Lecture 17 – Energy Storage

Dr. Yu Zhang

ECE, UCSC

ECE180J

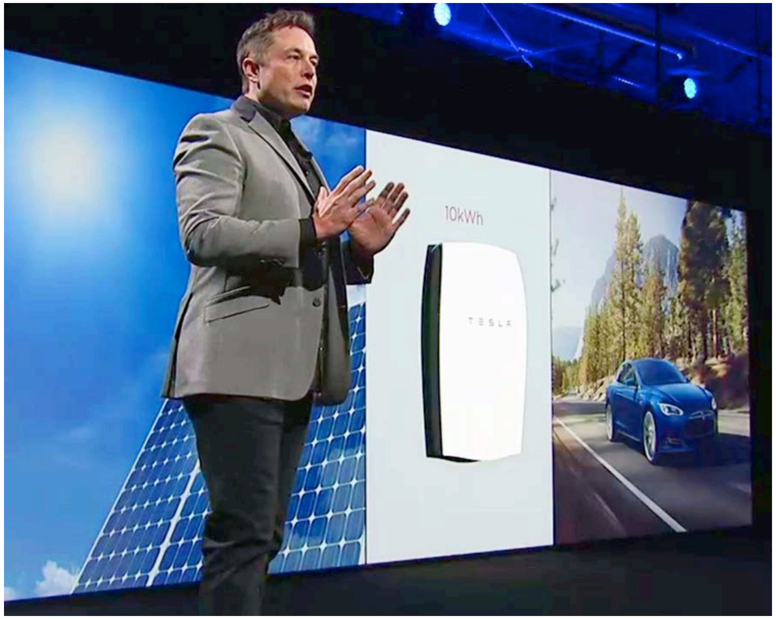
Outline

- Energy Storage Overview
- Energy Storage Functionality
- Energy Storage Technologies
- Energy Storage Comparison

1. B2
2. Dave Mooney, NREL: *GCEP Tutorial*

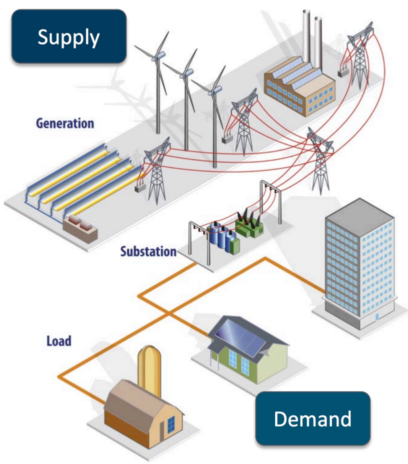
Energy Storage

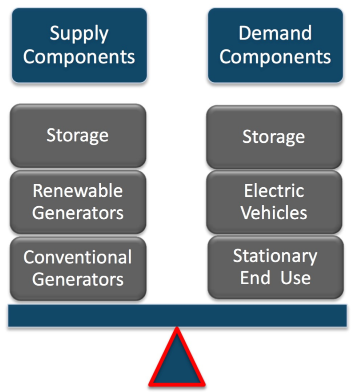
- Energy storage (accumulator/battery): capture of energy produced at one time for use at a later time.
- Energy storage involves converting energy from forms that are difficult to store to more conveniently/economically storable forms.



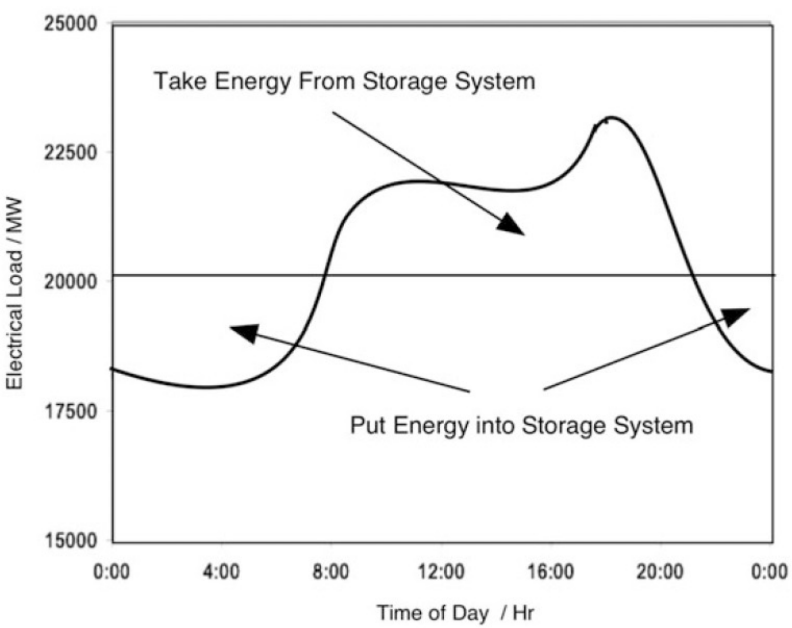
Why is everyone talking about storage?

Supply-Demand Balance





- System operators balance the supply and demand at all times.
- Storage can play a role on both sides and be operated at different timescales.



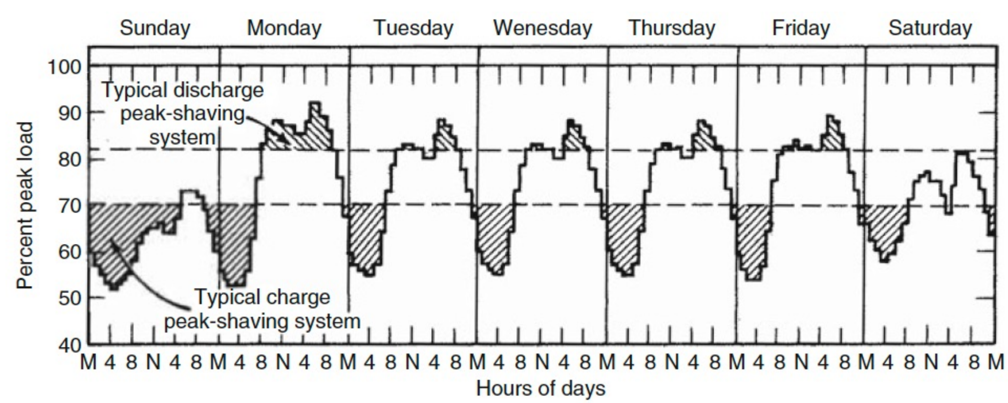


Fig. Hourly data on electric load show possible use of a storage system.

Grid Flexibility

Some energy sources do not provide energy at a constant rate, but instead, are intermittent.

- Biofuels, such as switch grass, sugar cane, corn, and oilseeds are only available during part of the year.
- Solar, wind, and ocean motion energy sources have roughly daily cycles.

The time dependence of the uses of energy often does not correspond to the time variance of such sources.
If these were to match perfectly, there would be no need for a storage mechanism.

Solar and wind add **variability** and **uncertainty** to the generation supply, increasing the need for grid **flexibility.**

Renewables Now and Ahead…

➢ 2009 US Recovery Act

- $40 billion: energy efficiency & renewables programs
- $13 billion: tax credits for renewables production

➢ Goals

- USA (EU) : wind energy → 20% of the nation's demand by 2030 (2020)
- D

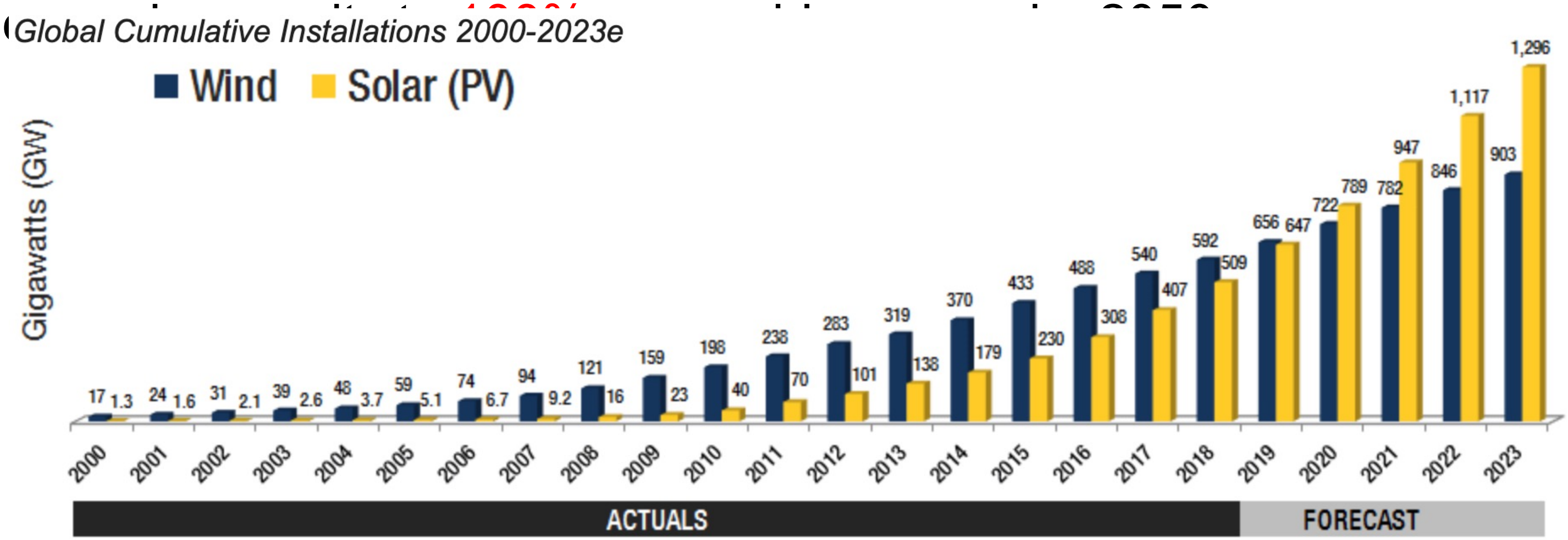
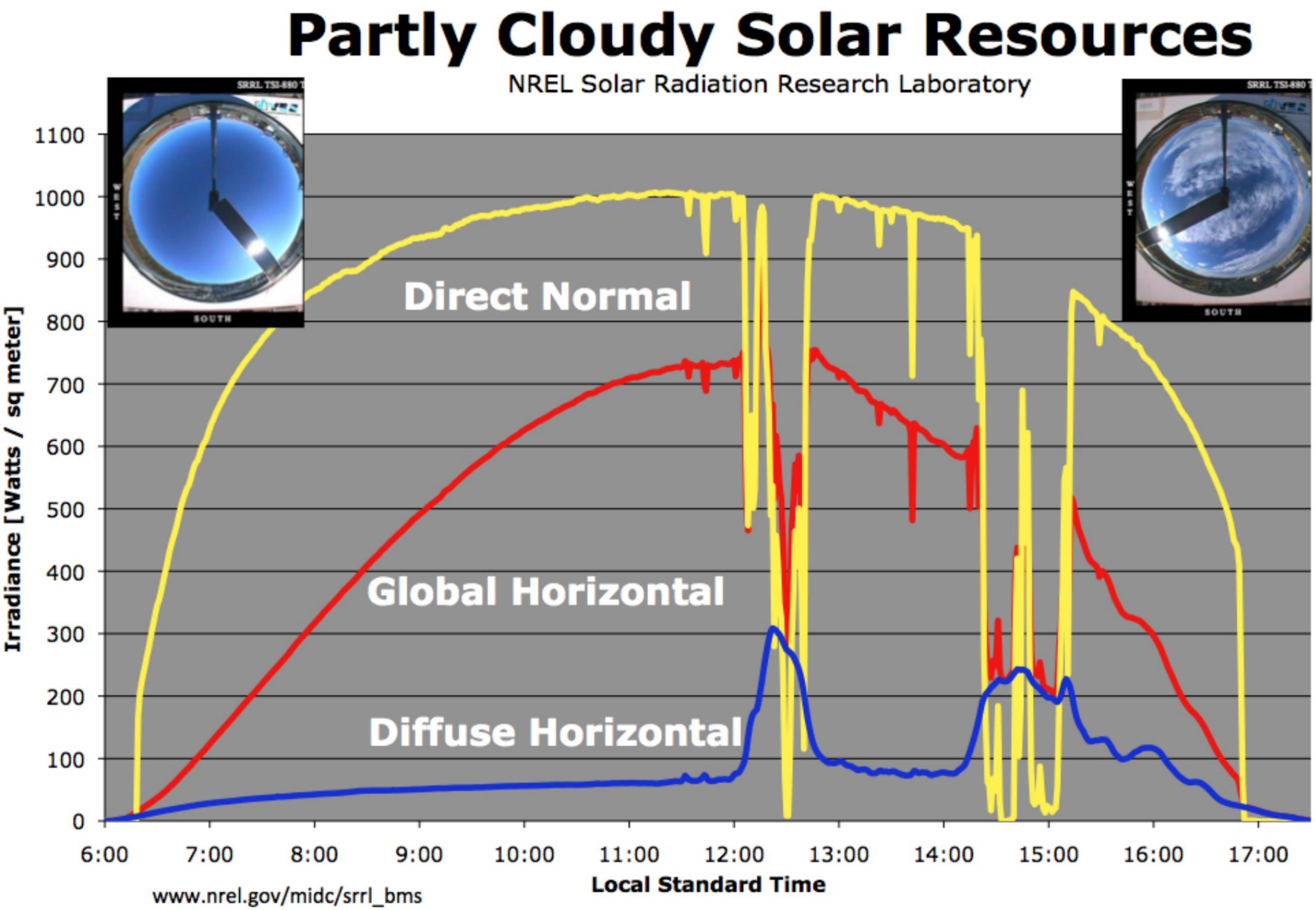
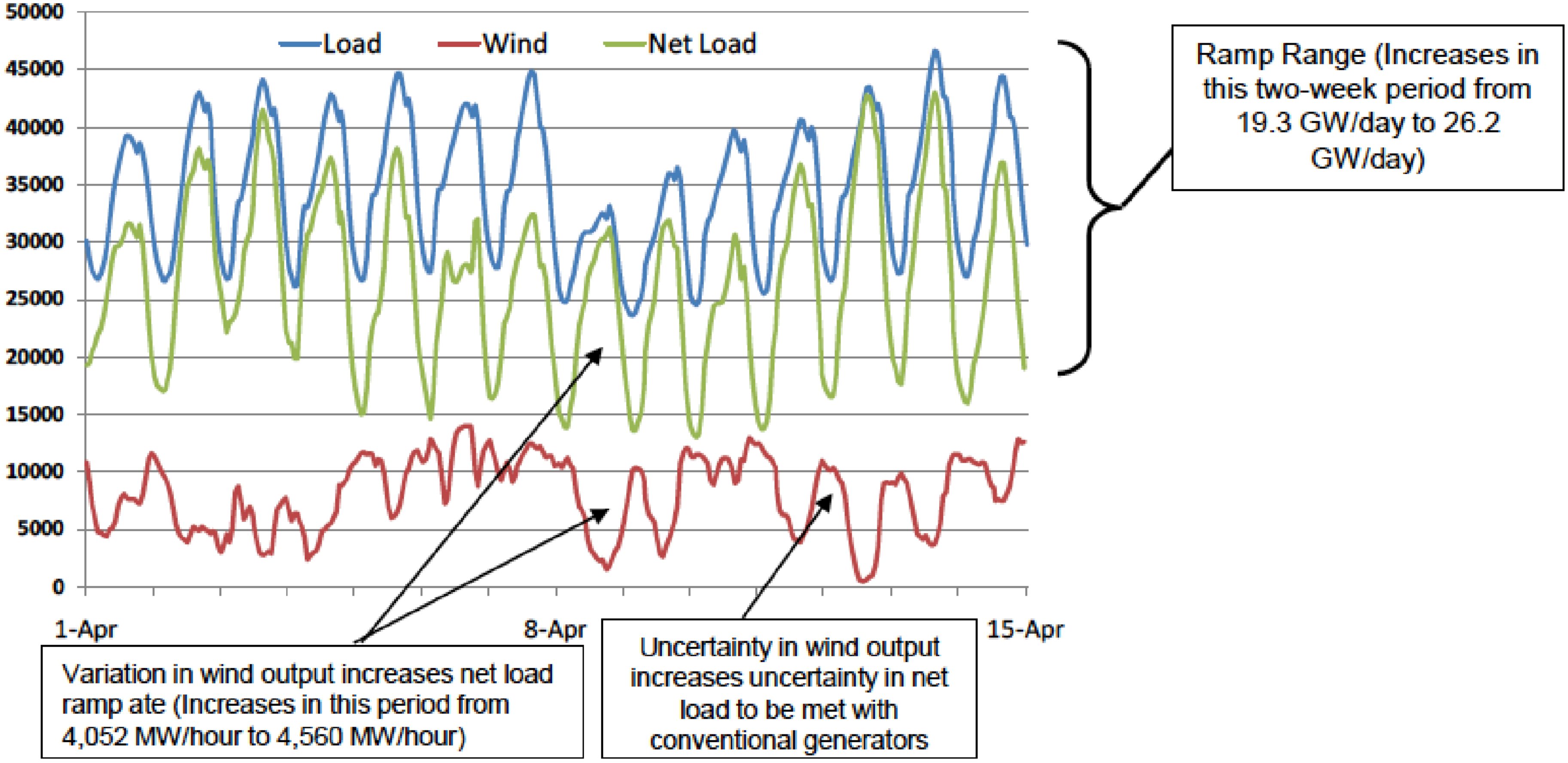


Fig source: http://www.fi-powerweb.com/Renewable-Energy.html

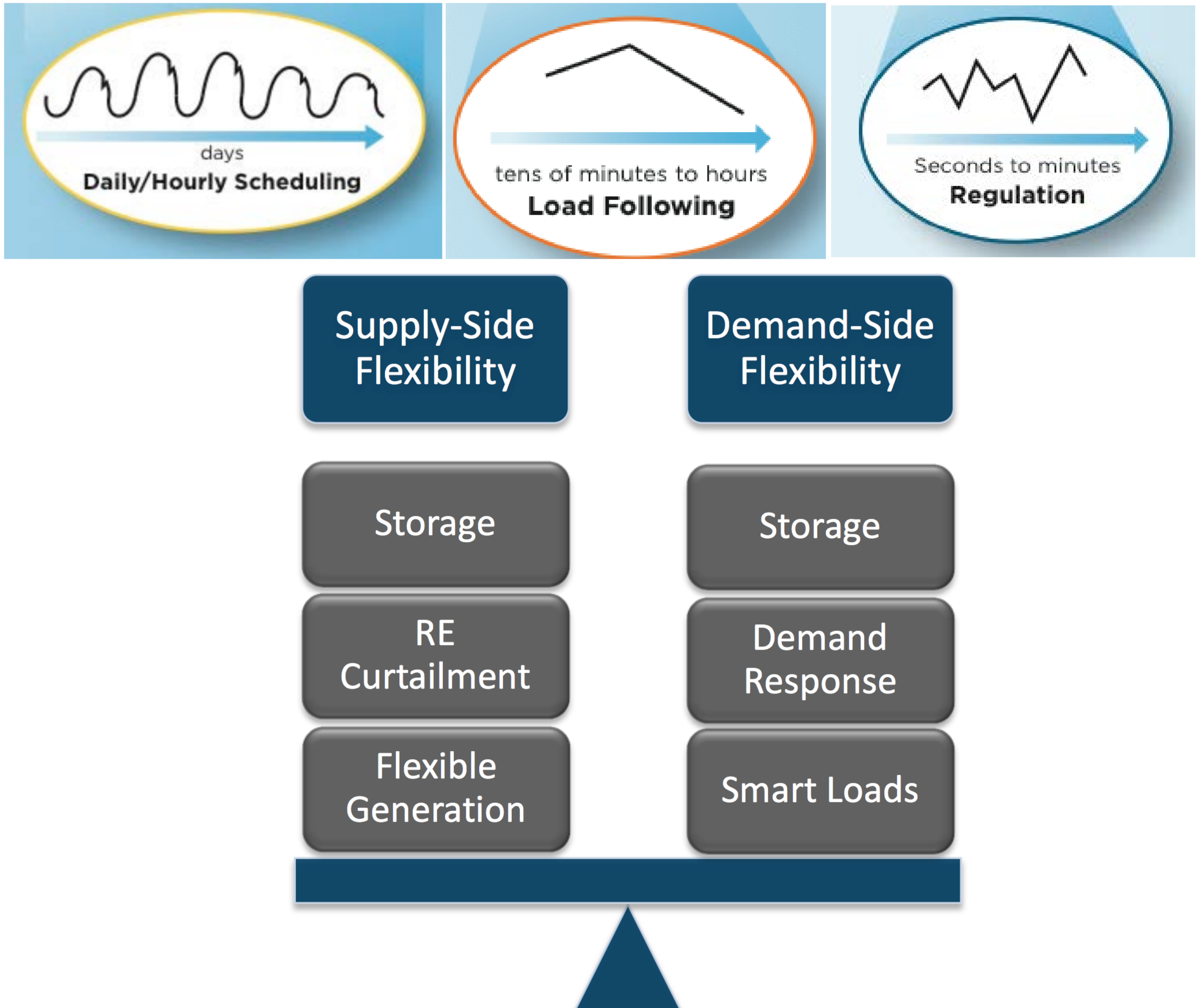
Uncertainty from Solar



Uncertainty from Wind

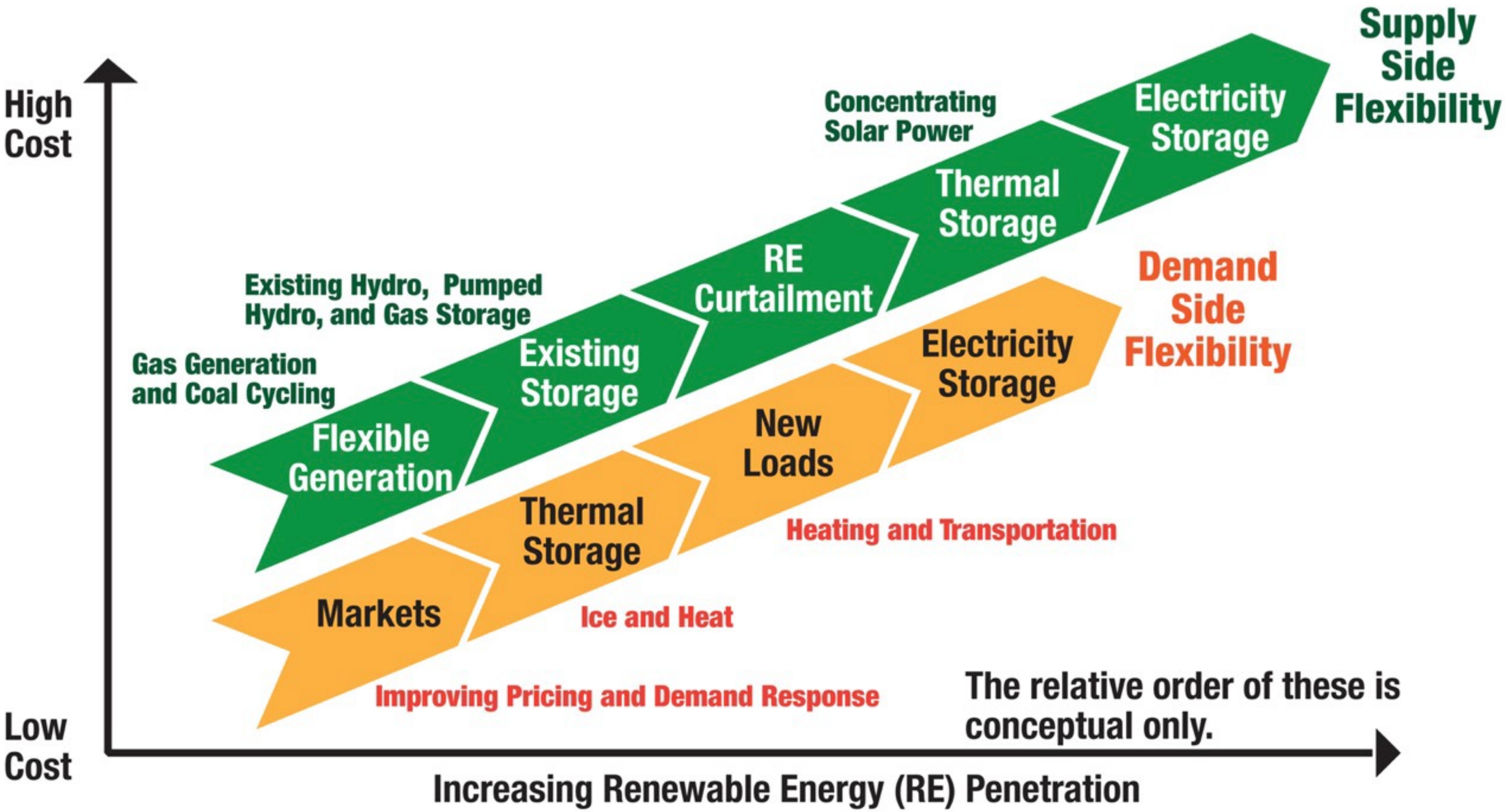


Flexibility to Maintain Balance

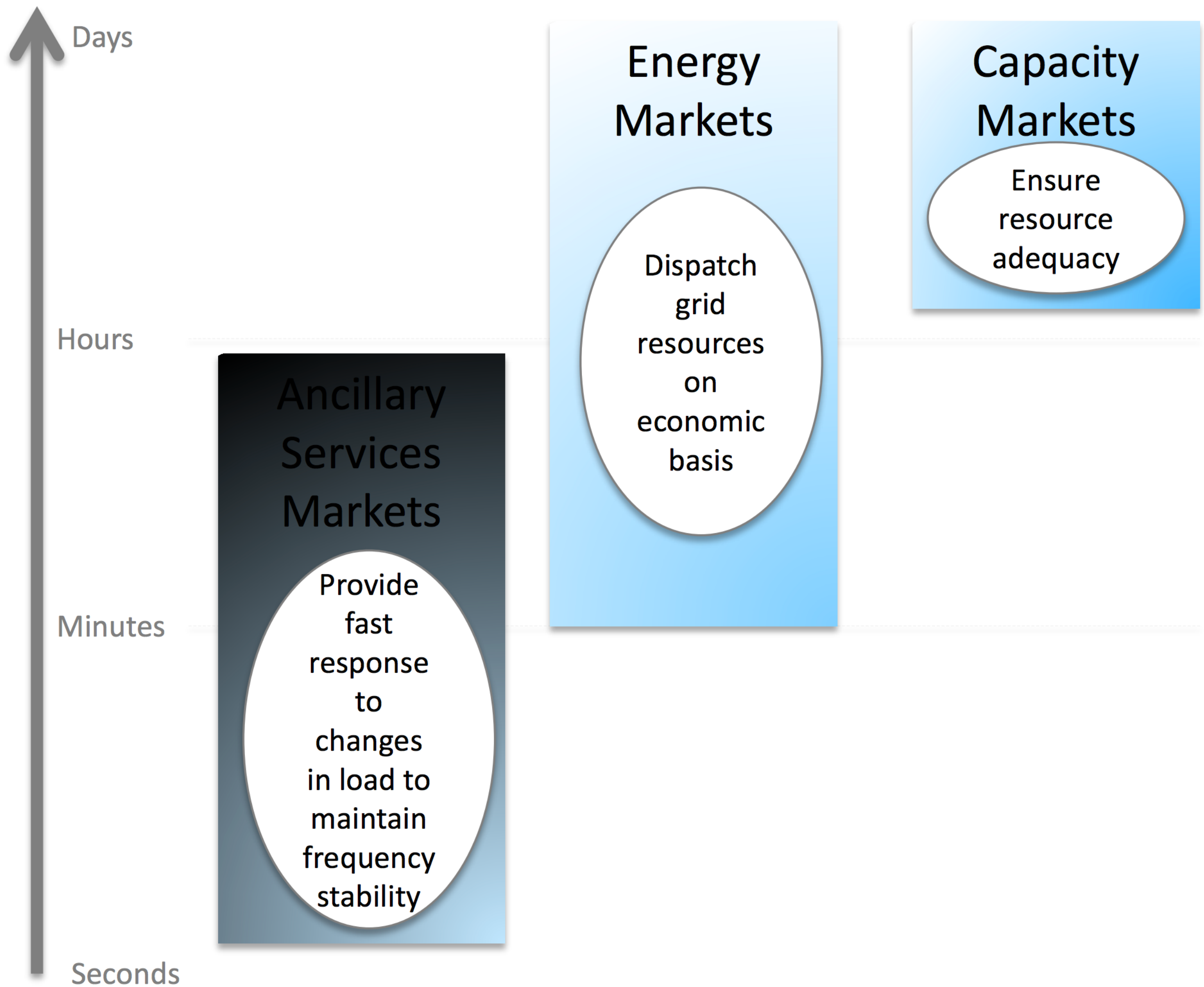


Storage is one of many *options for providing more flexible supply and demand at multiple timescales.*

Flexibility Supply Curve



Market Design for Grid Flexibility

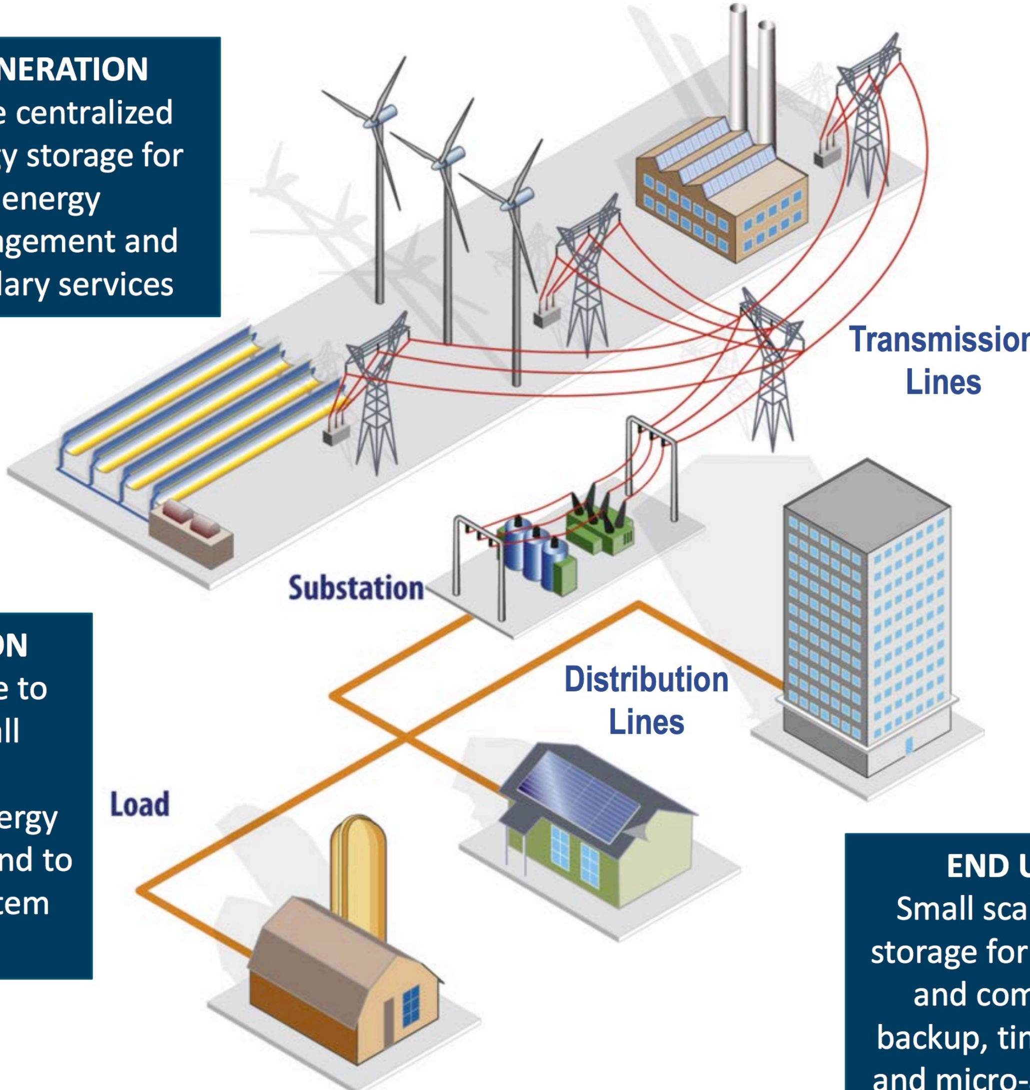


Market design can impact operational mechanisms to support power system flexibility and reliability

Energy Storage Applications

GENERATION
Large centralized energy storage for energy management and ancillary services

TRANSMISSION
Centralized or distributed energy storage for time-shifting renewable generation, congestion management, and upgrade deferments

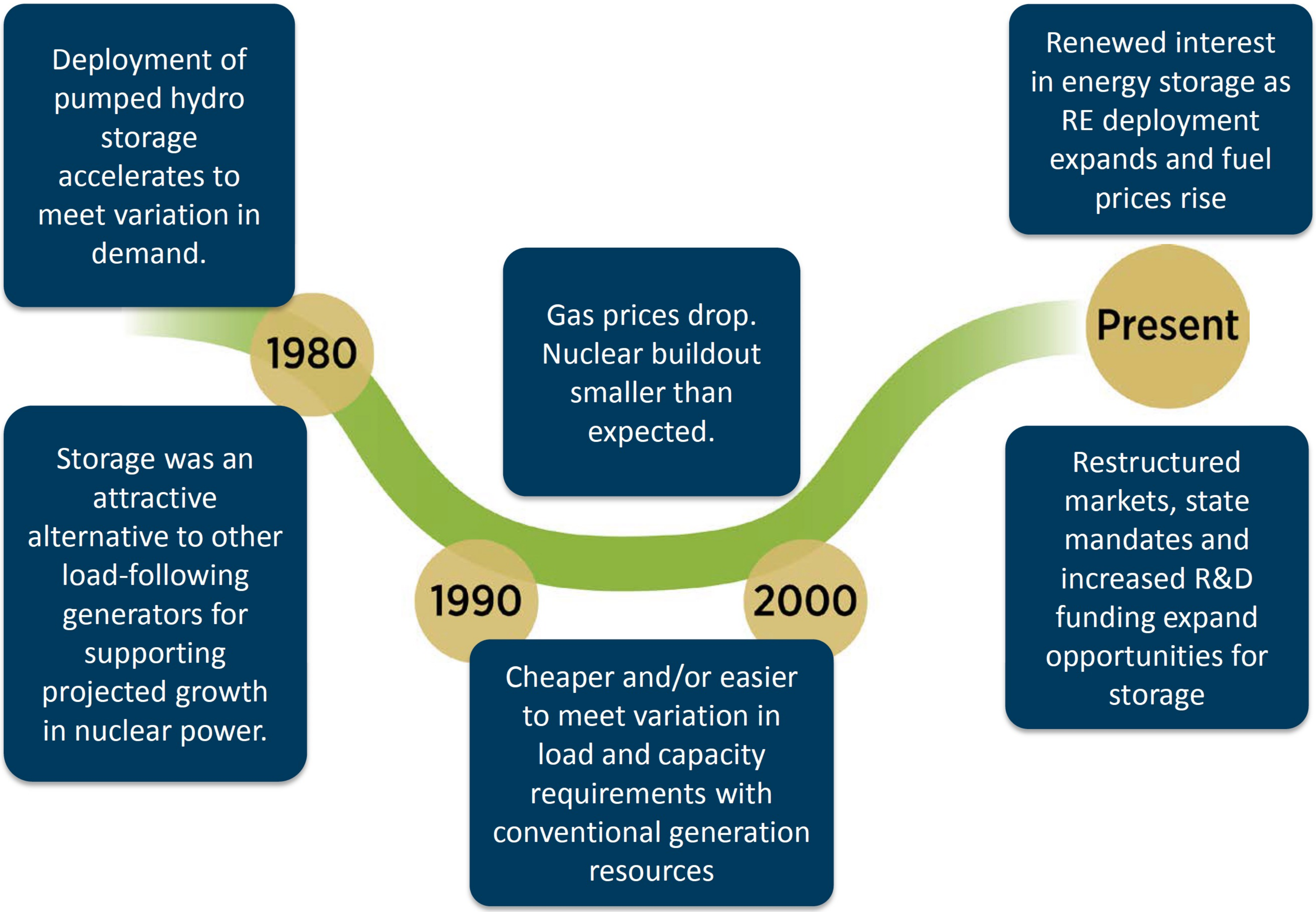


END USERS
Energy storage for backup or high-quality power for commercial and industrial users

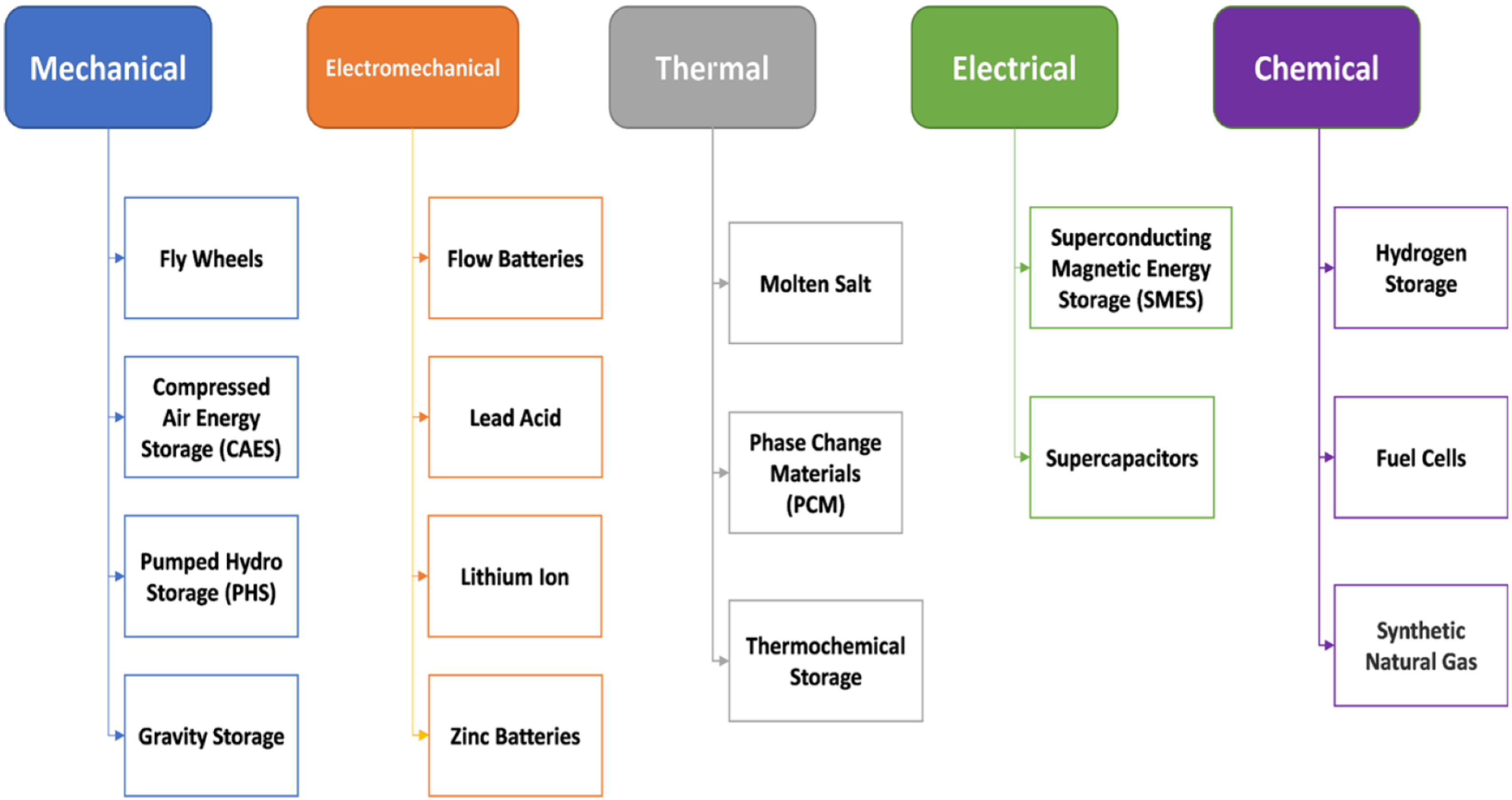
DISTRIBUTION
Energy storage to support small distributed generation, energy management, and to help defer system upgrades

END USERS
Small scale energy storage for residential and commercial backup, time-shifting and micro-generation

Interest in Energy Storage



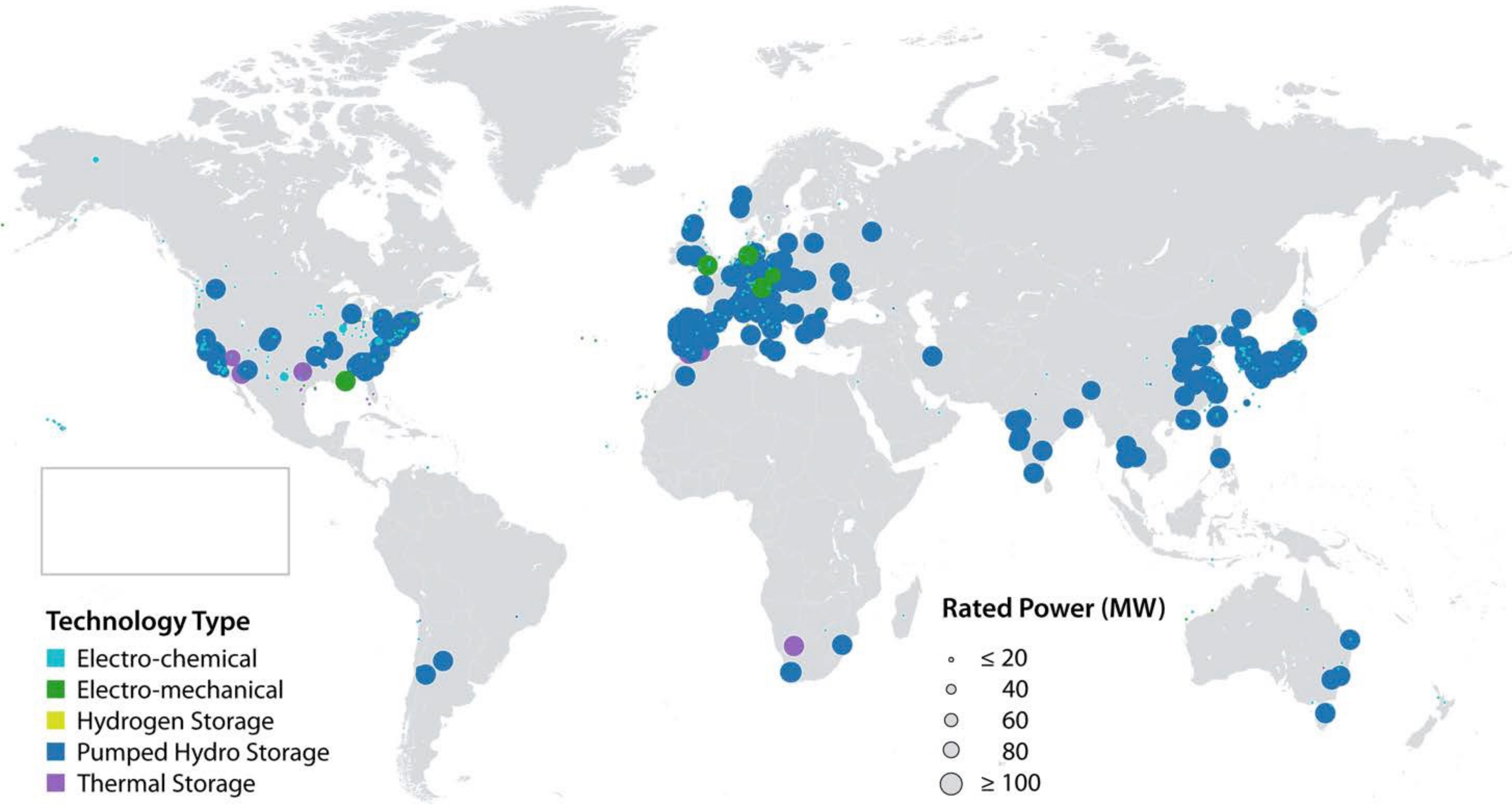
Classification of Energy Storage Systems



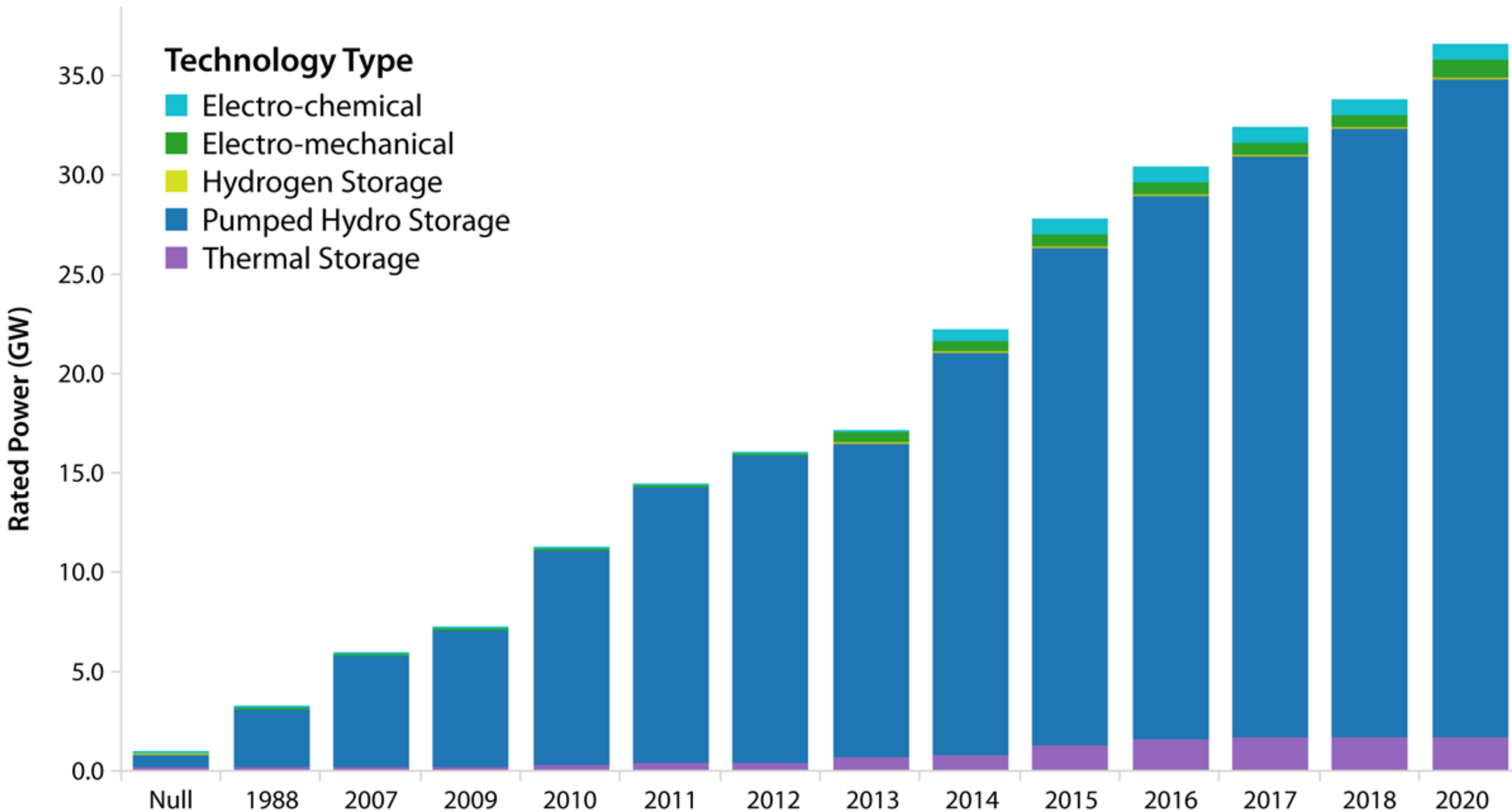
Technology Maturity

Type	Laboratory / Research	Pilot / Development	Demonstration	Commercial / Deployment	Mature
Mechanical					Pumped Storage Hydro
Electro-mechanical	Adiabatic Compressed Air Energy Storage		Compressed Air Energy Storage (2nd gen)	Compressed Air Energy Storage (1st gen), Flywheel Energy Storage	
Thermal				Molten Salt Energy Storage	
Electrical	Nano-Supercapacitor		Supercapacitor, Superconducting Magnetic Energy Storage		
Electro-chemical	Zn/air, Zn-Cl, Advanced Li-ion, Novel Battery Chemistries	Li-ion, Fe/Cr, $NaNiCl_2$	ZnBr, NiMH, Advanced Lead-Acid, Li-ion Batteries	Lead-Acid, NiCd, Sodium-Sulfur Batteries, Li-ion	Lead-Acid Batteries
Chemical		Hydrogen Storage, Synthetic Natural Gas Storage	Hydrogen storage		

Global Energy Storage Operational Capacity



Energy Storage Projects in the Pipeline



Important Terms

- **Capacity**
  - capacity of a power plant means the amount of power it can generate.
  - capacity of a storage system means the volume of energy it can store.

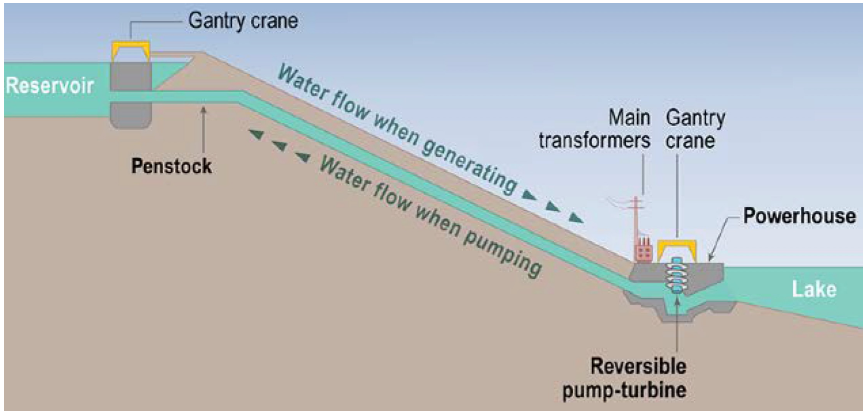
- **Response time:** the time it takes for a system to provide energy at its full rated power.
- **Discharge time:** the amount of time a storage technology can maintain its output; e.g., 1 MW battery that has a discharge time of 5 hours can provide 5 MWh of energy.

- **Depth of Discharge (DoD):** the percentage of capacity discharged. Deep discharges (>50% DoD) shorten the lives of some batteries, while others operate best this way.

Mechanical Storage

Pumped-Storage Hydropower (PSH)

- Water runs through turbines from the upper reservoir to the lower one, producing electricity.
- Water can be pumped back up to the storage area at the higher elevation (recharging the system).
- In some cases this involves the use of two-way turbines. This can make sense if the price of electricity varies significantly at different times of the day/week.



Technology characteristics

- Power capacity: 100 – 1,000 MW
- Discharge time: 4 – 12 hours
- Response time: seconds to minutes
- Efficiency: 70-85%
- Lifetime: >30 years
- Losses: water evaporation, leakage around the turbine, friction of the moving water.

Primary application: energy mgmt, load balancing

PSH Status

Global operational capacity: ~142 GW
U.S. operational capacity: ~20 GW

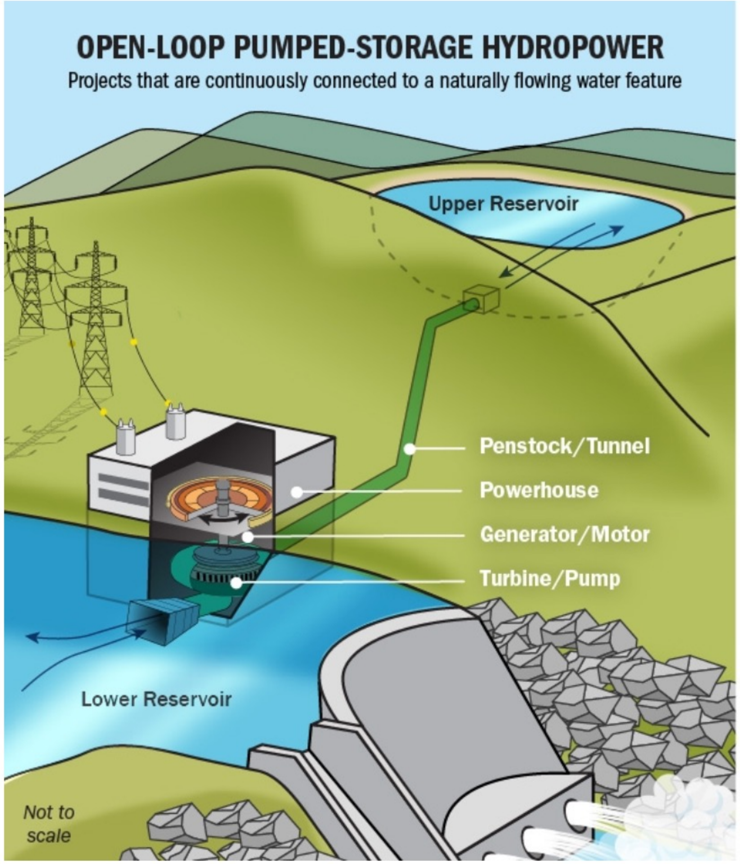
Pumped-storage currently accounts for 95% of all utility-scale energy storage in the US!

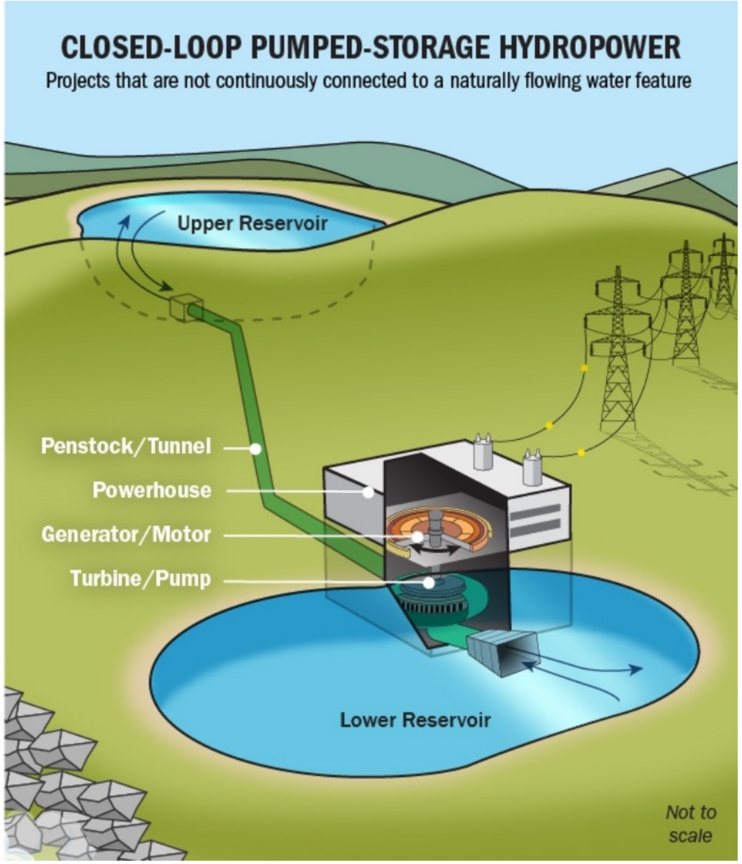
Examples of large pumped hydro systems

Country	Name	Capacity (MW)
Argentina	Rio Grande-Cerro Pelado	750
Australia	Tumut Three	1500
Austria	Malta-Haupstufe	730
Bulgaria	PAVEC Chaira	864
China	Guangzhou	2400
France	Montezic	920
Germany	Goldisthal	1060
	Markersbach	1050
India	Purulia	900
Iran	Siah Bisheh	1140
Italy	Chiotas	1184
Japan	Kannagawa	2700
Russia	Zagorsk	1320
Switzerland	Lac des Dix	2099
Taiwan	Mingtan	1620
United Kingdom	Dinorwig, Wales	1728
United States	Castaic Dam	1566
	Pyramid Lake	1495
	Mount Elbert	1212
	Northfield Mountain	1080
	Ludington	1872
	Mt. Hope	2000
	Blenheim-Gilboa	1200
	Raccoon Mountain	1530
	Bath County	2710

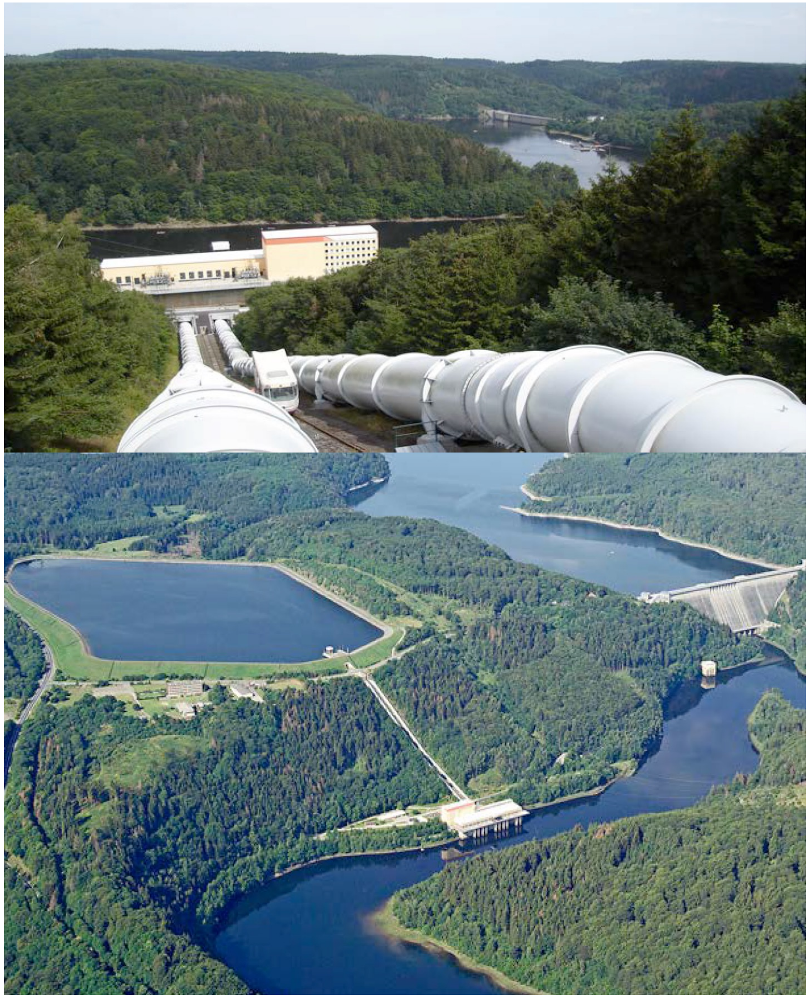
Open-loop vs Closed-loop

- Open loop: there is an ongoing hydrologic connection to a natural body of water.
- Closed loop: the reservoirs are not connected to an outside body of water.





Pros and Cons of PSH



Pros

- Cheapest way to store large quantities of energy with high efficiency over a long time
- Mature technology

Cons

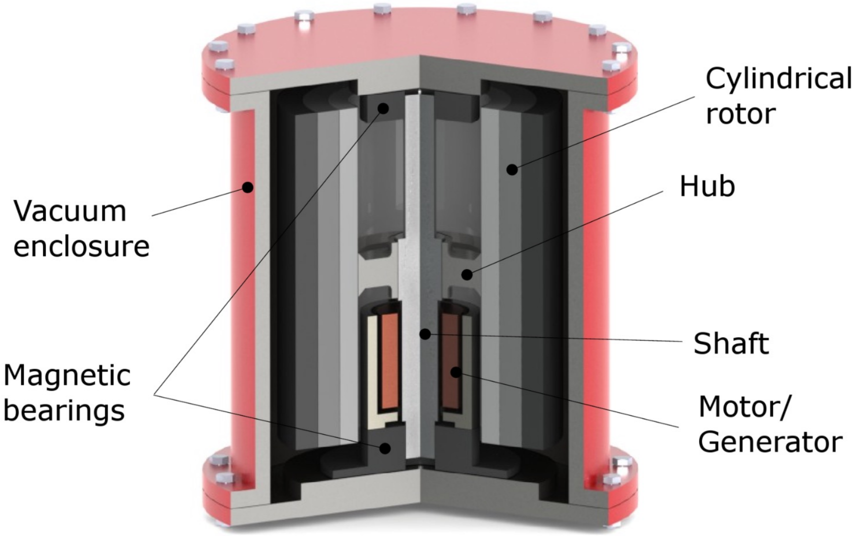
- Lack of suitable sites
- Not fitted for distributed generation
- Relatively low energy density has indirect environmental impact

Electro-Mechanical Storage

Flywheel Energy Storage (FES)

FES works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy.

Rotors made of high strength carbon-fiber composites, suspended by magnetic bearings, and spinning at speeds from 20,000 – 50,000 rpm in a vacuum enclosure.

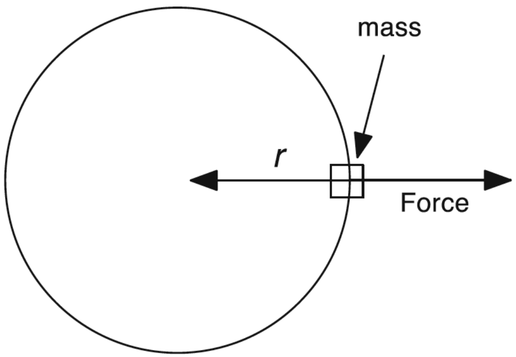


Linear vs Rotational Kinetic Energy

$$E_{\text{lin}} = \frac{1}{2} m v^2$$

$$E_{\text{rota}} = \frac{1}{2} I \omega^2 = \frac{1}{2} \omega^2 \int \rho(x) r^2 dx$$

where I is the moment of inertia
ω is the angular velocity
$\rho(x)$ is the mass distribution
r is the distance from the center of rotation.



The centrifugal force is given by

$$\text{Force} = (\text{mass})(\text{acceleration}) = m r \omega^2$$

- Strength of the material for flywheel must be able to withstand the centrifugal force!
- High cycle fatigue is a type of fatigue caused by small elastic strains under a high number of load cycles before failure occurs.

Specific Energy

The kinetic energy per unit mass:

$$\boxed{\frac{E_{\text{kin}}}{\text{mass}} = \frac{\sigma_{\max}}{\rho} K_{\text{m}}}$$

where $\sigma_{\max}$ is the maximum allowable stress, ρ is the material density, and K_{m} the shape factor. Note that the ratio $\sigma_{\max}/\rho$ leads to a strength-to-weight ratio, not just the material's strength.

Shape	K_{m}
Brush shape	0.33
Flat disk	0.6
Constant-stress disc	1.0
Thin rim only	0.5
Thin rim on constant-stress disk	0.6–1.0

Object	K, shape factor	Mass (kg)	Diameter (m)	Angular velocity (rpm)	Energy stored	Energy stored (kWh)
Bicycle wheel	1	1	0.7	150	15 J	4×10^{-7}
Flintstone's stone wheel	0.5	245	0.5	200	1680 J	4.7×10^{-4}
Train wheel, 60 km/h	0.5	942	1	318	65,000 J	1.8×10^{-2}
Large truck wheel, 18 mph	0.5	1000	2	79	17,000 J	4.8×10^{-3}
Train braking flywheel	0.5	3000	0.5	8000	33 MJ	9.1
Electrical power backup flywheel	0.5	600	0.5	30,000	92 MJ	26

Maximum Power and Rotational Velocity

The maximum torque that can be withstood: $\tau_{\max} = {}^{2}\!/_{3}\pi\sigma_s R_0^3$

where R_0 is the shaft radius and σ_s is the maximum shear strength of the shaft material.

The torque involved in a change in the rotational velocity:

$$\tau = I\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{\pi}{2}\rho T R^4 \frac{\mathrm{d}\omega}{\mathrm{d}t}$$

for a disk of radius R and thickness T.

$$\boxed{\begin{aligned} P_{\max} &= \frac{\pi}{2}\rho\omega T R^4 \frac{\mathrm{d}\omega_{\max}}{\mathrm{d}t} = 2\,\frac{\pi}{3} R_0^3\,\sigma_{\max} \\ \omega_{\max} &= \frac{1}{R}\left(\frac{2\sigma_{\max}}{\rho}\right)^{1/2} \end{aligned}}$$

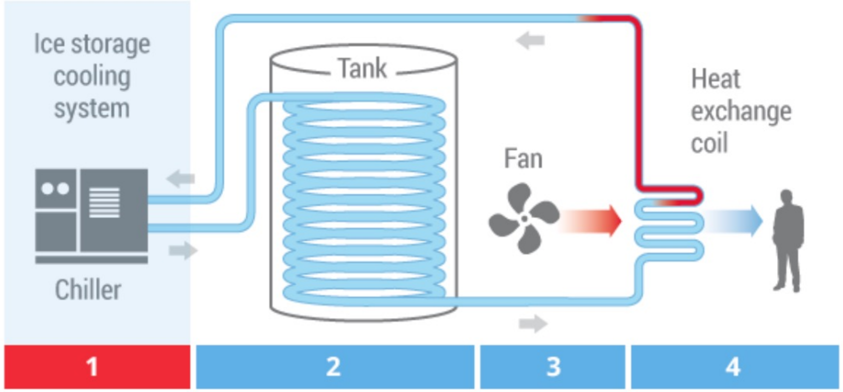
Thermal Storage

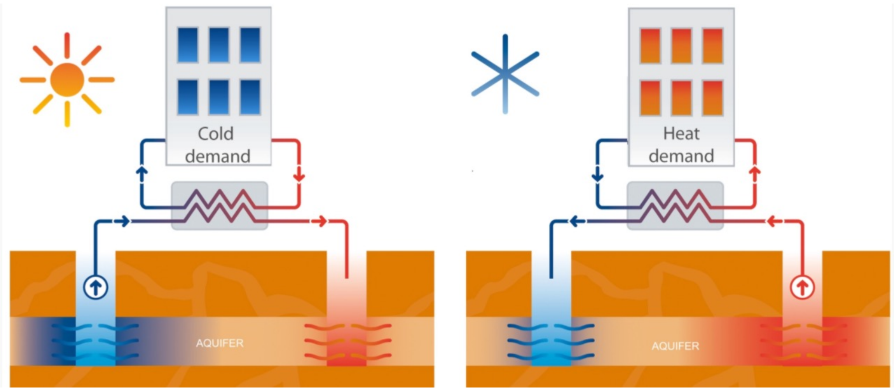
Thermal Energy Storage (TES)

- Maintain high temperature: Residential and commercial heating needs, CSP, etc.
- Maintain cold temperatures: The storage of food or for other chiller applications.

Two general types of thermal storage mechanisms:

- The use of the sensible heat in various solid and/or liquid materials.
- Involves the latent heat of phase change reactions.





TES Taxonomy

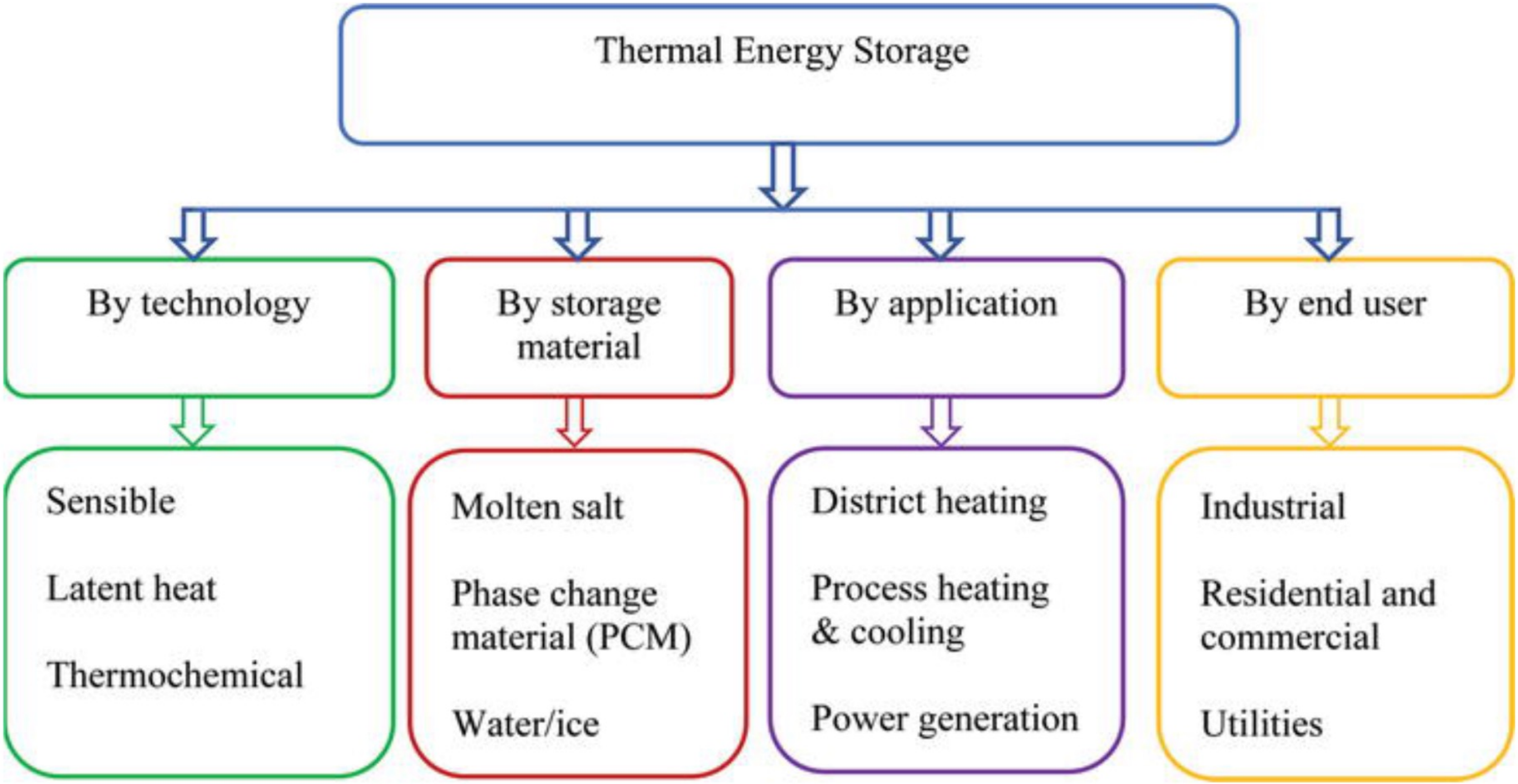


Fig source: https://www.intechopen.com/books/thermal-energy-battery-with-nano-enhanced-pcm/seasonal-solar-thermal-energy-storage

Sensible Heat

- Adding energy to a material by heating it to a higher temperature.
- The energy that is involved in changing its temperature is called "sensible heat".

The amount of heat q that can be transferred from a given mass of material at one temperature to another at a lower temperature is given by

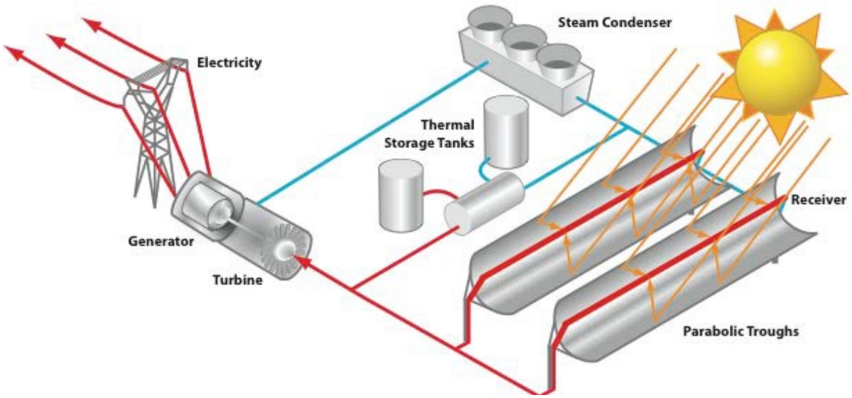
$$q = \rho C_P V \Delta T \tag{3.1}$$

where ρ is the density, C_p the specific heat at constant pressure, and V the volume of the storage material. ΔT is the temperature difference.

Table 3.1 Thermal properties of some common materials

Material	Density (kg m^{-3})	Specific heat (J kg^{-1} K^{-1})	Volumetric thermal capacity (10^6 J m^{-3} K^{-1})
Clay	1458	879	1.28
Brick	1800	837	1.51
Sandstone	2200	712	1.57
Wood	700	2390	1.67
Concrete	2000	880	1.76
Glass	2710	837	2.27
Aluminum	2710	896	2.43
Steel	7840	465	3.68
Magnetite	5177	752	3.69
Water	988	4182	4.17

Molten Salt Energy Storage



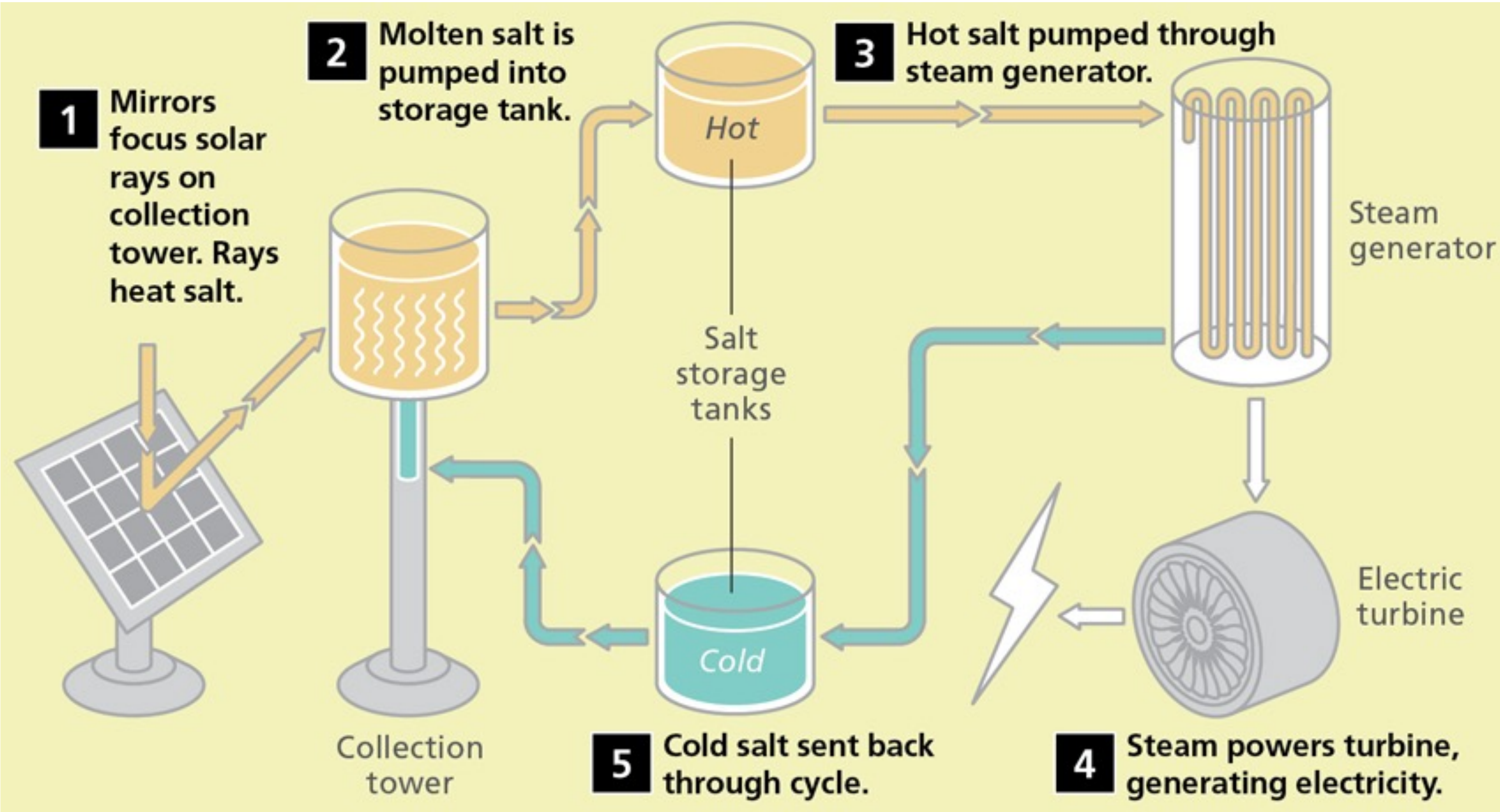
Global operational capacity: ~1.3 GW
U.S. operational capacity: ~281 MW

Technology characteristics

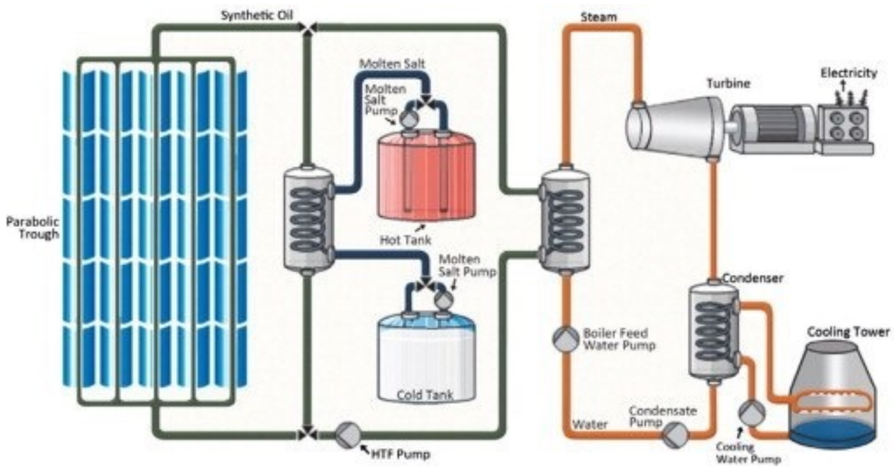
- Power capacity: MW scale
- Discharge time: hours
- Response time: minutes
- Efficiency: 80-90%
- Lifetime: 30 years

Primary application: Shifting and smoothing output for CSP plants

How Molten Salt Storage Works



Molten Salt Energy Storage (cont'd)



Pros

- Commercial
- Large scale
- Most economically viable storage for solar

Cons

- Primarily only for CSP applications
- Can be corrosive

Latent Heat

- Energy in hidden form which is supplied/extracted to change the state of a substance without changing its temperature.
- Examples: Latent heat of fusion and latent heat of vaporization involved in phase changes, i.e. a substance condensing or vaporizing at a specified temperature and pressure.

The latent heat for a given mass of a substance is given by

$$Q = mL$$

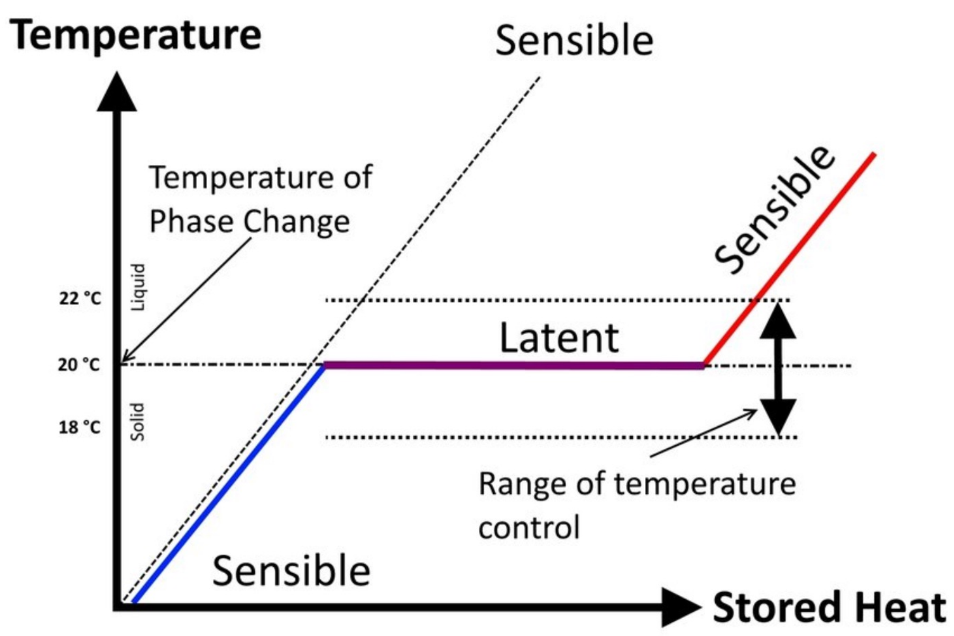
- Q is the amount of energy released or absorbed during the change of phase of the substance (e.g., in kJ or Btu),
- m is the mass of the substance (e.g., in kg or lb)
- L is the specific latent heat for a particular substance (e.g., in kJ/kg or Btu/lb)

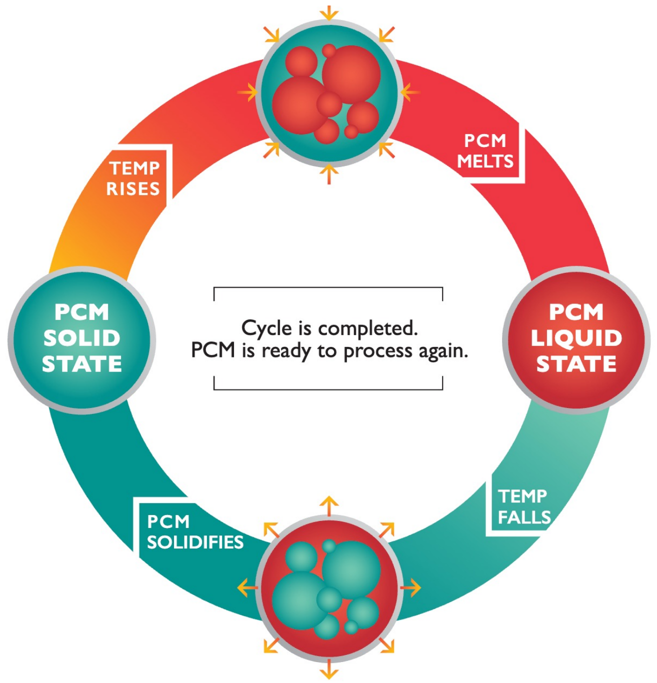
SLH: Specific latent heat

Substance	SLH of fusion (kJ/kg)	Melting point (°C)	SLH of vaporization (kJ/kg)	Boiling point (°C)
Ethyl alcohol	108	−114	855	78.3
Ammonia	332.17	−77.74	1369	−33.34
Carbon dioxide	184	−78	574	−57
Helium			21	−268.93
Hydrogen(2)	58	−259	455	−253
Lead[9]	23.0	327.5	871	1750
Nitrogen	25.7	−210	200	−196
Oxygen	13.9	−219	213	−183
Refrigerant R134a		−101	215.9	−26.6
Refrigerant R152a		−116	326.5	-25
Silicon[10]	1790	1414	12800	3265
Toluene	72.1	−93	351	110.6
Turpentine			293	
Water	334	0	2264.705	100

Phase Change Materials (PCM)

- PCM: A substance which releases/absorbs sufficient energy at phase transition (from solid to liquid, or vice versa) to provide useful heat/cooling.
- The heat of fusion is generally much higher than the sensible heat.
  e.g., ice requires 333.55 J/g to melt, but then water will rise one degree further with the addition of just 4.18 J/g.

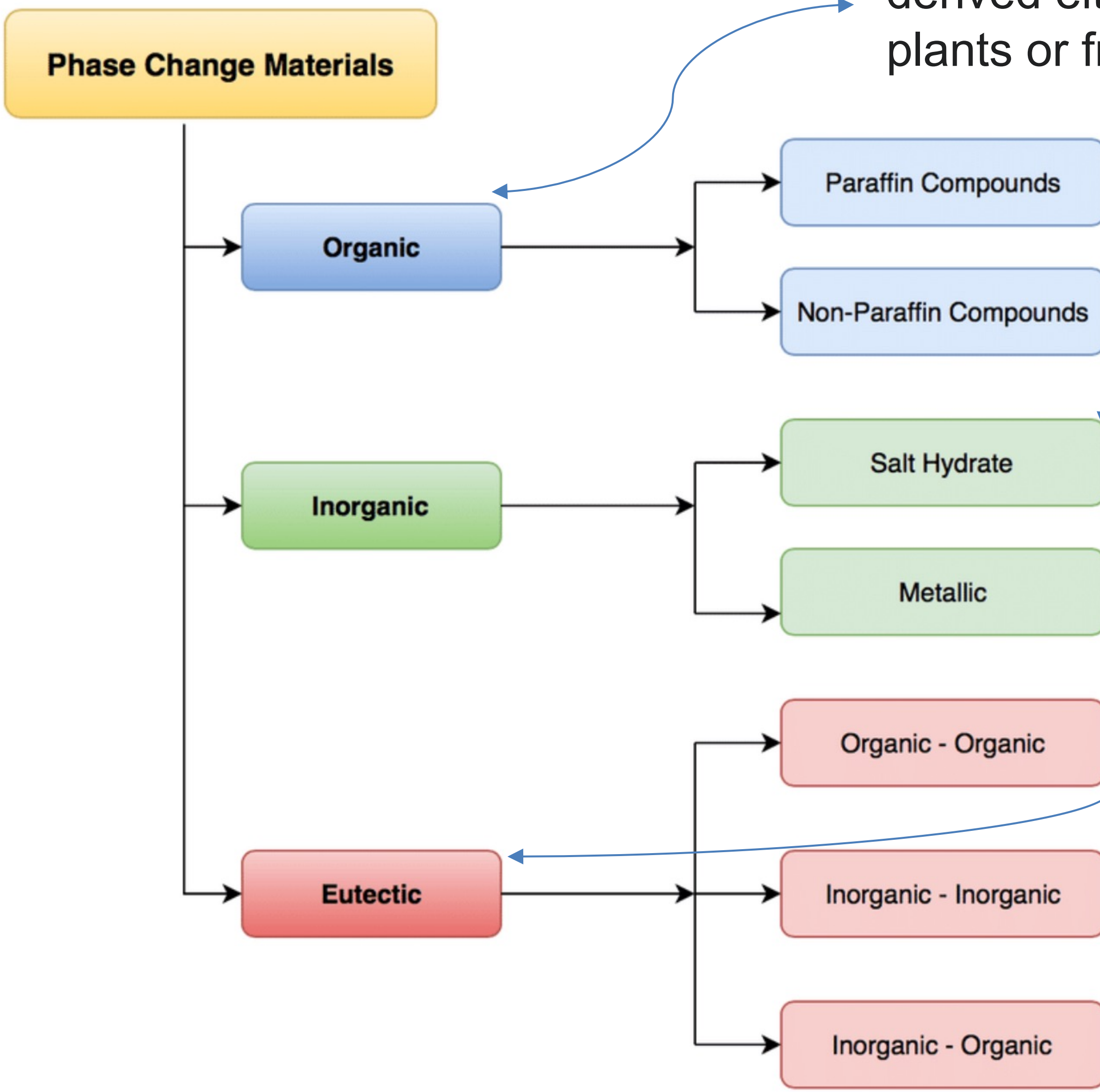




[1] Jan Skovajsa etc, Phase Change Material Based Accumulation Panels in Combination with Renewable Energy Sources and Thermoelectric Cooling, 2017.
[2] https://www.microteklabs.com/understanding-pcms.

Classification of PCM

organic (carbon-containing) materials derived either from petroleum, from plants or from animals.

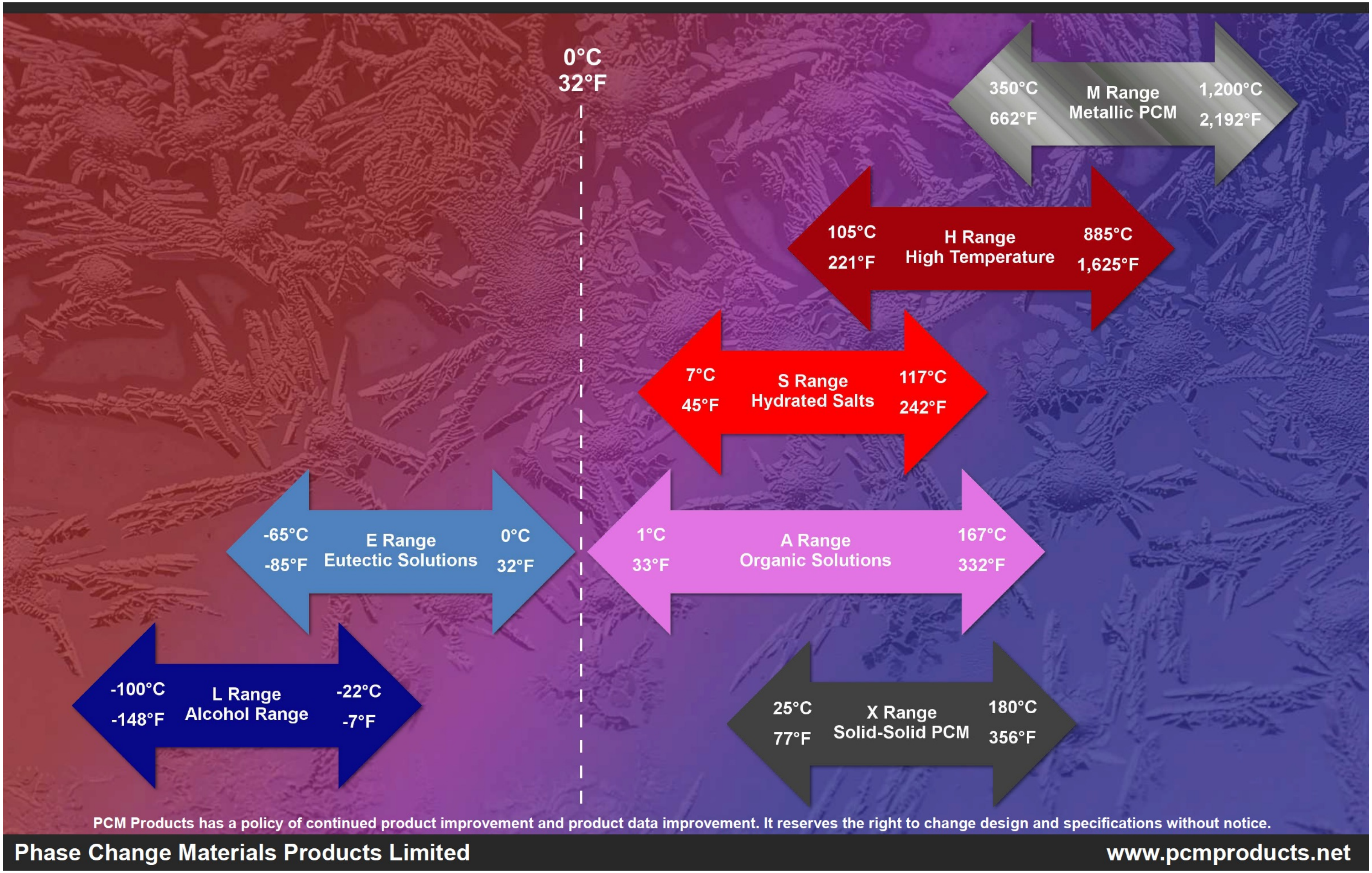


salt hydrates, which generally either use natural salts from the sea or from mineral deposits or are by-products of other processes.

consists a mixture of two or more compounds which has low melting point than that of each individual one. It is a solution which has phase change temperature below 0°C.

Source: Jerol Soibam, Numerical Investigation of a heat exchanger using Phase Change Materials (PCMs) for small-scale combustion appliances, 2018.

PCM (cont'd)


0°C
32°F
350°C
662°F
M Range
Metallic PCM
1,200°C
2,192°F
105°C
221°F
H Range
High Temperature
885°C
1,625°F
7°C
45°F
S Range
Hydrated Salts
117°C
242°F
-65°C
-85°F
E Range
Eutectic Solutions
0°C
32°F
1°C
33°F
A Range
Organic Solutions
167°C
332°F
-100°C
-148°F
L Range
Alcohol Range
-22°C
-7°F
25°C
77°F
X Range
Solid-Solid PCM
180°C
356°F
PCM Products has a policy of continued product improvement and product data improvement. It reserves the right to change design and specifications without notice.
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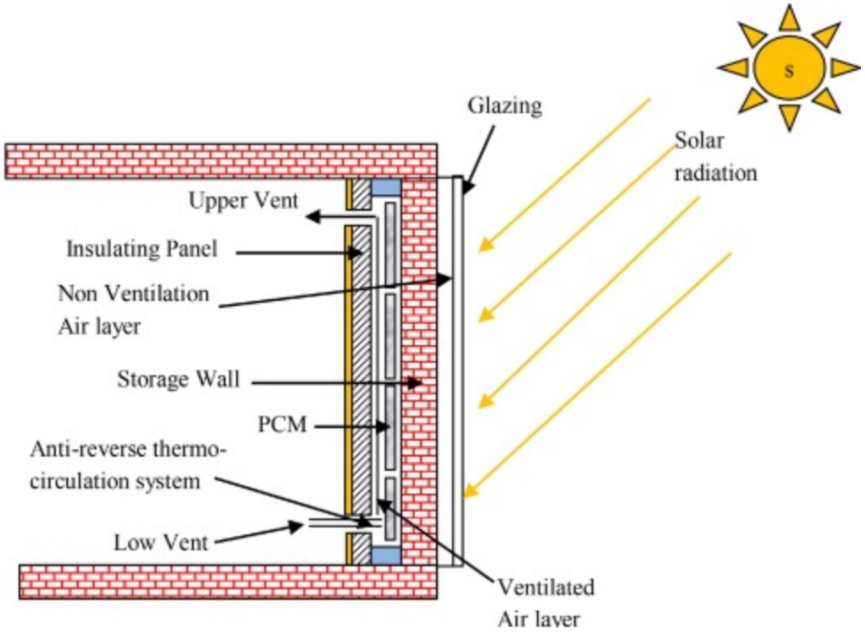
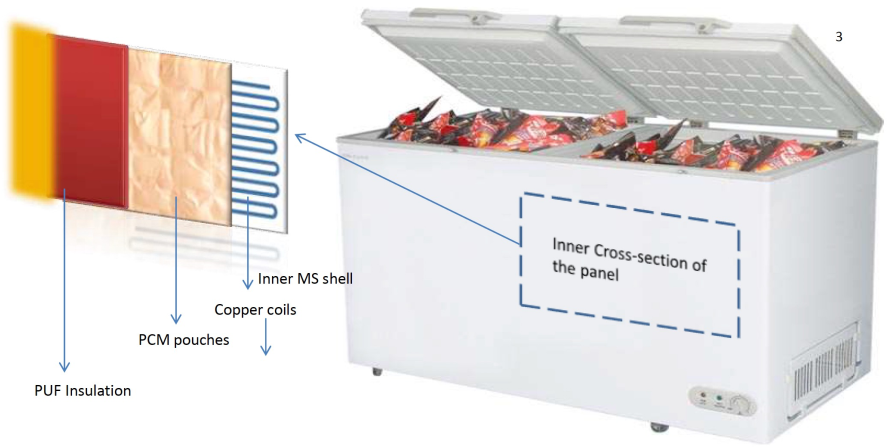
Applications of PCM





[NASA: Phase Change Material Heat Exchangers]

https://www.pluss.co.in/applications-PCM.php

Electrical Storage

Supercapacitor (SC)

- SC (aka ultracapacitor or double-layer capacitor), differs from a regular capacitor in that it has very high capacitance.
- Capacitors store energy by means of static charges as opposed to electrochemical reactions (batteries).
- Applying a voltage differential on the positive and negative plates charges the capacitor.
- All capacitors have voltage limits. Supercapacitor is confined to 2.5–2.7V while the electrostatic capacitor can withstand high volts.

	Value	Applications
Electrostatic capacitor	a few pico-farads (pf) to low microfarad (µF)	tune radio frequencies and filtering
Electrolytic capacitor	microfarads (µF)	filtering, buffering and signal coupling
Supercapacitor	Farads (F)	energy storage undergoing frequent (dis) charge cycles at high current and short duration

SC vs Regular Capacitors

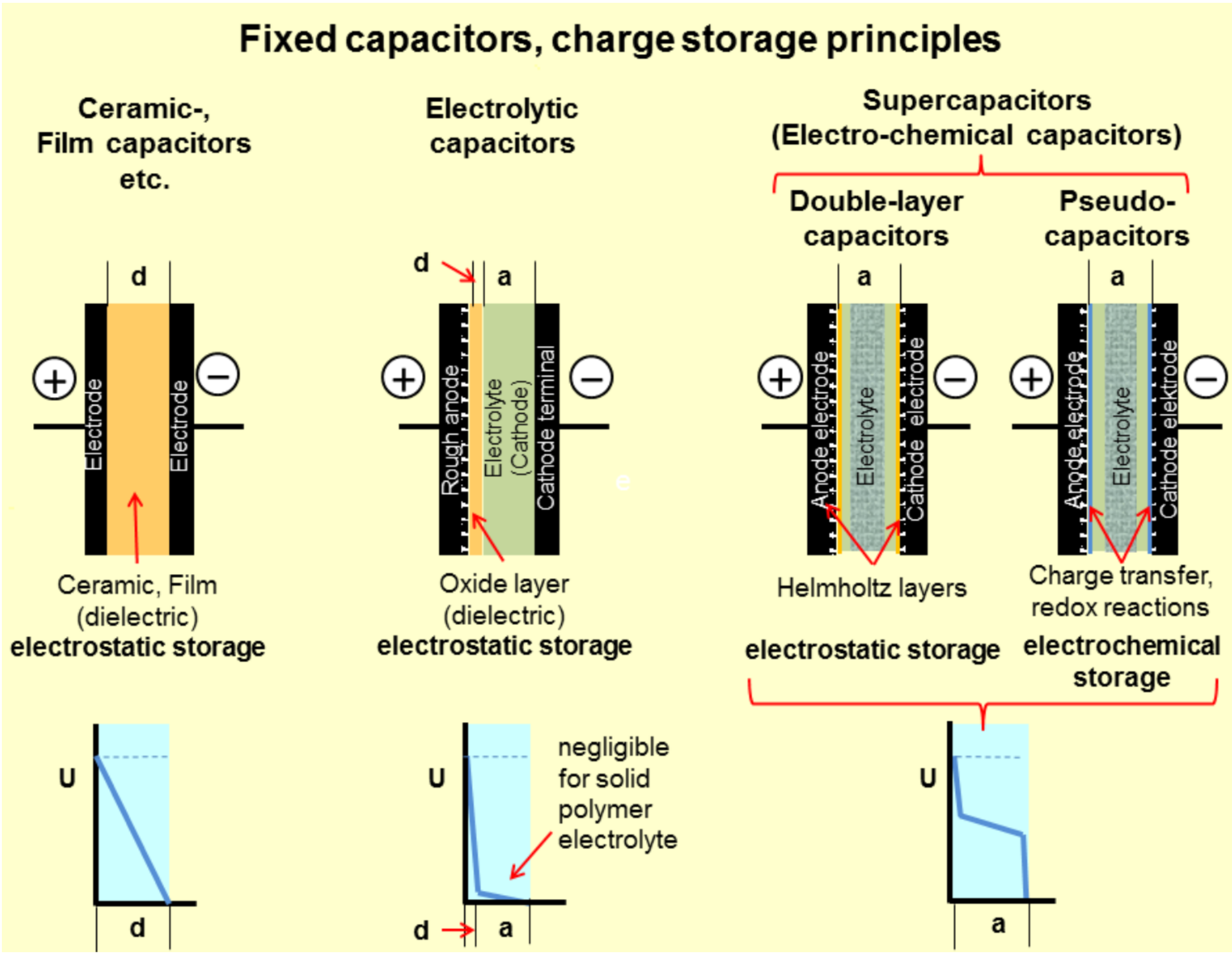
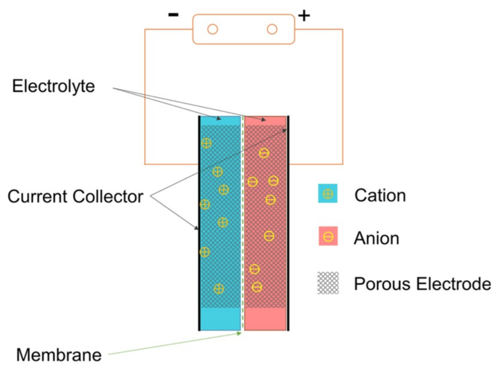
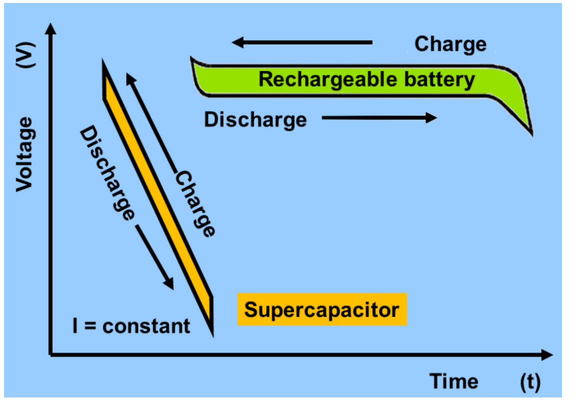
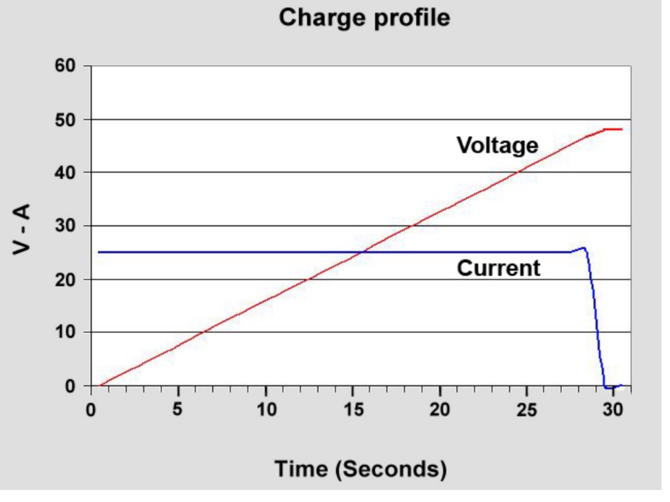


Fig: Charge storage principles of different capacitor types and their internal potential distribution (from wiki).

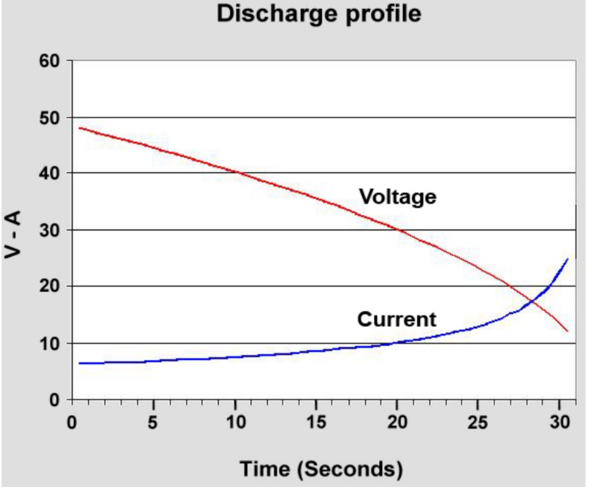
Charging/Discharging Profiles of SC





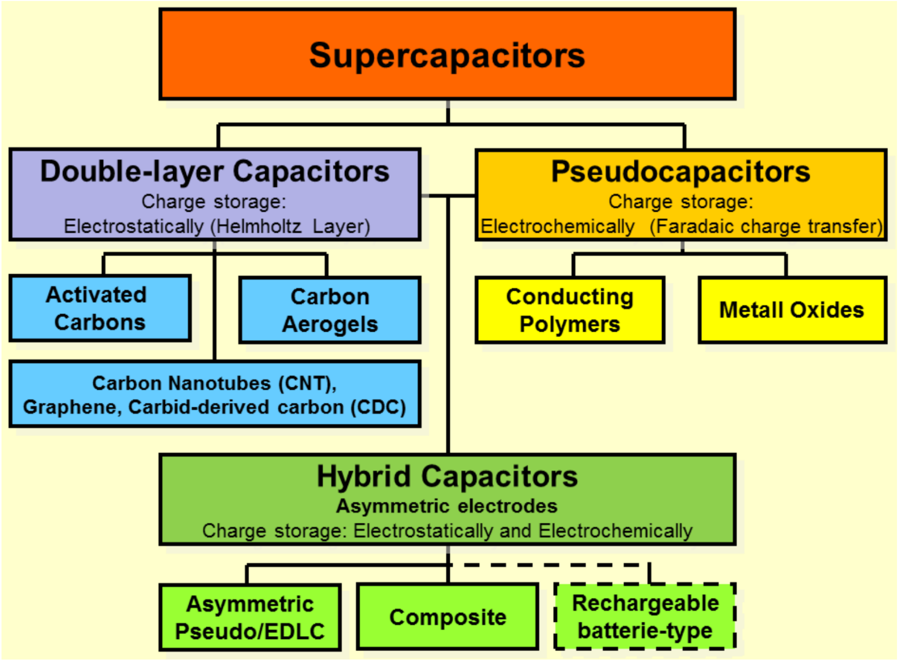


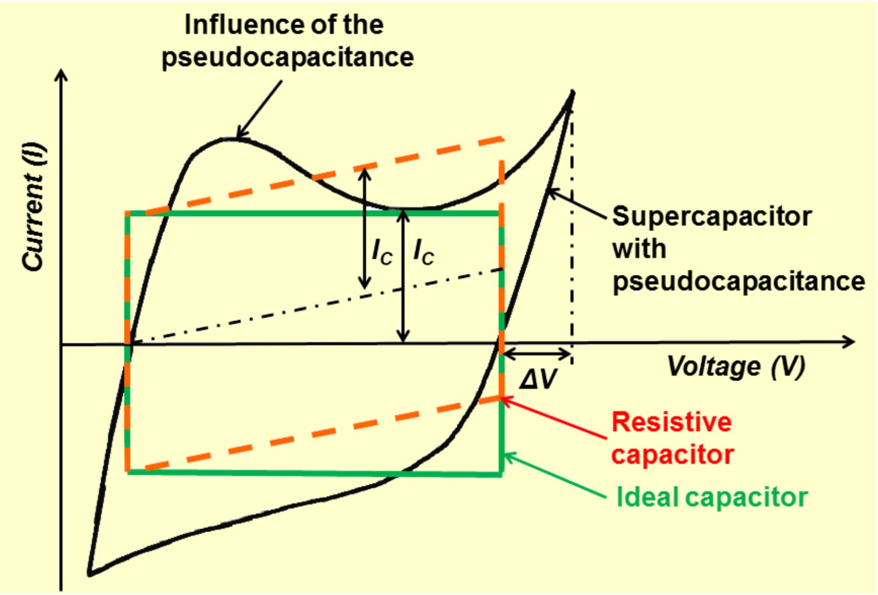
Voltage increases linearly on charge.
Current stops flowing when full
(no need of full-charge detection).



Voltage drops linearly on discharge.
An DC-DC converter maintains the wattage level by drawing higher current with dropping voltage.

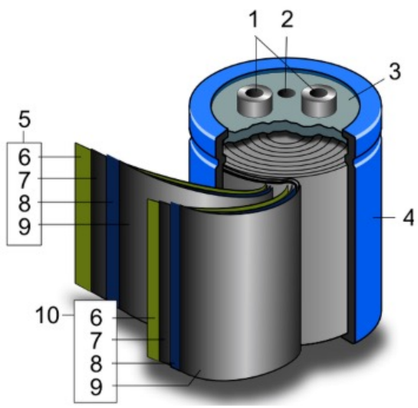
Supercapacitor (cont'd)



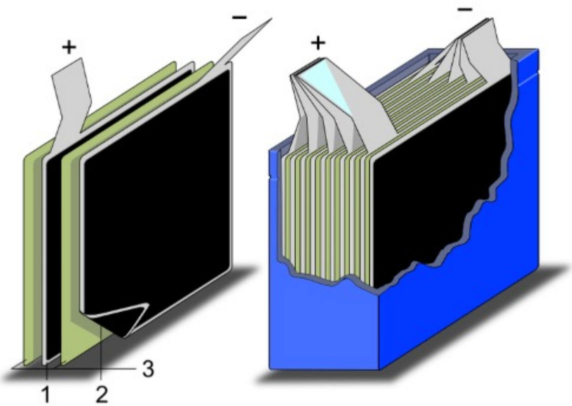


- Electrostatic double-layer capacitors (EDLCs) – activated carbon electrodes with much higher electrostatic double-layer capacitance than pseudo-capacitance.
- Pseudocapacitors – transition metal oxide or conducting polymer electrodes with a high electrochemical pseudo-capacitance.
- Hybrid capacitors – asymmetric electrodes, one exhibits mostly electrostatic and the other mostly electrochemical capacitance.

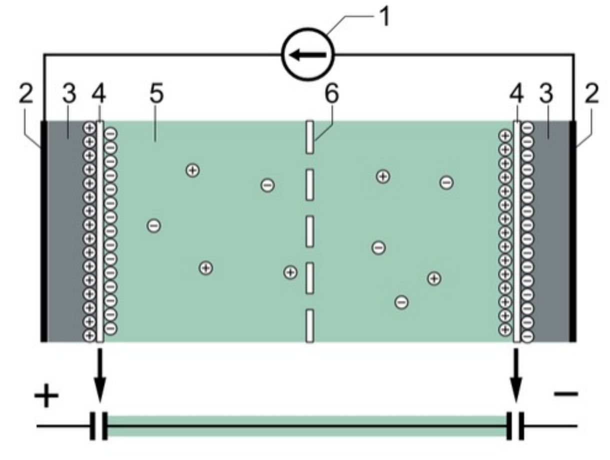
SC Schematic Construction



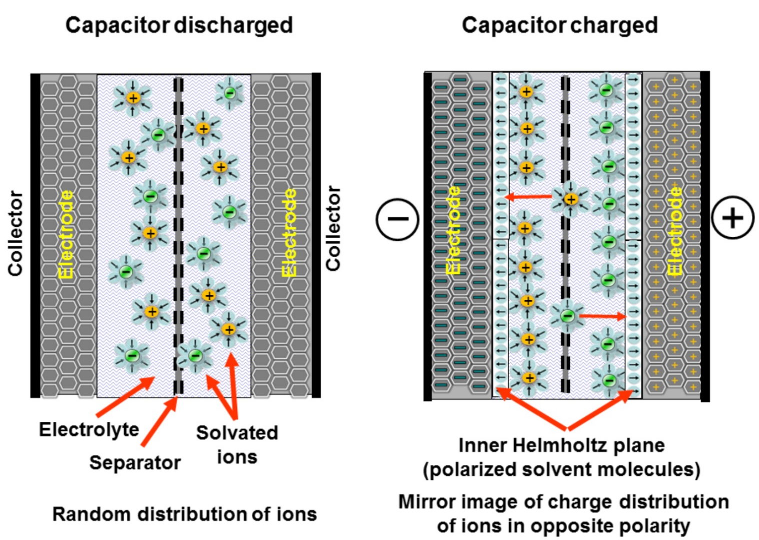
Schematic construction of a wound supercapacitor 1. terminals, 2. safety vent, 3. sealing disc, 4. aluminum can, 5. positive pole, 6. separator, 7. carbon electrode, 8. collector, 9. carbon electrode, 10. negative pole



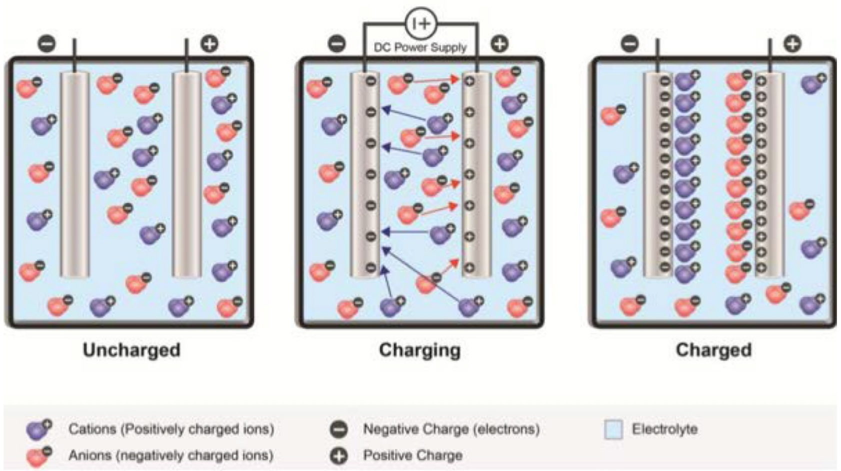
Schematic construction of a supercapacitor with stacked electrodes 1. positive electrode, 2. negative electrode, 3. separator



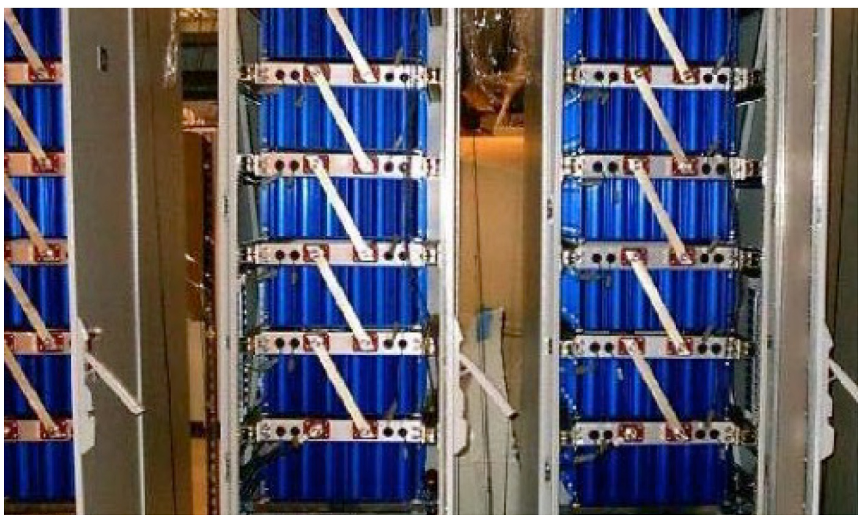
Typical construction of a supercapacitor: (1) power source, (2) collector, (3) polarized electrode, (4) Helmholtz double layer, (5) electrolyte having positive and negative ions, (6) separator.



SC Technology Characteristics



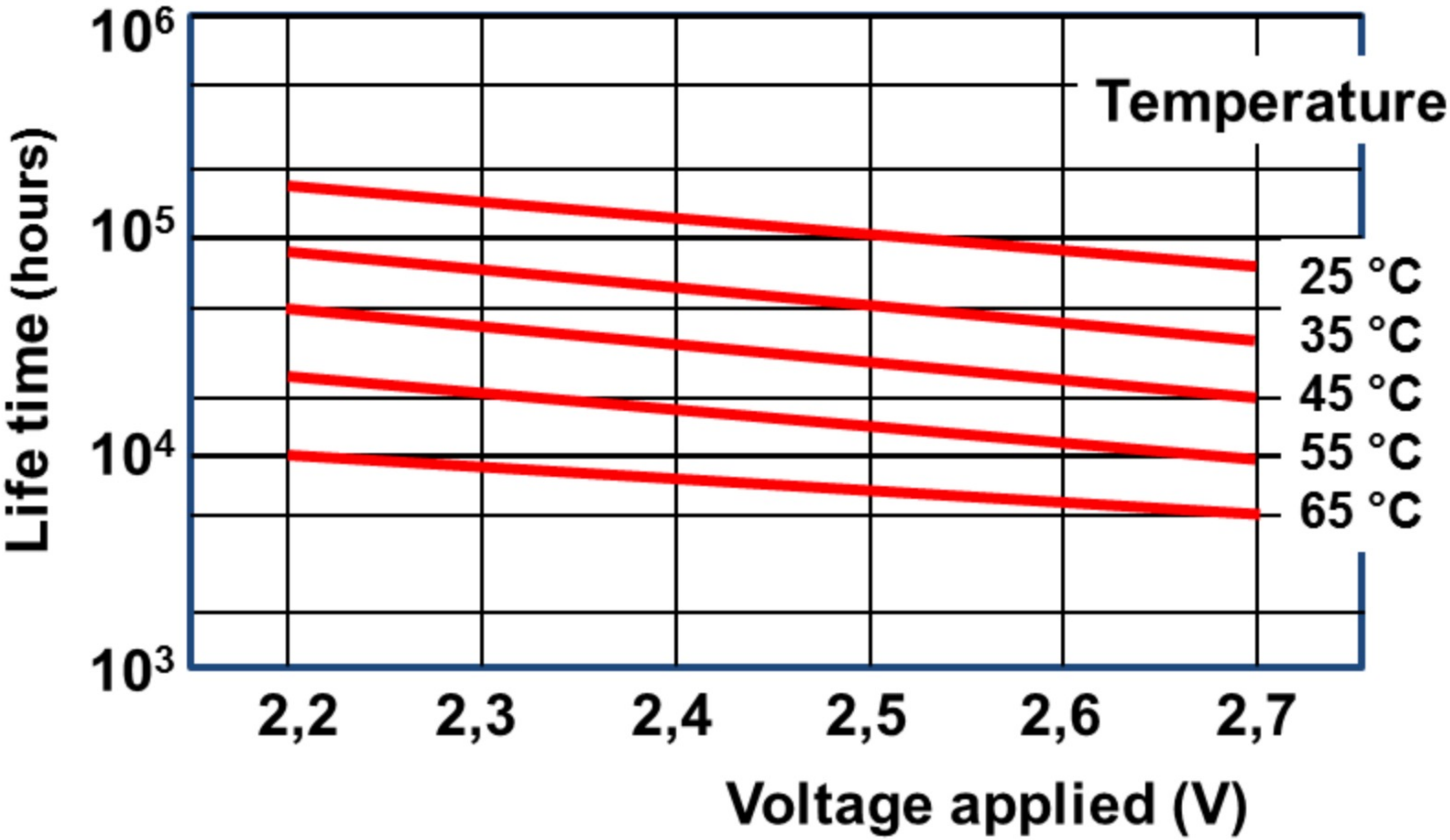
- Power capacity: kW to GW
- Discharge time: ms – minutes
- Response time: 10-20 ms
- Efficiency: 80-98%
- Lifetime: 4-20 years



<u>Primary application:</u>
Used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: Power quality, voltage support.

Video: [The “Best” Car Jump Starter]

SC Lifetime



Life time (hours)
10^6
10^5
10^4
10^3
Temperature
25 °C
35 °C
45 °C
55 °C
65 °C
2,2
2,3
2,4
2,5
2,6
2,7
Voltage applied (V)

Pros and Cons of Supercapacitors

Bridging the gap between electrolytic capacitors and rechargeable batteries.

- Store 10–100 times more energy per unit volume or mass than electrolytic capacitors.
- Deliver charge much faster than batteries, and tolerate many more charge/discharge cycles.
- SC discharges from 100% to 50% in 30-40 days. Lead and lithium-based batteries self-discharge about 5 percent per month.

Pros	• **Virtually unlimited cycle life (millions of time)** • **Charges in seconds** • **High efficiency and specific power** • **Scalable and flexible** • **Excellent low-temperature (dis) charge performance**
Cons	• Low specific energy • Requires power conditioning to deliver a steady power output • Expensive per unit of energy capacity • High self-discharge • Low cell voltage

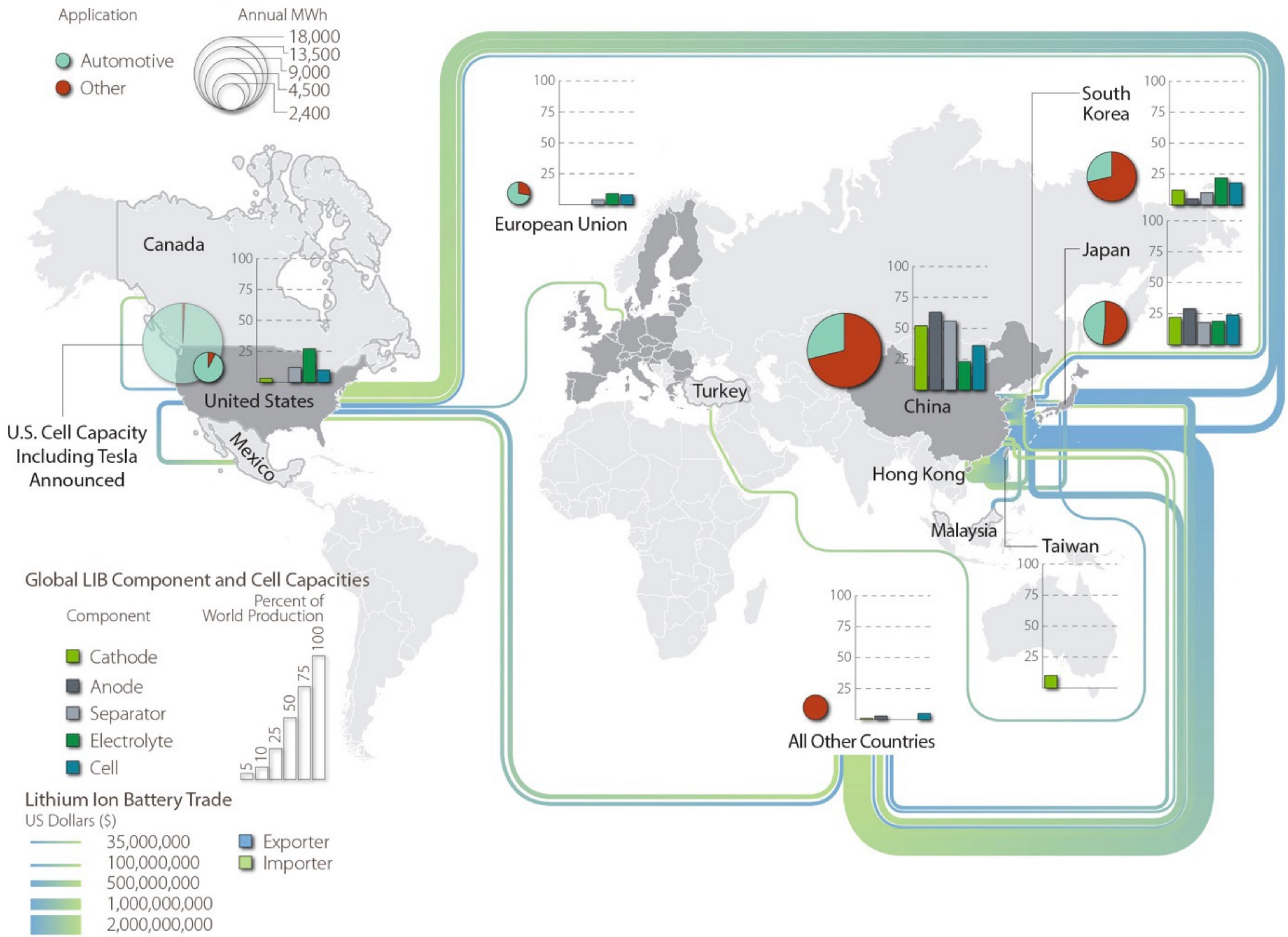
Electro-Chemical Storage

Lithium-Ion Batteries (LIB)

Nobel Prize organization: “this lightweight, rechargeable and powerful battery is now used in everything from mobile phones to laptops and electric vehicles. It can also store significant amounts of energy from solar and wind power, **making possible a fossil fuel-free society**.”

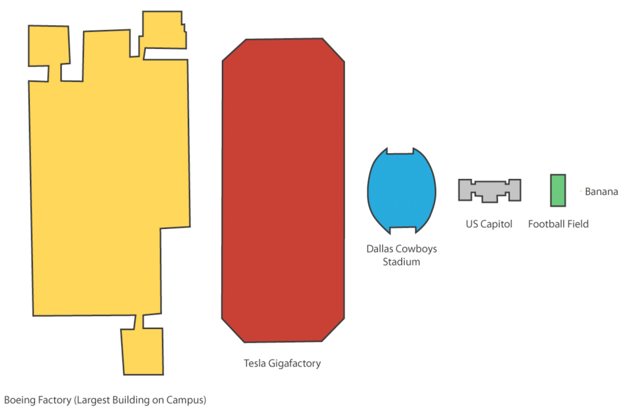
3 different shapes: i) cylindrical, ii) flat or pouch, iii) rigid plastic case with large threaded terminals

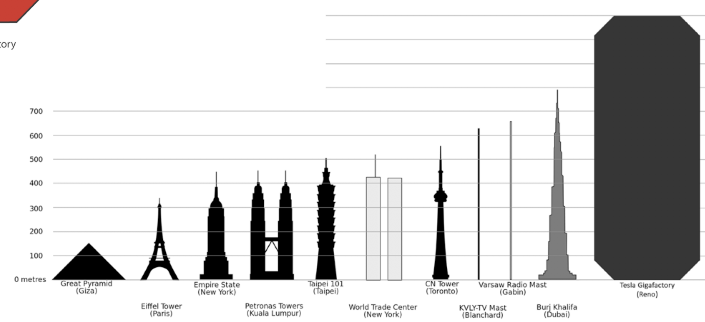
LIB Cell Capacities by Applications



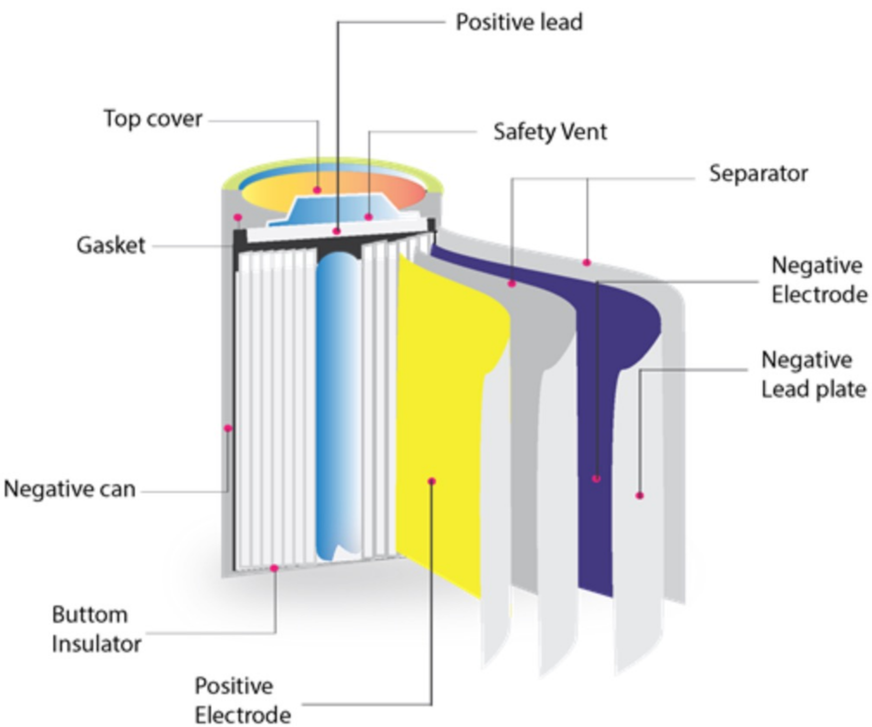
Tesla Gigafactory

The Tesla Gigafactory 1 is a lithium-ion battery factory under construction at the Tahoe Reno Industrial Center in Nevada.





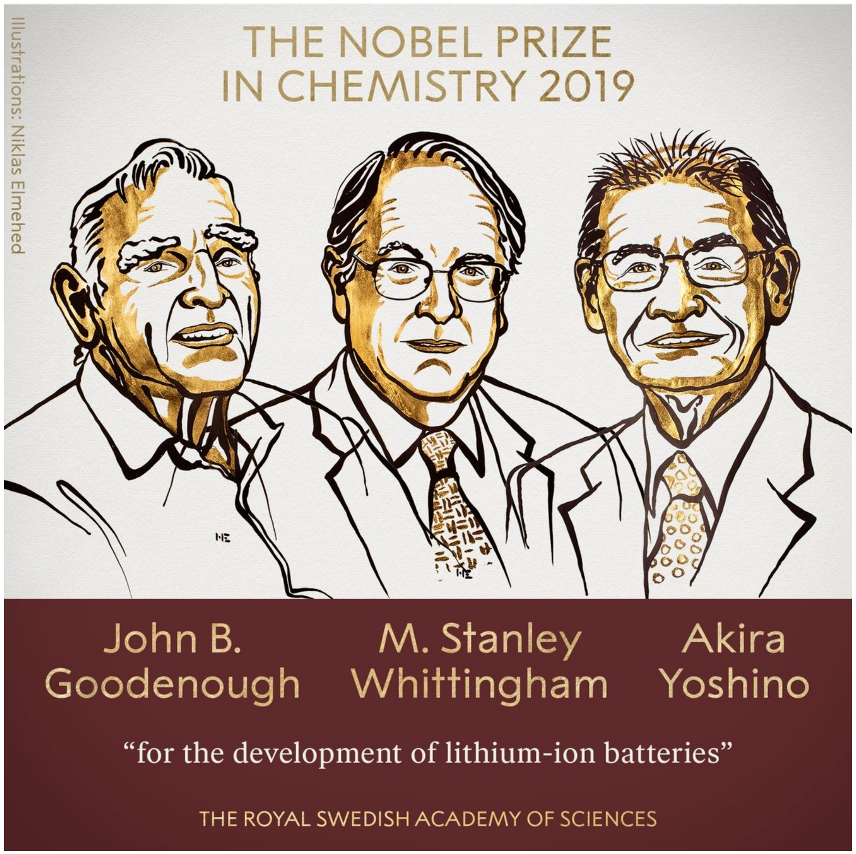
Key Components of LIB



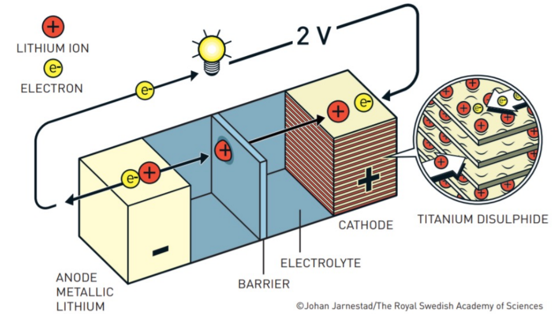
- **Anode**: Typically made up of carbon and coated on copper foil.
- **Cathode**: Typically made up of ternary cobalt, nickel, and manganese; coated on the aluminum foil.
- **Separator**: Micro-porous films are used for electrode separation.
- **Electrolyte**: The conductive pathway for transporting ions between two electrodes; typically comprised of lithium salt, such as $LiPF_6$, $LiBF_4$ or $LiClO_4$ in an organic solvent. Recent advances involve using a solid as the electrolyte material; e.g., ceramics.

https://www.quora.com/Whats-inside-a-Li-ion-battery

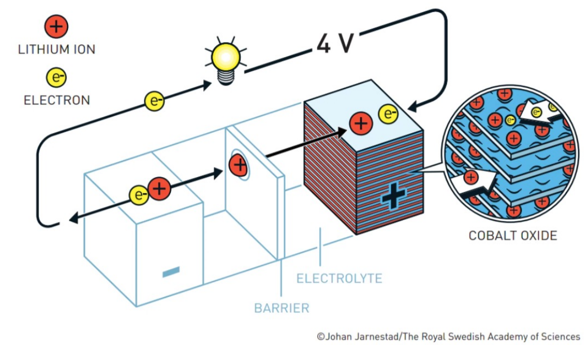
Nobel Prize in Chemistry 2019



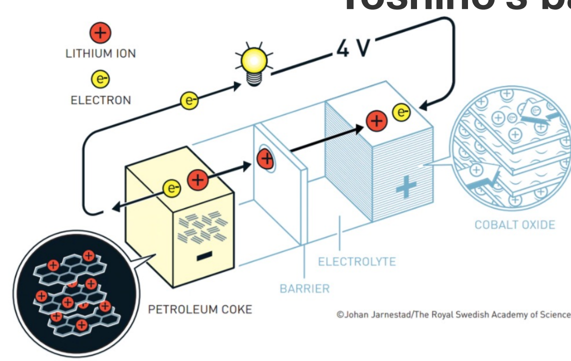
Whittingham's battery.



Goodenough's battery.

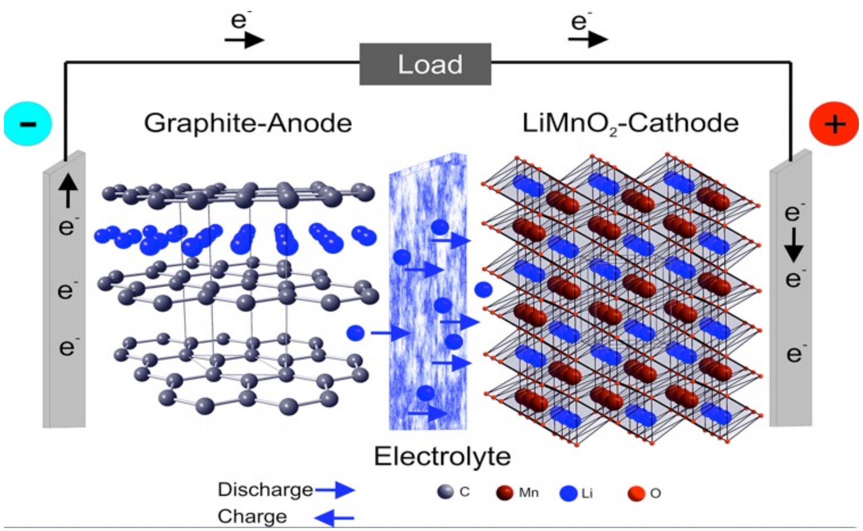


Yoshino's battery.



https://www.thermofisher.com/blog/microscopy/the-history-of-the-lithium-ion-battery/

LIB Working Principles



- Li-ion batteries use an intercalated lithium compound at the cathode and typically graphite at the anode.
- When the battery discharges, lithium ions move from the anode to the cathode and back when charging.

The electrochemical reactions take place in a Li-ion battery are:

$$\mathrm{LiMO_2} \rightleftarrows \mathrm{Li}_{1-x}\mathrm{MO_2} + x\mathrm{Li}^+ + xe^- \text{ (at the cathode)}$$

$$x\mathrm{Li}^+ + xe^- + x\mathrm{C_6} \leftrightarrows x\mathrm{LiC_6} \text{ (at the anode)}$$

The overall cell reaction (L-to-R: charging; R-to-L: discharging) is:

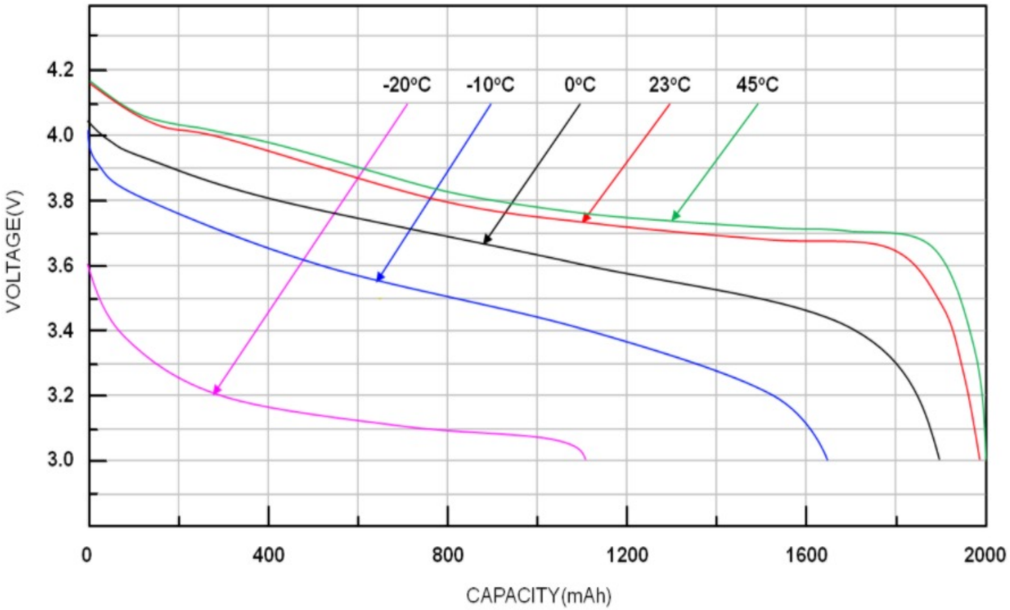
$$\mathrm{LiMO_2} + \mathrm{C_6} \rightleftarrows \mathrm{Li}_{1-x}\mathrm{MO_2} + \mathrm{Li}_x\mathrm{C_6} \ (x = 0.5,\ V \sim 3.7 \text{ volts})$$

LIB Classification

Chemical name	Material	Abbr,	Short form or Nickname	Comments
Lithium Cobalt Oxide	$LiCoO_2$ (60% Co)	LCO	Li-cobalt	High capacity; for cell phone laptop, camera
Lithium Manganese Oxide	$LiMn_2O_4$	LMO	Li-manganese, or spinel	Most safe; lower capacity than Li-cobalt but high specific power and long life. Power tools, e-bikes, EV, medical, hobbyist.
Lithium Iron Phosphate	$LiFePO_4$	LFP	Li-phosphate	Same as above
Lithium Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$ (10–20% Co)	NMC	NMC	Same as above
Lithium Nickel Cobalt Aluminum Oxide	$LiNiCoAlO_2$ 9% Co)	NCA	NCA	Gaining importance in electric powertrain and grid storage
Lithium Titanate	$Li_4Ti_5O_{12}$	LTO	Li-titanate	Same as above

https://pt.slideshare.net/FAL1/types-of-lithium-ion-batteries-v2/3
https://medium.com/@bisresearch2018/advanced-battery-technologies-play-a-pivotal-role-in-the-electric-vehicle-ecosystem-4e8dadb45aef

LIB Characteristics and Applications



Tech characteristics:

- Power capacity: W-MW scale
- Discharge time: 1min-8 hrs
- Response time: 10-20 ms
- Efficiency: 85-98%
- Lifetime: 5-15 yrs

<u>Primary application:</u>

- Most commonly in the electronics industry: provide portable electricity, EVs, powering electronic gadgets such as mobile phones, laptops and tablets.

https://pt.slideshare.net/FAL1/types-of-lithium-ion-batteries-v2/3
http://www.pasticheenergysolutions.com/applications/

LIB Pros and Cons

Fig a: Samsung Galaxy Note 7 recall

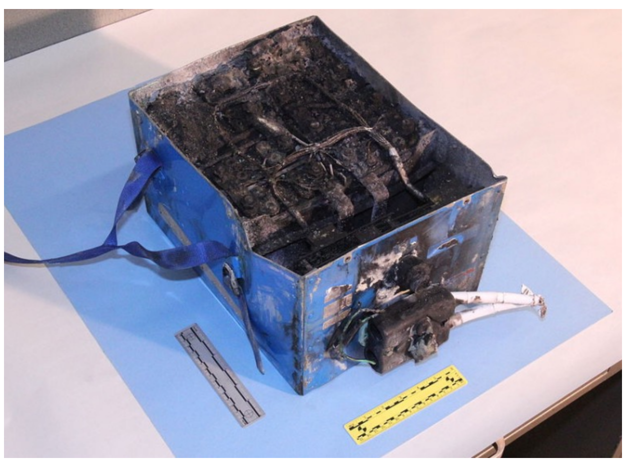


Fig b: The heavily burned battery from JA829J

Pros

- High efficiency
- Suitable for many portable (small to medium scale) applications
- Offer better resilience to self-discharge and can hold a charge for a long period.

Cons

- Limited lifecycle
- Thermal management: Internal circuitry is needed to keep the cells protected from completely discharging or overcharging in extreme temperatures and current surges.
- Environmental and safety concerns.
- Most lithium-ion batteries are charger-specific.

Li-Ion vs Supercapacitor

- The chemistry of a battery determines the operating voltage; charge and discharge are electrochemical reactions.
- The capacitor is non-electrochemical and the maximum allowable voltage is determined by the type of dielectric material.

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6V nominal
Specific energy (Wh/kg)	5 (typical)	120–240
Specific power (W/kg)	Up to 10,000	1,000–3,000
Cost per kWh	$10,000 (typical)	$250–$1,000 (large system)
Service life (industrial)	10-15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

Source: Maxwell Technologies, Inc.

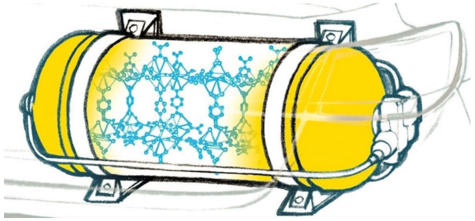
Top 12 Global Li-ion Battery Manufacturers

Rank*	Company	2017 Installed Manufacturing Capacity**	Country	Revenue***	Market Cap****
1	LG Chem	17 GWh	Korea	$23.1 Billion	$23.9 Billion
2	BYD	16 GWh	China	$15.5 Billion	$15.4 Billion
3	Panasonic	8.5 GWh	Japan	$71.8 Billion	$31.8 Billion
4	AESC	8.4 GWh	Japan	NA	NA
5	CATL	7.5 GWh	China	$3.0 Billion	$23.3 Billion
6	Guoxuan High-Tech	6 GWh	China	$718 Million	$2.3 Billion
7	Samsung SDI	6 GWh	Korea	$5.7 Billion	$14.0 Million
8	Lishen	3 GWh	China	NA	NA
9	CBAK	2.5 GWh	China	$58.4 Million	$19.2 Million
10	CALB	2.4 GWh	China	NA	NA
11	LEJ	2.3 GWh	Japan	NA	NA
12	Wanxiang	2.1 GWh	China	$1.7 Billion	$2.6 Billion

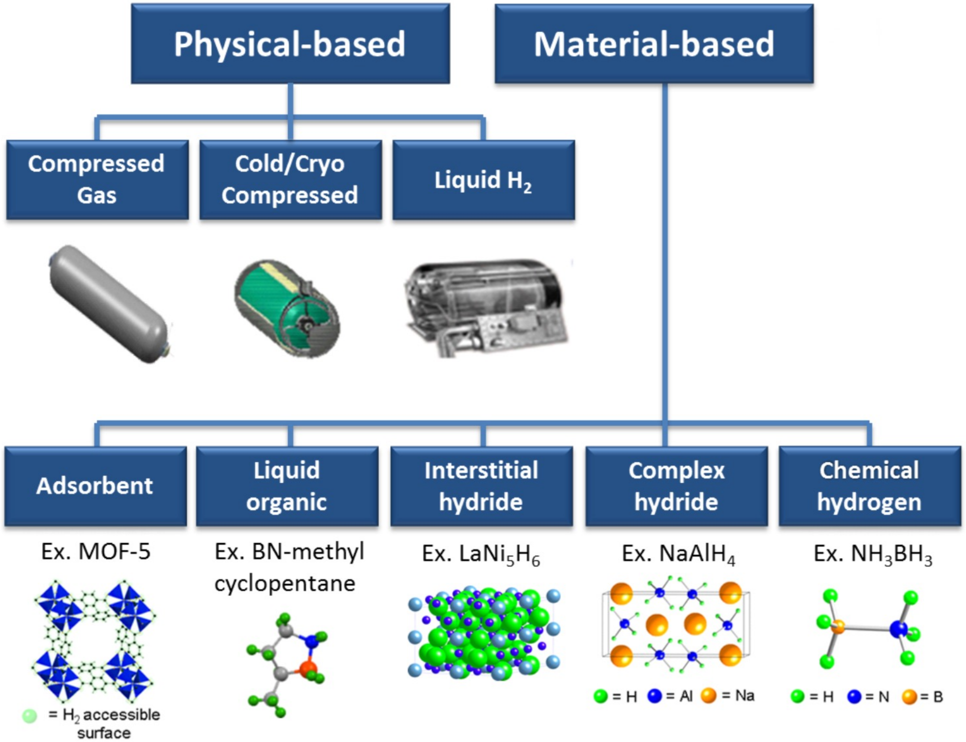
Table source: https://www.thomasnet.com/articles/top-suppliers/battery-manufacturers-suppliers/

Hydrogen Storage

How is Hydrogen Stored



Any methods for storing hydrogen for later use: mechanical approaches such as high pressures and low temperatures, or chemical compounds that release H_2 upon demand.

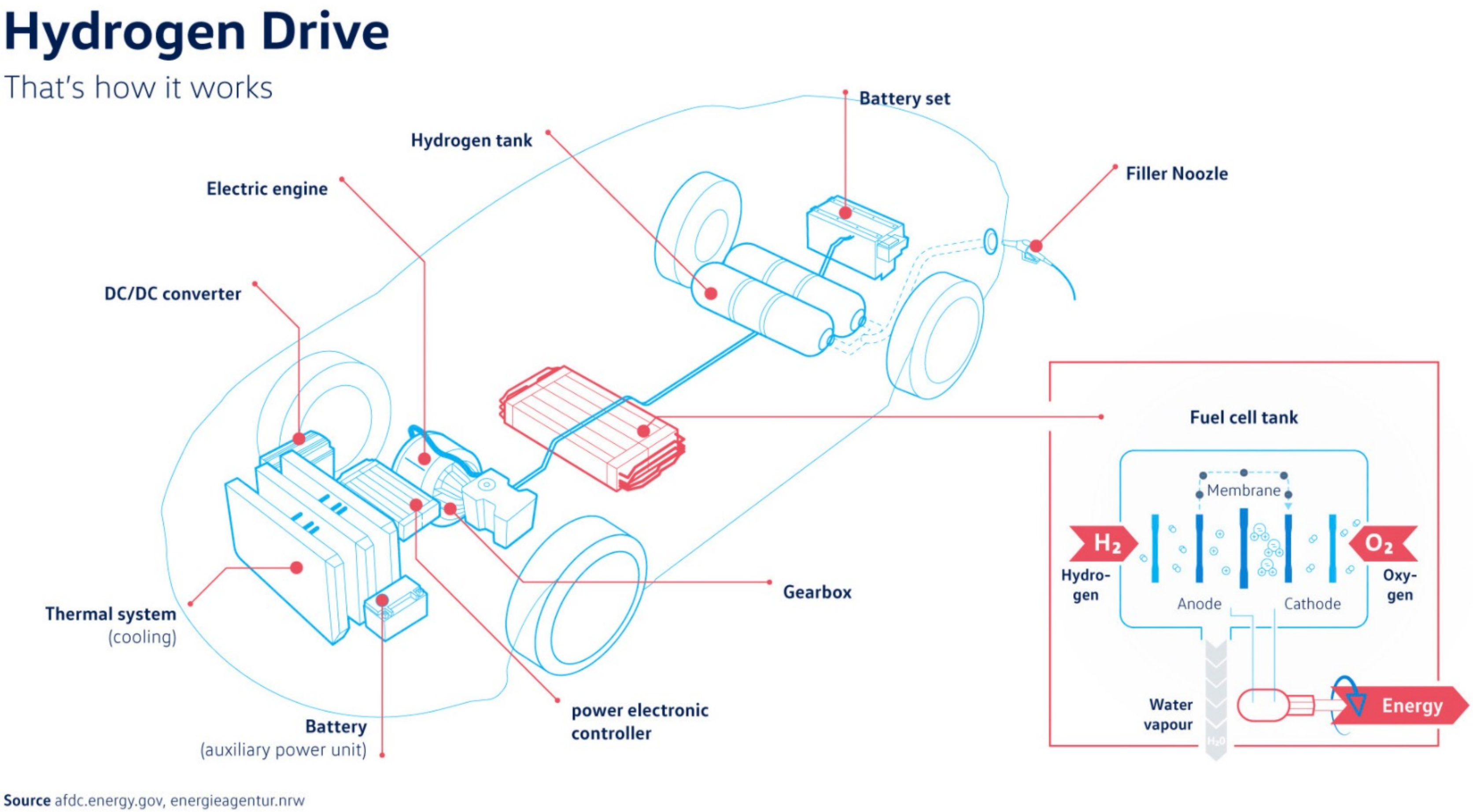


- Stored as a gas needs high-pressure tanks (350–700 bar).
- Stored as a liquid needs cryogenic temperatures (the boiling point of H_2 at 1atm is −252.8°C).
- Can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption).

https://www.energy.gov/eere/fuelcells/hydrogen-storage

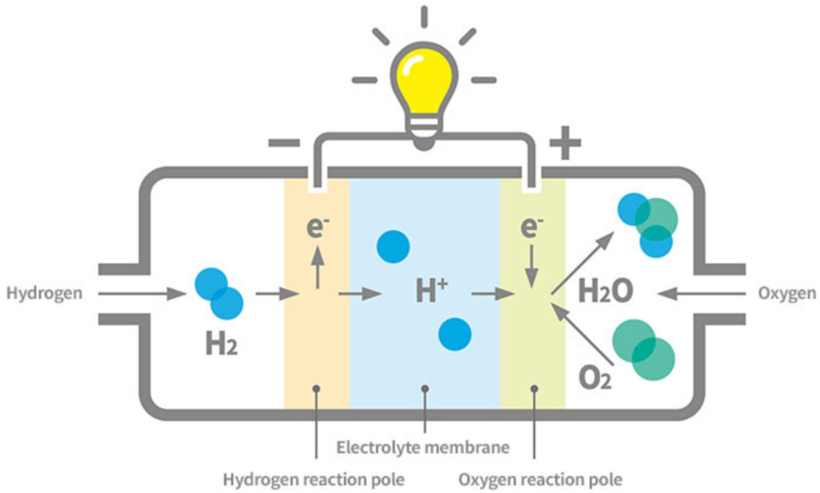
Fuel Cell Electric Vehicles (FCEVs)

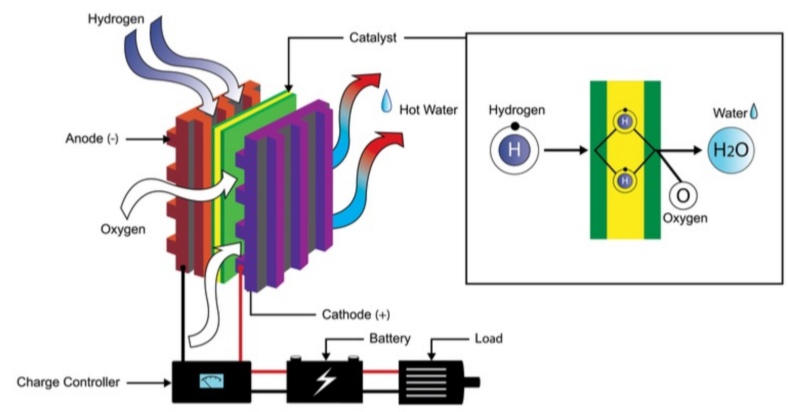
- FCEVs can be more efficient than conventional internal combustion engine vehicles and produce no tailpipe emissions – only emit water vapor and warm air.



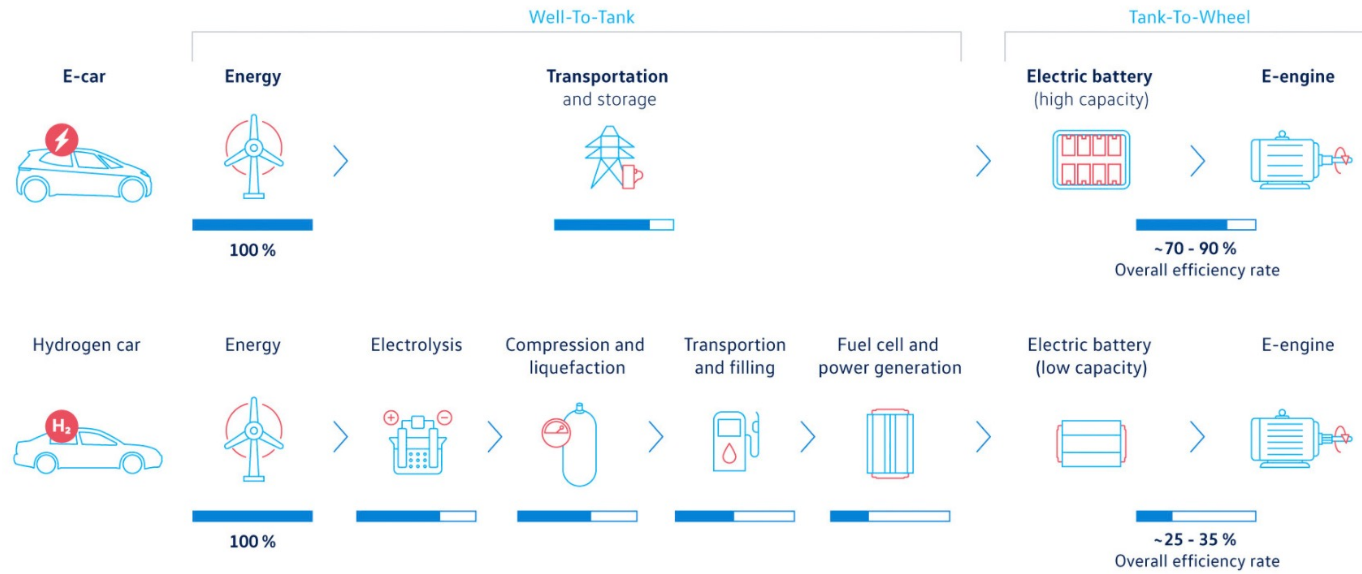
How Fuel Cells Work

- The most common: Polymer electrolyte membrane (PEM) fuel cell, where an electrolyte membrane is sandwiched between the cathode and anode.
- H_2 is introduced to the anode, and O_2 (from air) is into the cathode. The H_2 molecules break apart into protons and electrons due to an electrochemical reaction in the catalyst.
- Protons travel to the cathode. Electrons are forced to travel through an external circuit to provide power for the car.
- Finally, the protons, electrons, and oxygen molecules are recombined to form water.

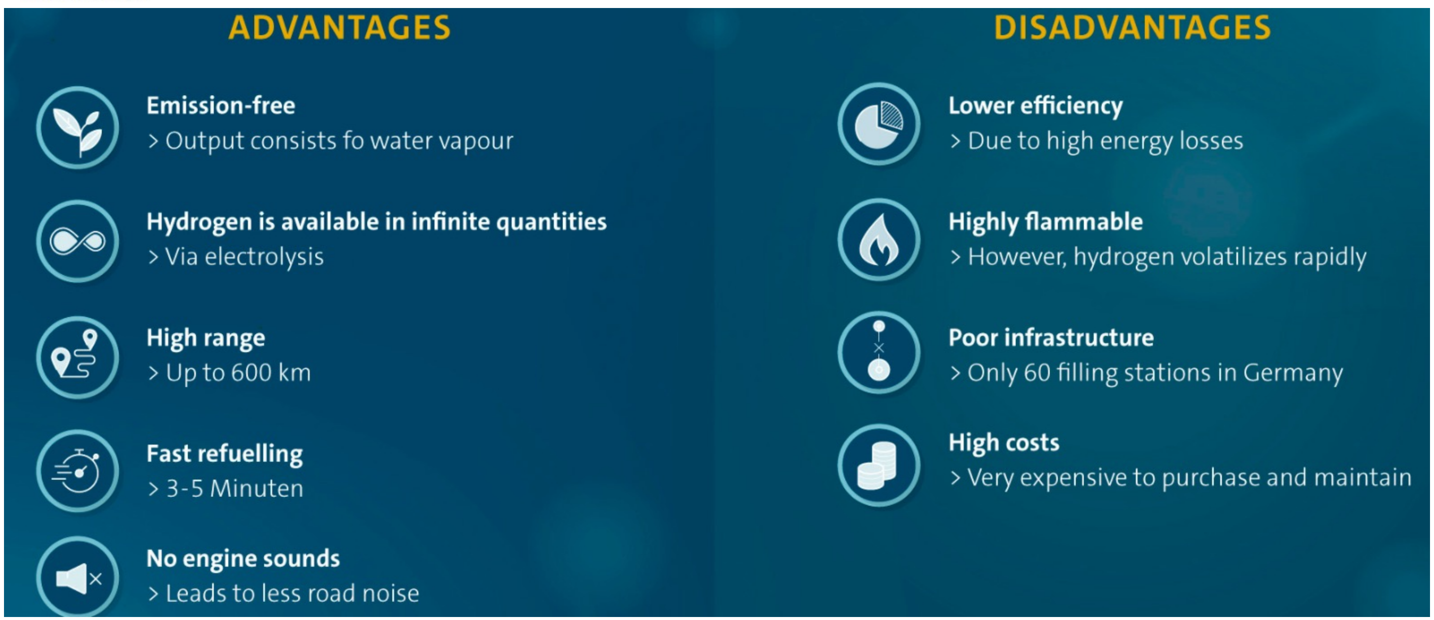




Hydrogen Cars vs E-Cars



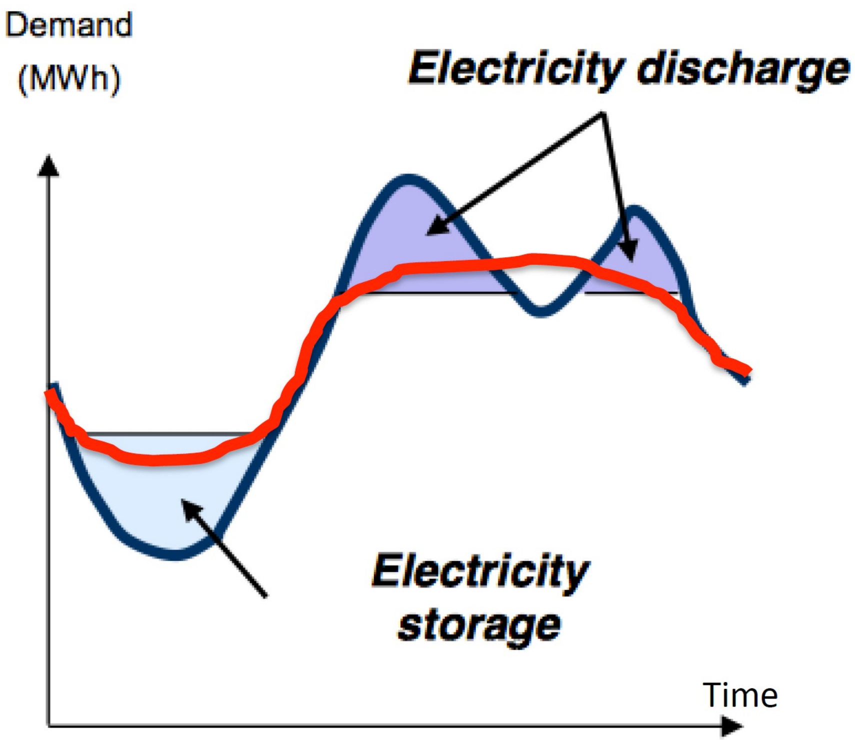
Source Volkswagen



https://insideevs.com/news/406676/battery-electric-hydrogen-fuel-cell-efficiency-comparison/

Comparisons of Energy Storage Techniques

Smoothing Demand by Storage



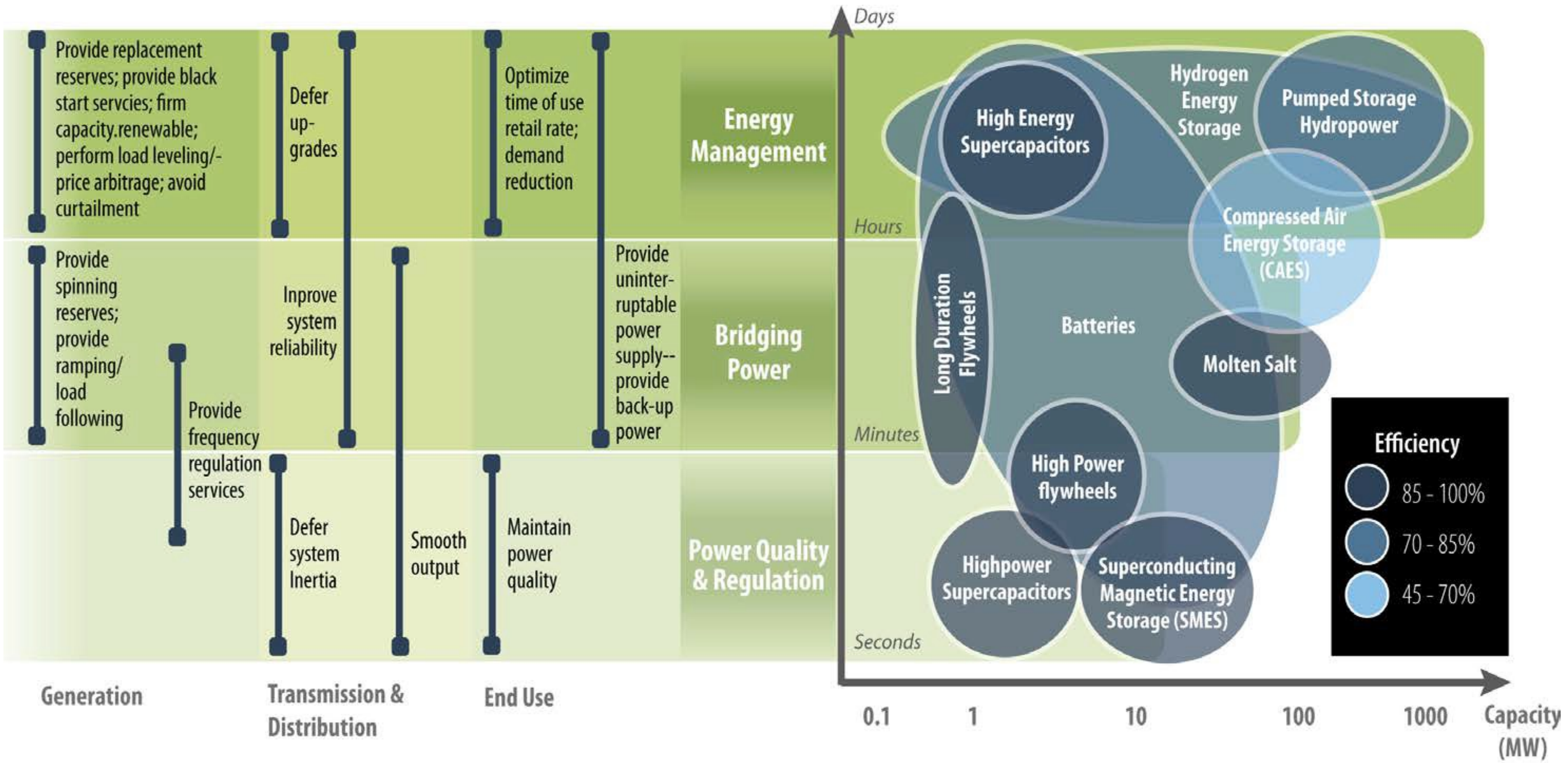
Seconds-to-minutes and minutes-to-hours: *Storage helps follow the variation in net load.*

Hourly: *Storage smooths the load to avoid activating more generation.*

Daily/weekly/seasonally: *Storage reduces the peak/off peak range during periods of peak demand.*

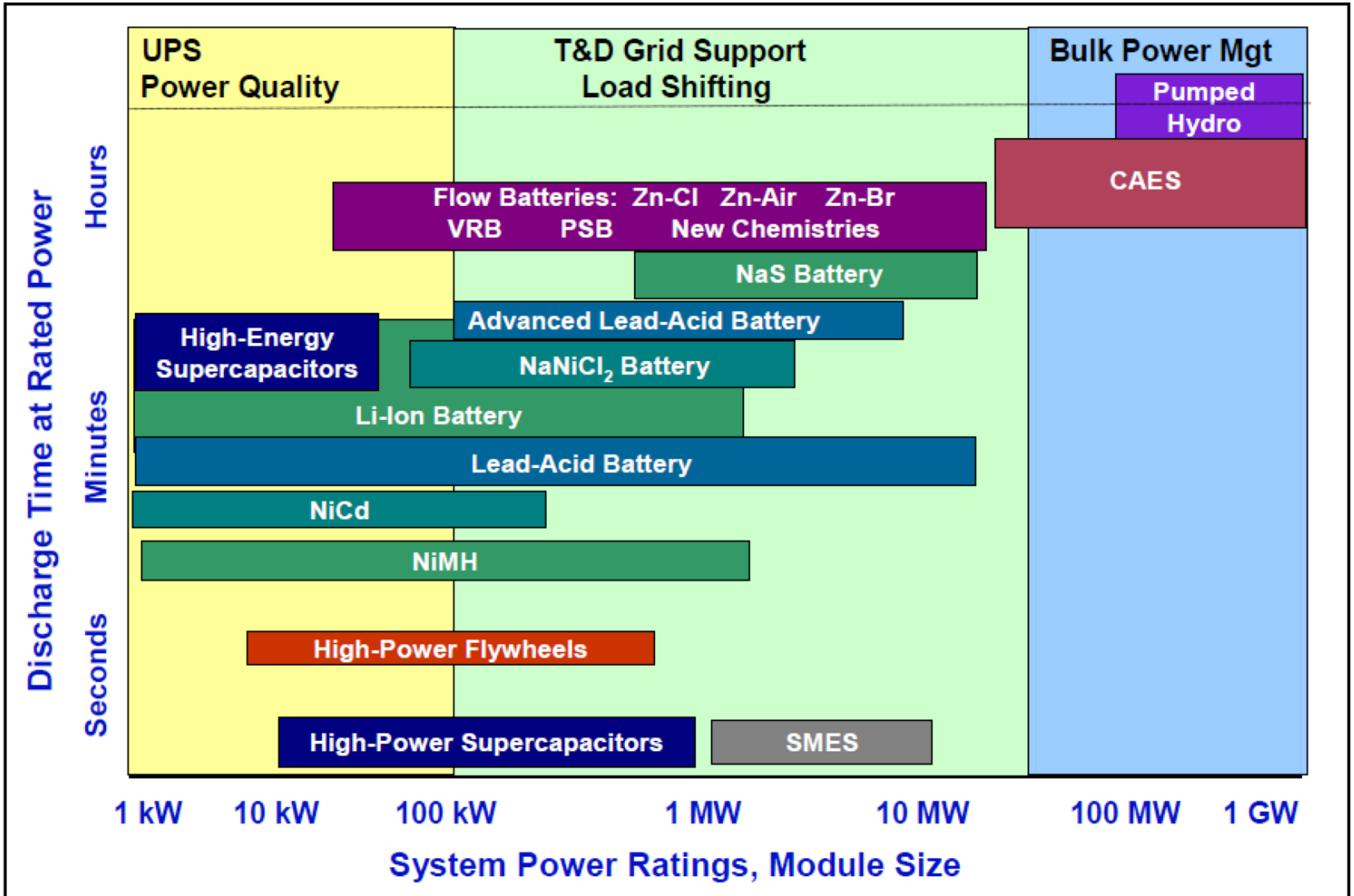
Storage can work at all timescales to smooth peaks and valleys in the demand curve

Energy Storage for Different Timescales



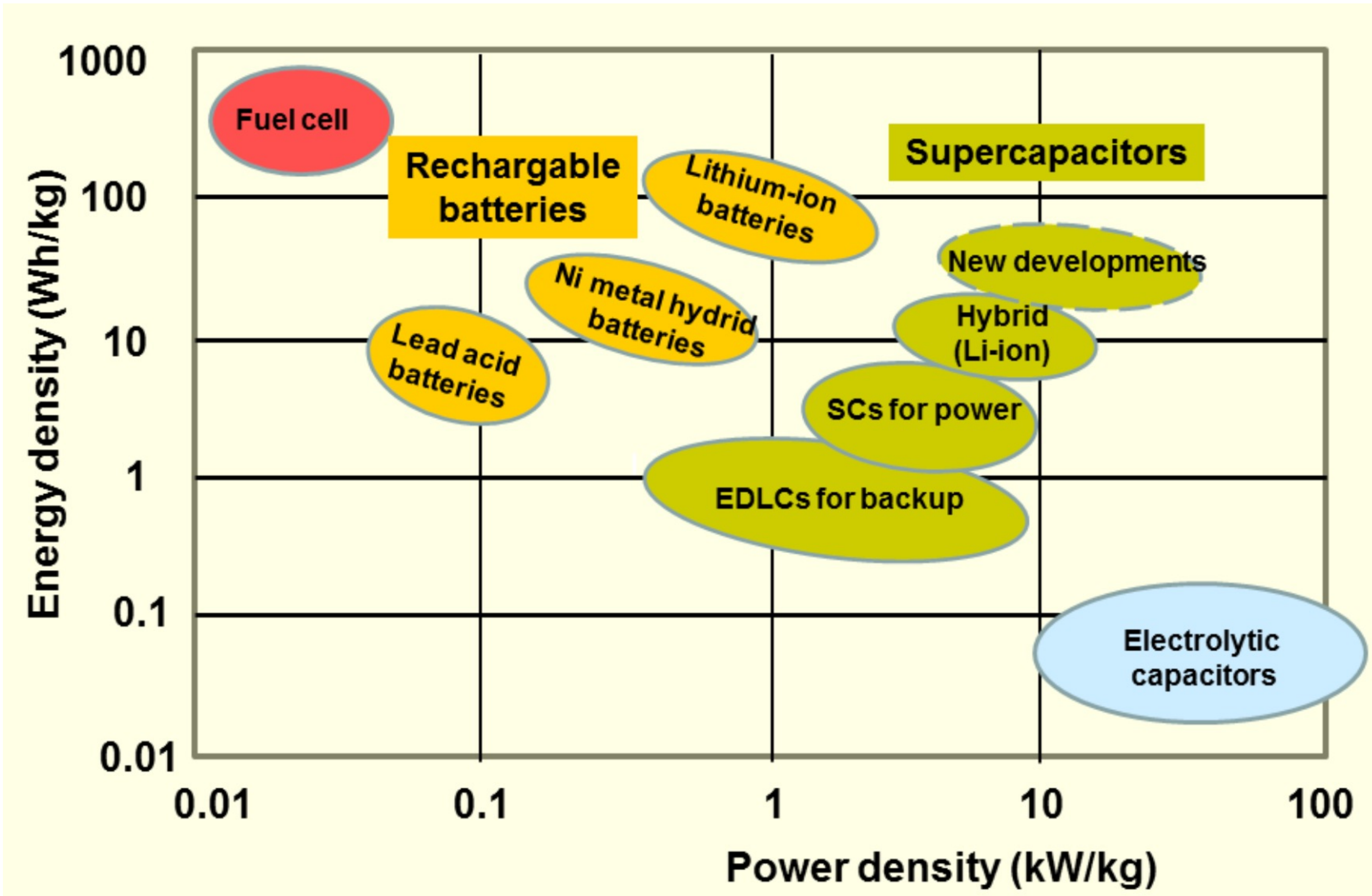
No single storage technology is likely to meet all applications

Discharge Time vs Power Ratings



Source: Akhil et al. 2013

Energy vs Power Density



The difference comes from batteries being able to store more energy, but capacitors can give off energy more quickly.

Life Cycle Cost