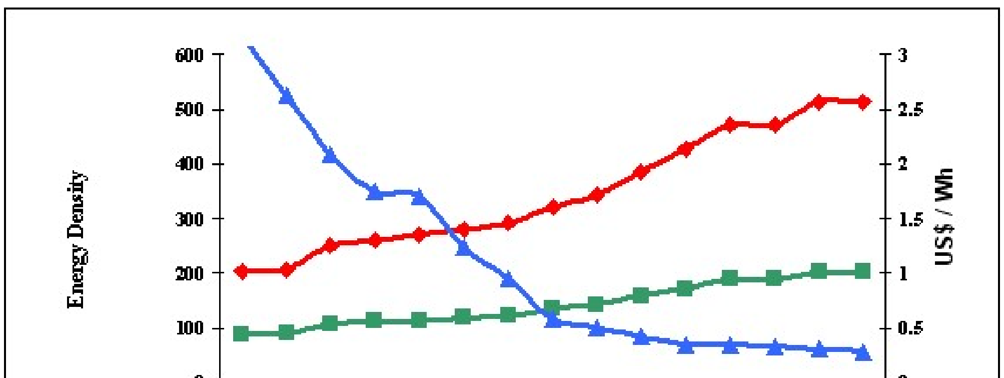
Energy storage

- Chemical energy storage:
  - Battery markets according to revenue:

Frost & Sullivan (2009)



  - Prices, e.g. Li-ion:



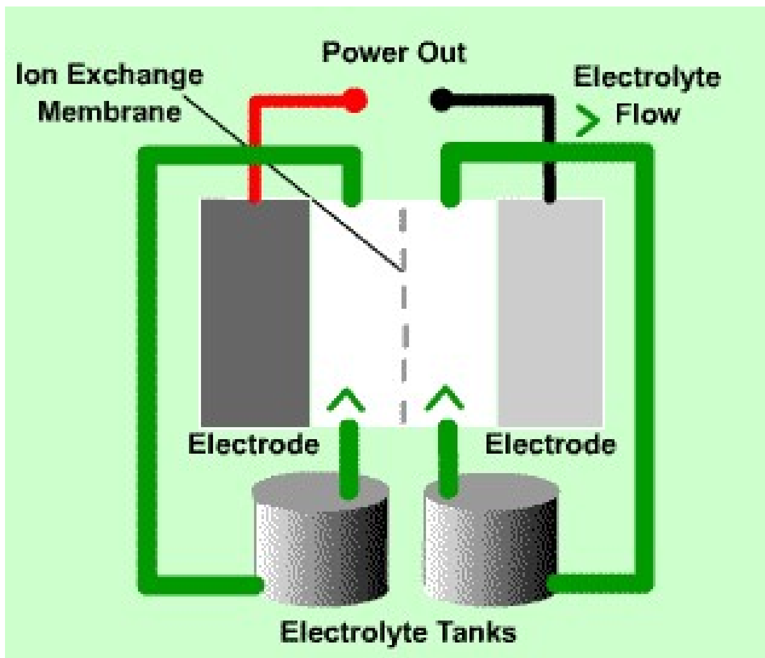
	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05
Wh/l	204	208	250	260	271	281	292	321	343	386	428	471	471	514	514
Wh/kg	88	90	108	113	114	119	123	135	143	159	172	189	189	202	202
US$/Wh	3.17	2.63	2.09	1.75	1.71	1.24	0.95	0.59	0.51	0.42	0.35	0.35	0.33	0.31	0.28

freedoniagroup.com

Energy storage

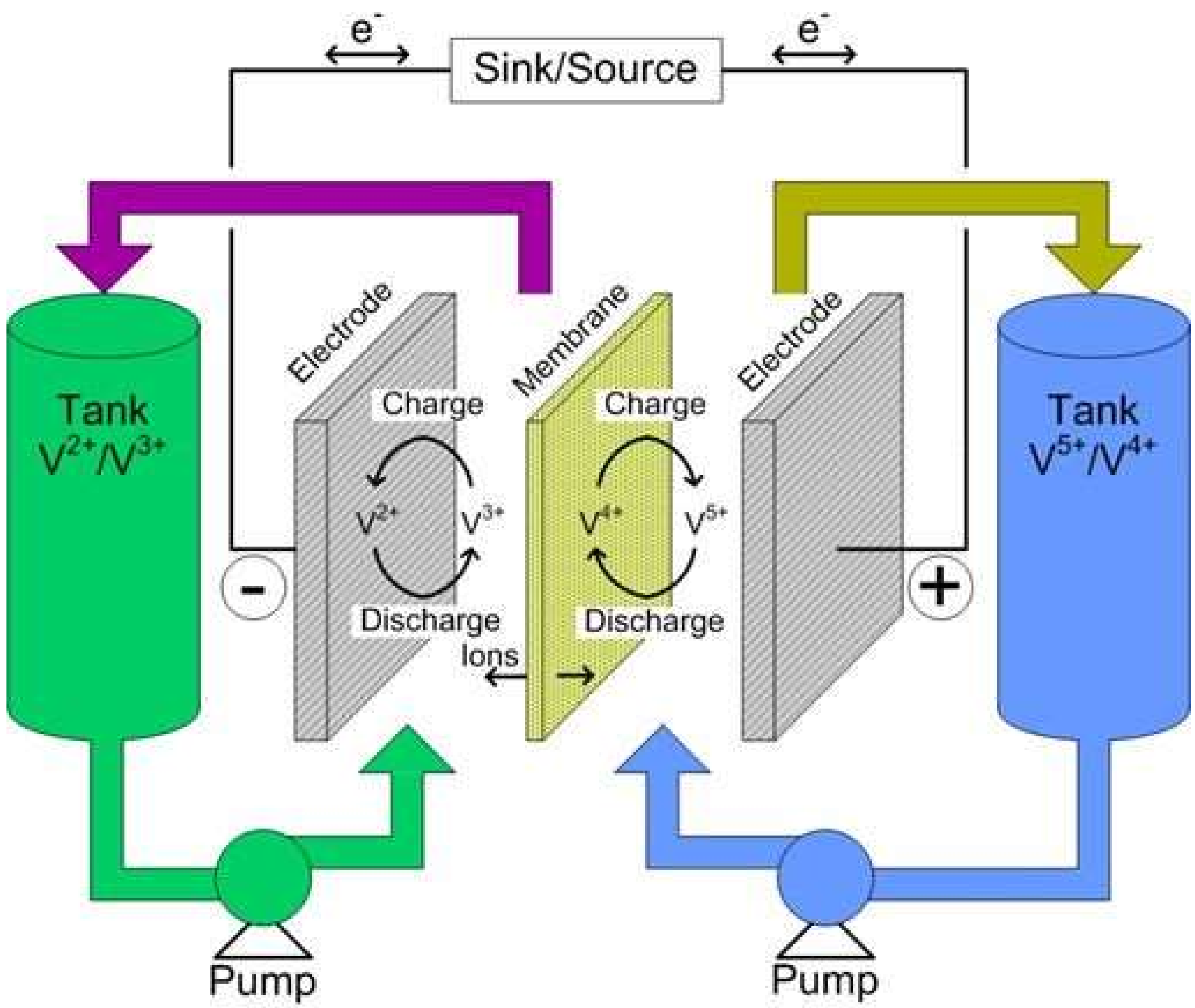
- Chemical energy storage:
  - Redox flow batteries:

Involve a gaseous or liquid fuel in one or both of the electrochemical half reactions. Flow battery technology utilizes an active element in a liquid electrolyte that is pumped through a membrane similar to a fuel cell to produce an electrical current. Pumping in one direction produces power from the battery, and reversing the flow with an external energy supply charges the system



Energy storage

- Chemical energy storage:
  - Flow batteries: e.g. Vanadium-based



Energy storage

- Vanadium flow battery system at EPFL: lepa.epfl.ch

Renewable Energy

- Outline:
  - Why energy storage
  - Overview over approaches
  - Energy storage:
    - Pumped hydro energy storage
    - Compressed air energy storage
    - Flywheels
    - Thermal energy storage
    - Chemical energy storage

Comparison

- Economics:

Table 17.3
Estimated Capital Costs for Representative Energy Storage Systems for Supplying Electric Power

System	Typical Size Range (MW_e)	$/kW$_e$	$/kW$_e$h
Pumped hydropower	100–1000	600–1000	10–15
Batteries:			
Lead-acid	0.5–100	100–200	150–300
Nickel–metal hydride	0.5–50	200–400	
Lithium ion	0.5–50	200–400	
Mechanical flywheels	1–10	200–500	100–800
Compressed-air energy storage (CAES)	50–1,000	500–1,000	10–15
Superconducting magnetic energy storage (SMES)	10–1,000	300–1,000	300–3,000
Supercapacitors	1–10	300	3,600

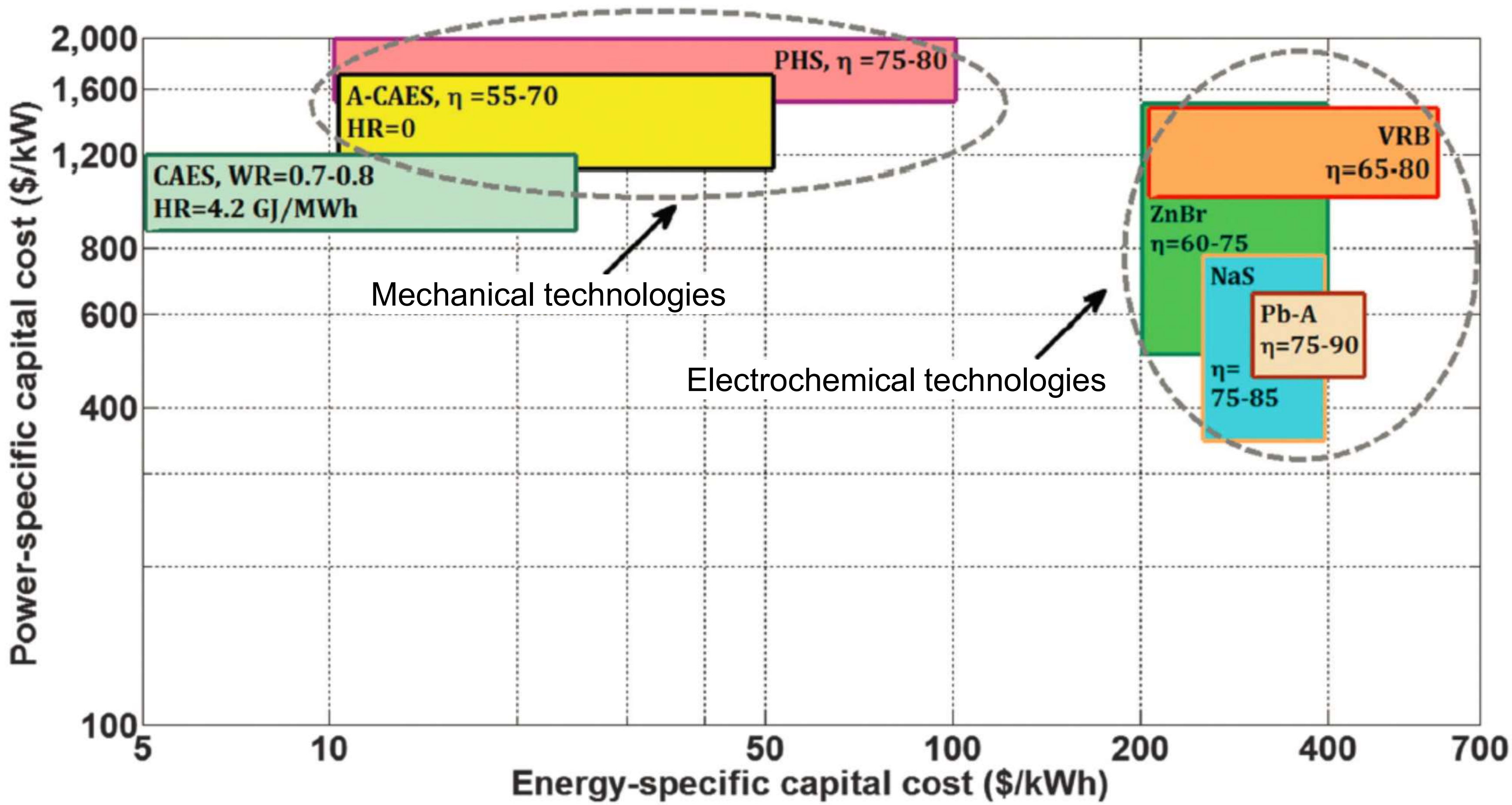
Sources: Turkenburg et al. (2000); Schoenung et al. (1996); Boes, Goldstein, and Nix (2000).

Figure 8: LCOE in the "breakthrough" scenario in 2013 and 2050

IEA, Technology roadmap, Energy storage, 2014.

Comparison

- Cost:

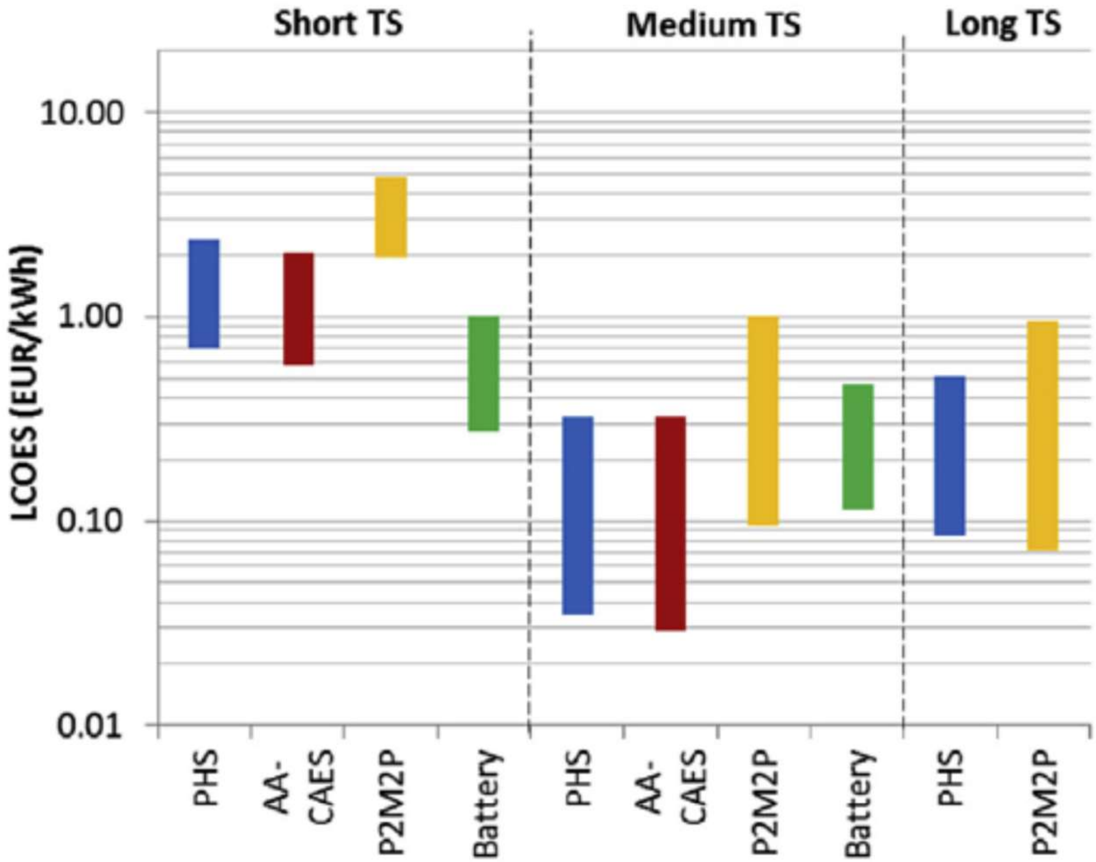


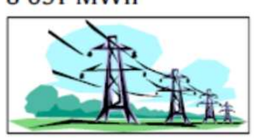
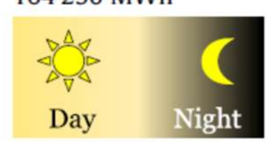
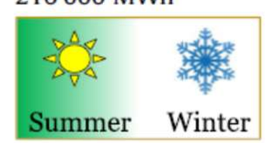
Safaei H. and Keith D.W., How much bulk energy storage is needed to decarbonise electricity?, *Energy Env. Sci.*, 8:3409-3417, 2015

Comparison

- Cost:

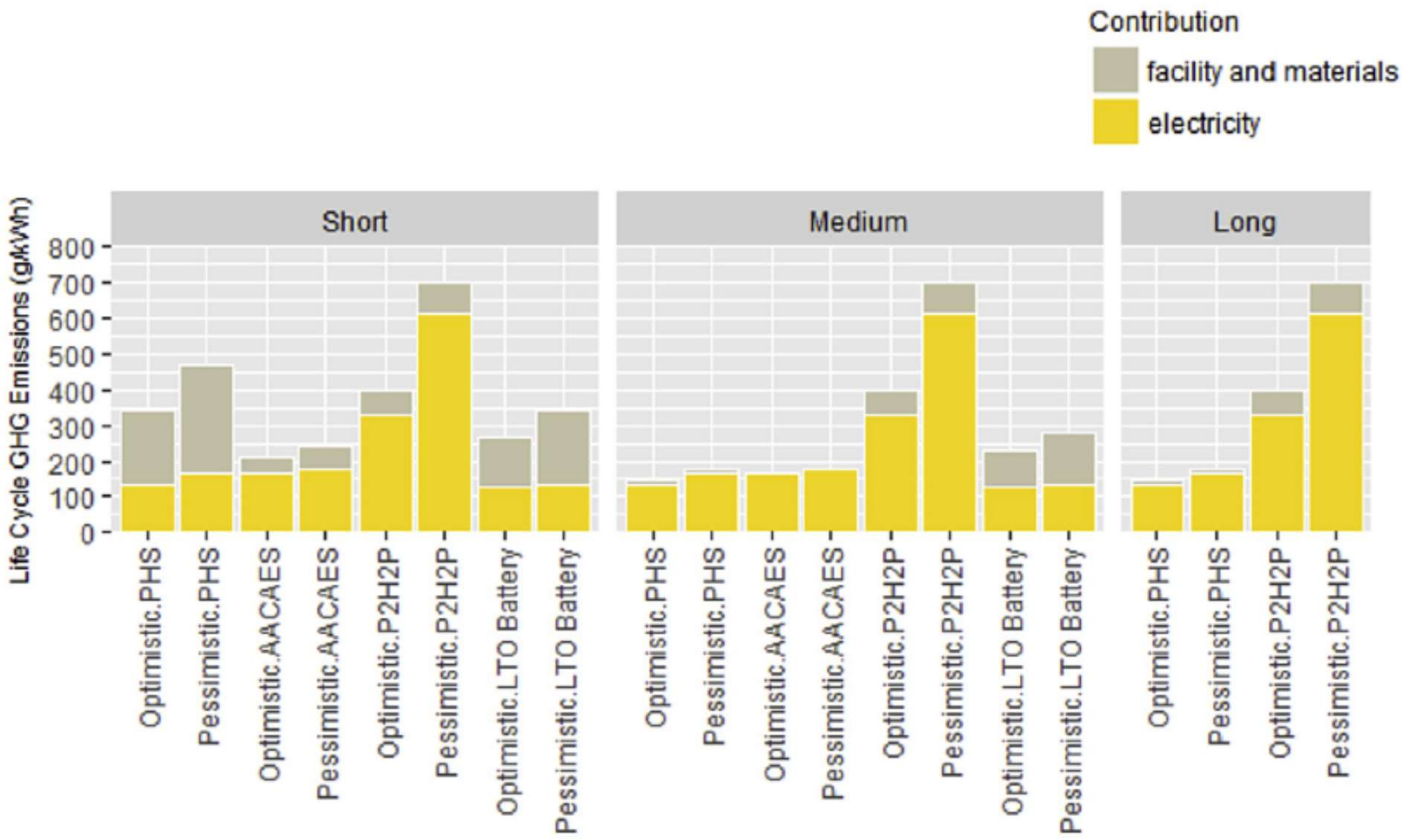
Abdon A. et al., Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales, *Energy*, 139:1173-1187, 2017



	Short TS 0.01 h	Medium TS 4.5 h	Long TS 2′160 h
100 MW Number of Cycles Annual Electricity Supply from Storage	20 per day 8′091 MWh	1 per day 164′250 MWh	1 per year 216′000 MWh
			

Comparison

- Environmental impact:

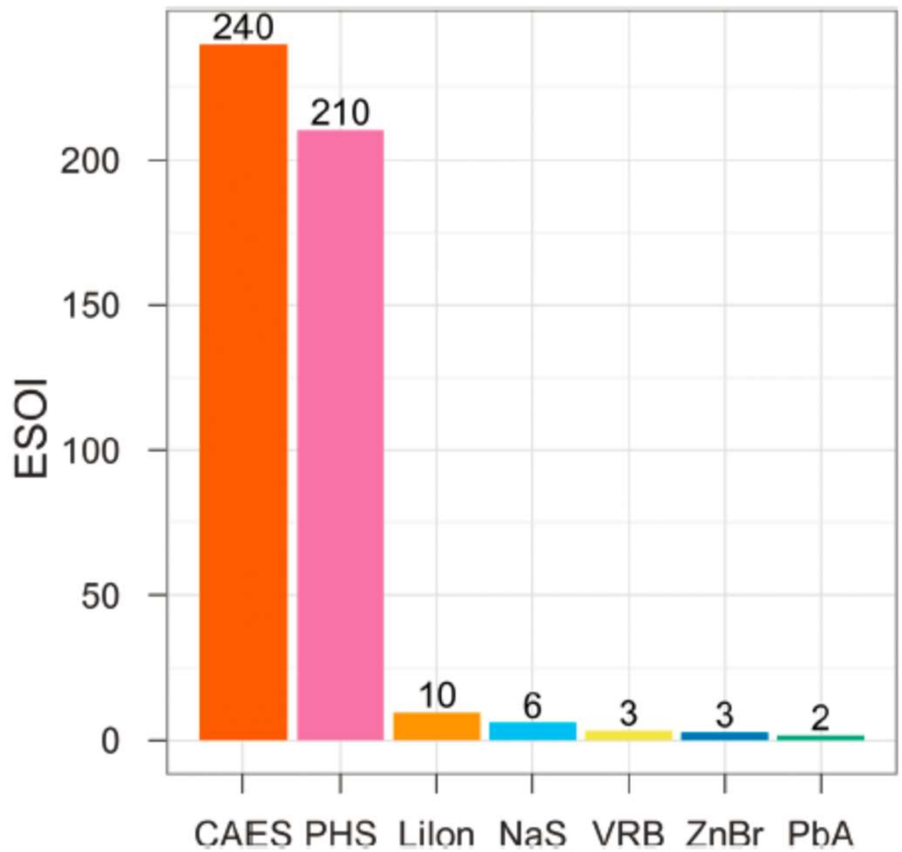


Abdon A. et al., Techno-economic and environmental assessment of stationary electricity storage technologies for different time scales, *Energy*, 139:1173-1187, 2017

Comparison

- Environmental impact:

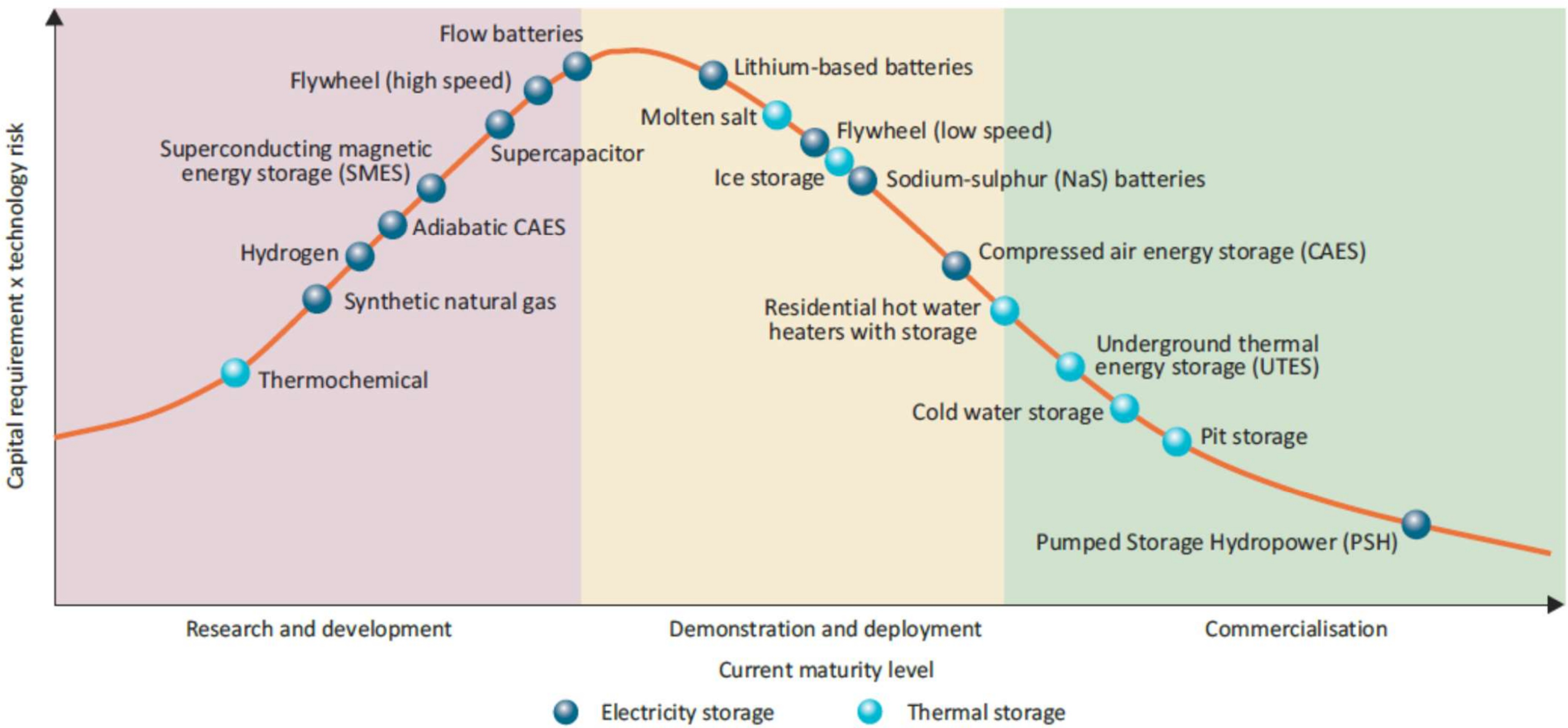
the ratio of the total electrical energy stored over the lifetime of a storage technology to its embodied primary energy



Barnart C.J. and Benson S.M., On the importance of reducing the energetic and material demands of electrical energy storage, *Energy Env. Sci.*, 6:1083-1092, 2013

Comparison

- Maturity:

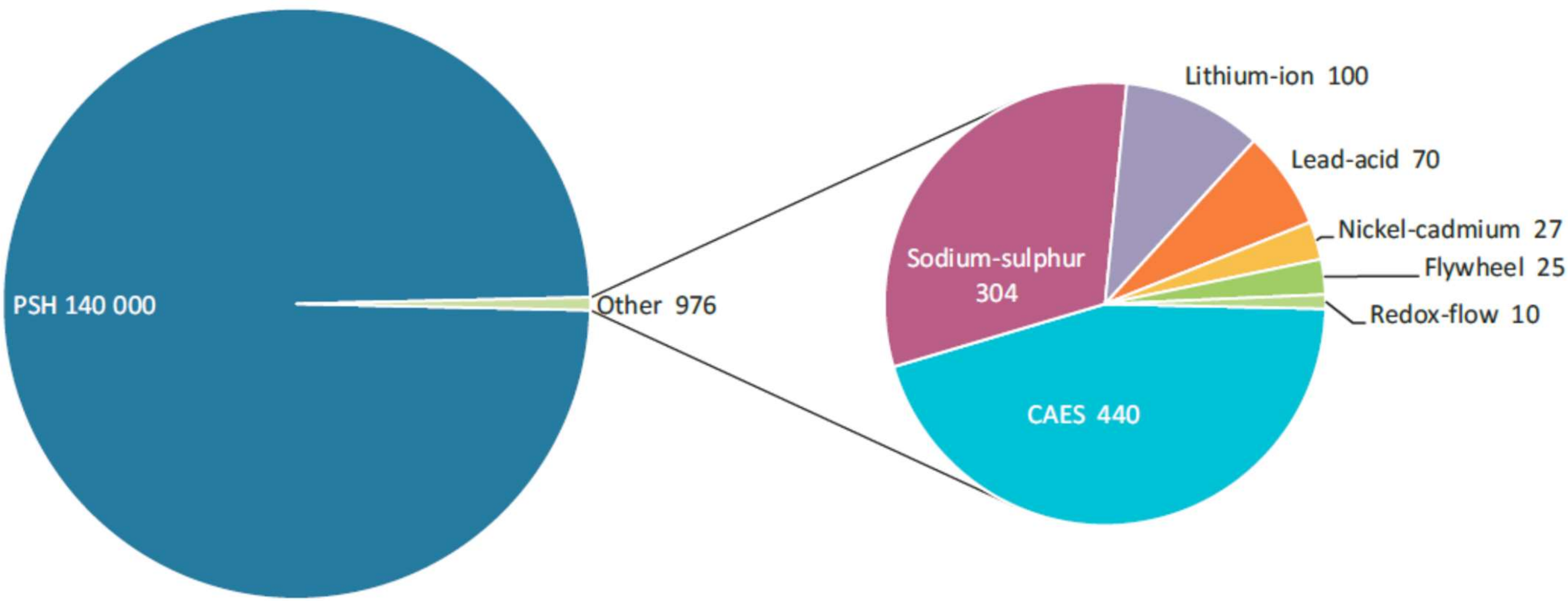


IEA, Technology roadmap, Energy storage, 2014.

Comparison

- Currently installed capacity:

Figure 4: Current global installed grid-connected electricity storage capacity (MW)

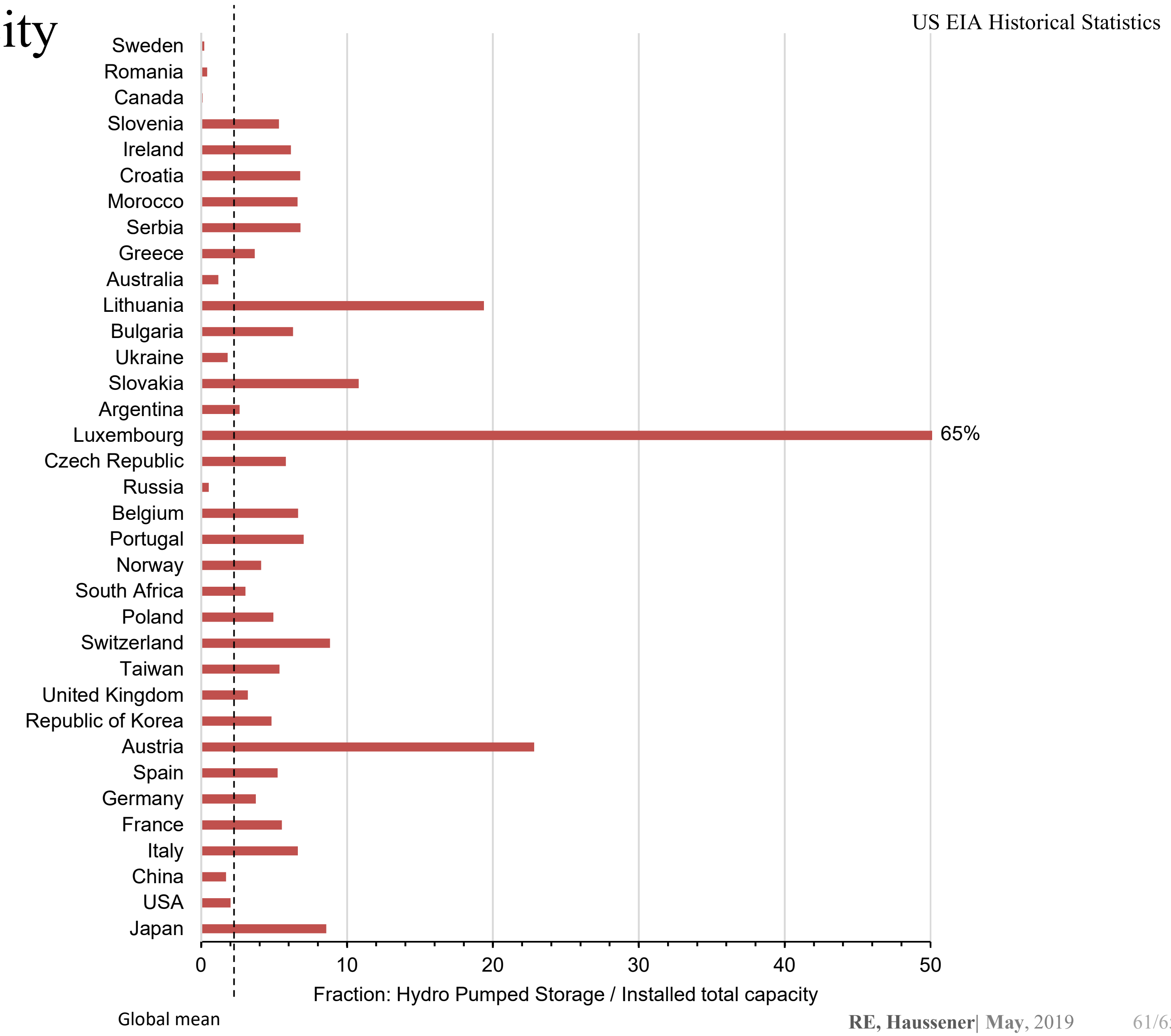


Source: IEA analysis and EPRI (Electric Power Research Institute) (2010), "Electrical Energy Storage Technology Options", Report, EPRI, Palo Alto, California.

IEA, Technology roadmap, Energy storage, 2014.

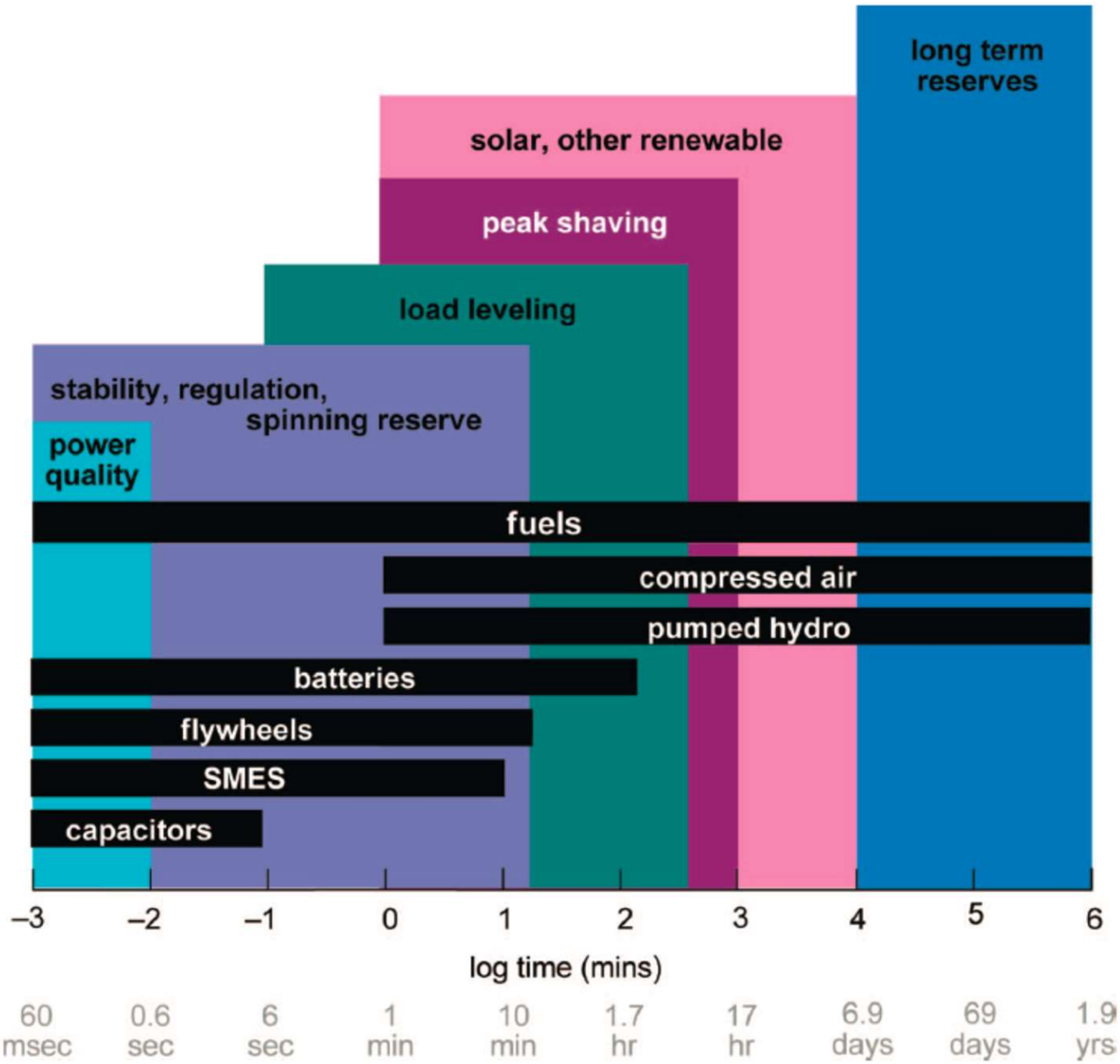
Pumped storage hydro

- Installed capacity



Comparison

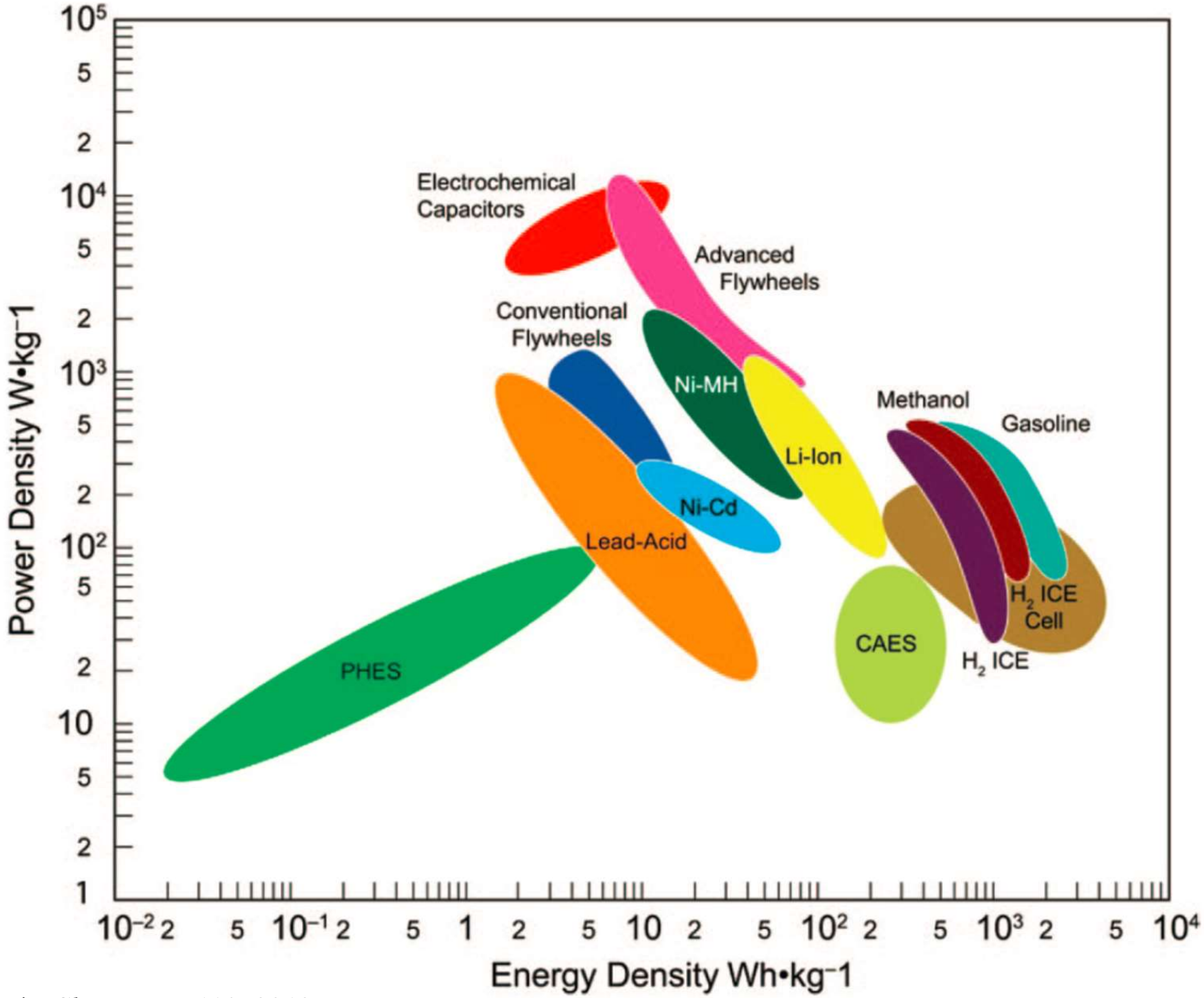
- Storage time:



Cook et al., *Chem. Rev.*, 110, **2010**.

Comparison

- Power and energy density:



Cook et al., *Chem. Rev.*, 110, **2010**.

Learning outcomes of todays lecture

- Energy storage:
  - Why is energy storage vital for a future energy economy
  - What storage options are useful for what energy and power densities and what time-scales?
  - General working principle of storage technologies:
    - Pumped hydro energy storage
    - Compressed air energy storage
    - Flywheels
    - Thermal energy storage (sensible, latent, thermochemical)
    - Chemical energy storage (fuels, batteries, flow batteries, capacitors)

Energy storage

- Literature
  - Books and review articles:
    - Tester et al., Sustainable energy: Choosing among options, MIT press, 2nd edition, 2012.
    - Rosen et al., Energy storage, Nova Publishers, 2012.
    - Cook et al., Solar Energy Supply and Storage for the Legacy and Nonlegacy Worlds, Chemical Reviews, vol. 110, pp. 6474–6502, 2010.