T.C. BAŞBAKANLIK

AVRUPA BİRLİĞİ GENEL SEKRETERLİĞİ

INNOVATIVE EUROPEAN STUDIES on RENEWABLE ENERGY SYSTEMS

Energy Storage Systems and Power System Stability

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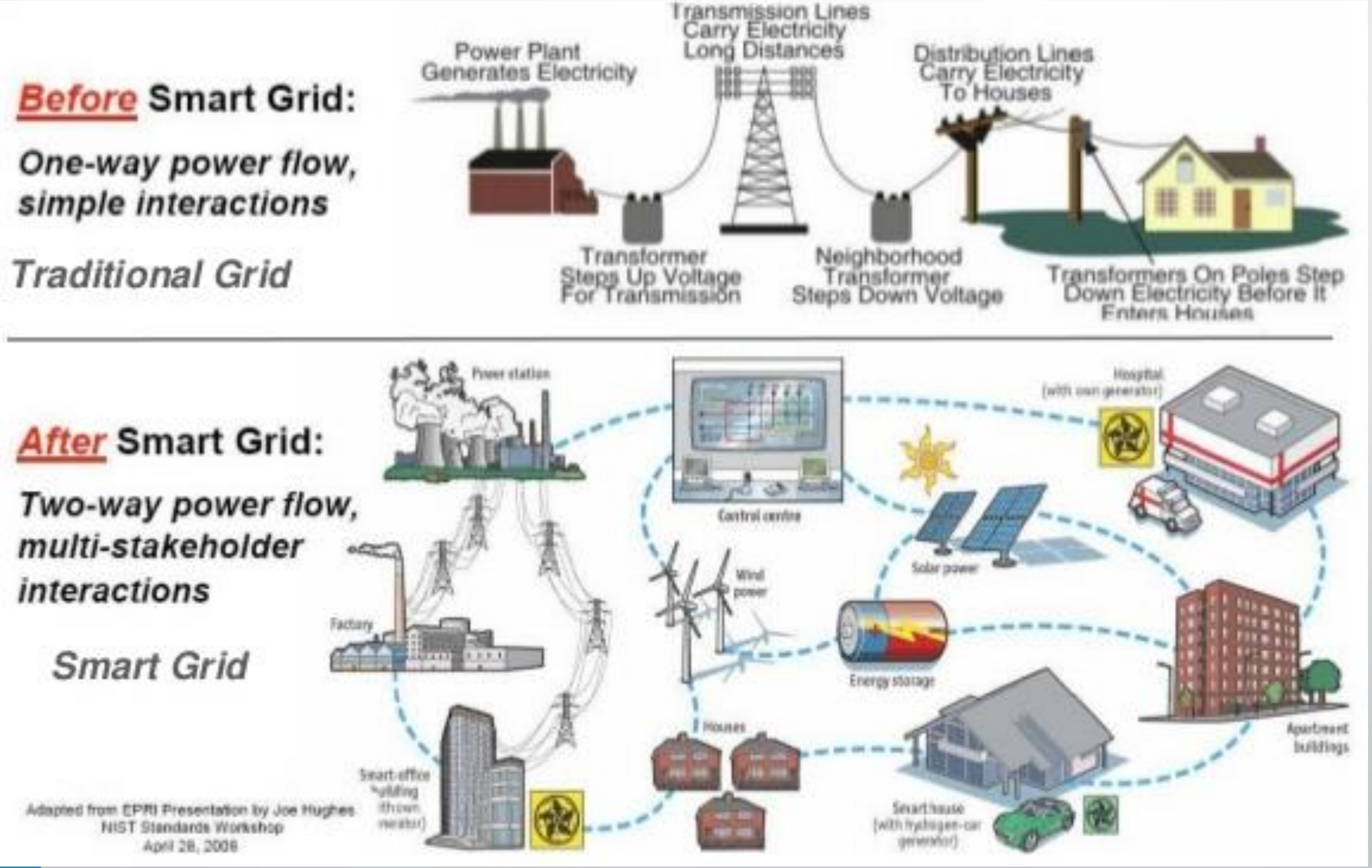
GAZİ UNIVERSITY

Outline

- Impacts of The Renewable Energy Penetration
- Energy Storage Technologies
  - Pumped Hydro Energy Storage
  - Compressed Air Energy Storage
  - Battery Energy Storage Systems
  - Flow Battery Energy Storage Systems
  - Hydrogen Based Energy Storage Systems
  - Flywheel Energy Storage Systems
  - Superconducting Magnetic Energy Storage Systems
  - Supercapacitor Energy Storage systems
- Improvements of Power System Stability

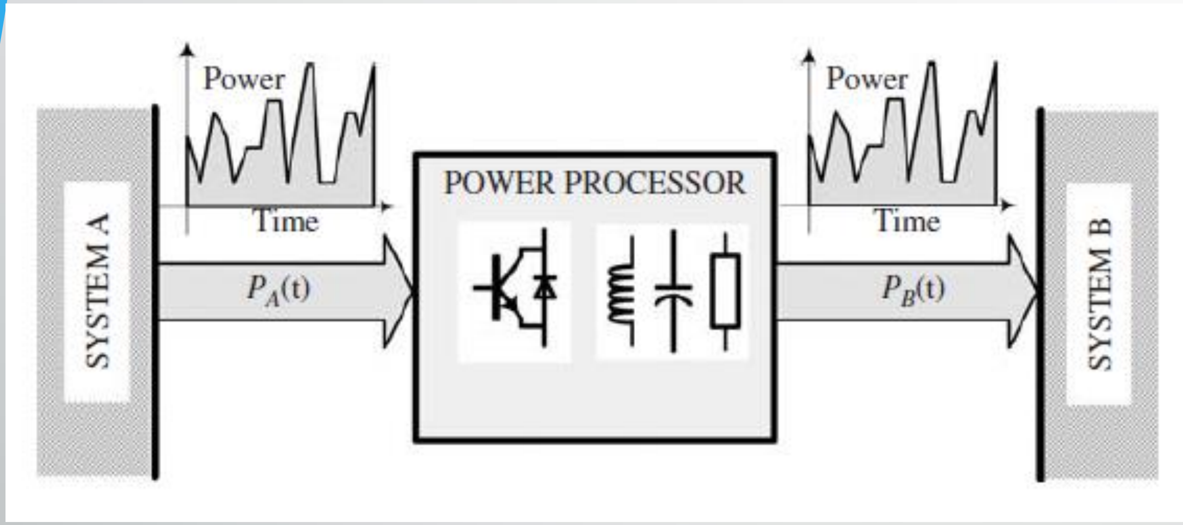
Control Systems

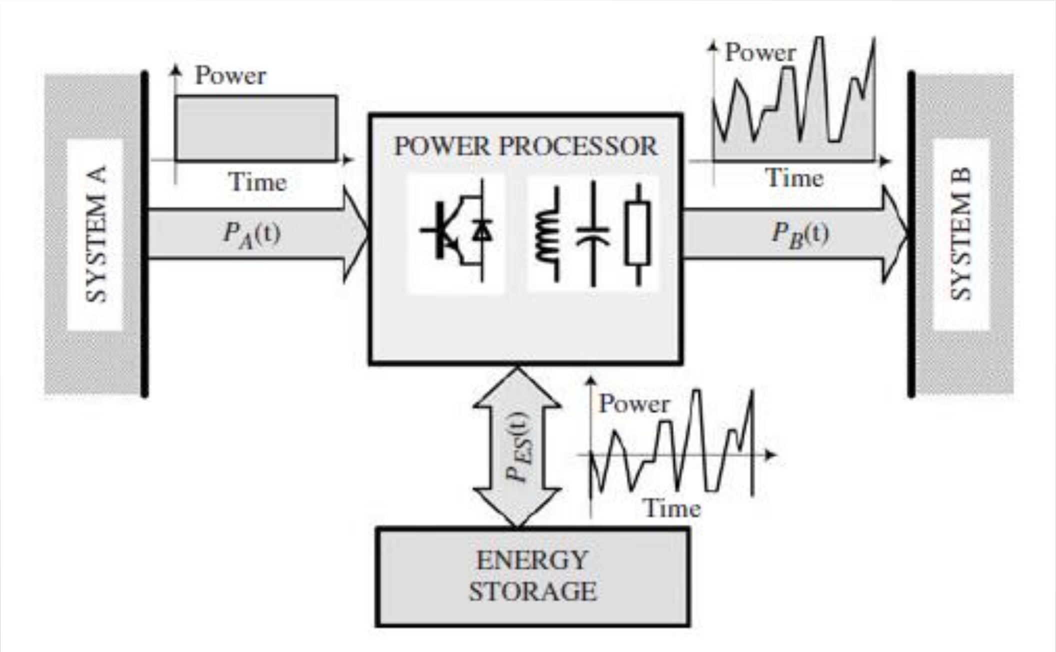
Evolution of The Power System



Impact of Renewable Energy Penetration

- Why are we talking about energy storage technologies?





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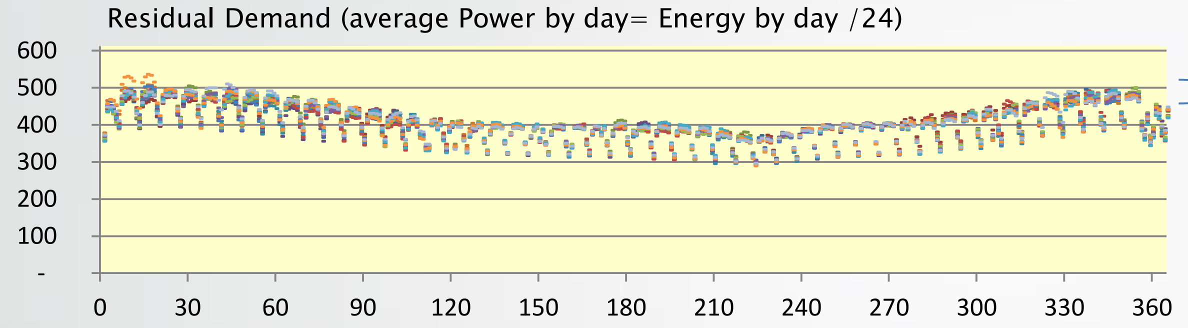
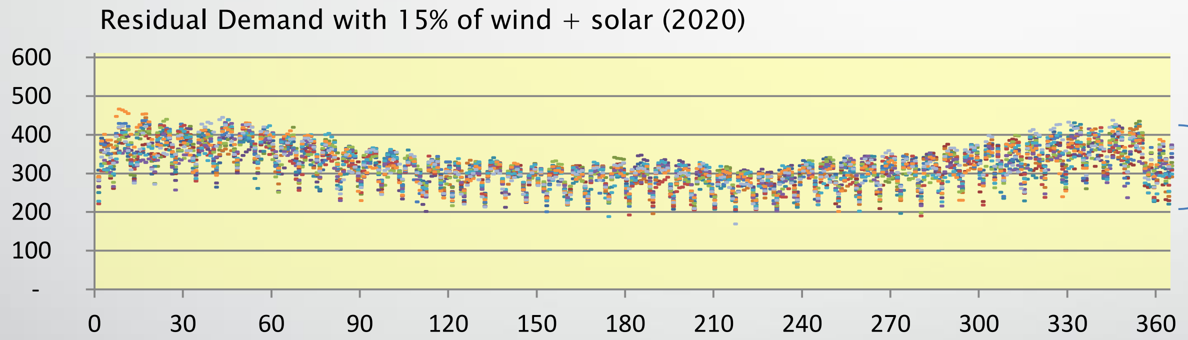


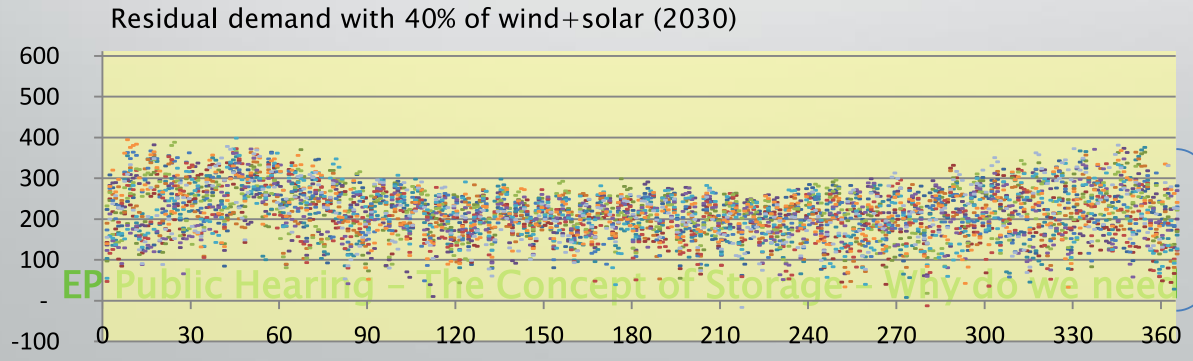
Average Variability
30 GW
10 / 70 GW

Average Load factor
5800 h



Average Variability
90 GW
30 / 150 GW

Average Load factor
5100 h



Average Variability
200 GW per day
100/300 GW

Average Load factor
3800 h

Source: EDF R&D, 25 September 2013

Impact of Renewable Energy Penetration

Countries	Installed capacity (GW) 2012*	% National mix 2012	2020 Objectives
Spain	28.9 22.5 + 0 + 6.3	22 %	29 %
Germany	63.9 31+ 0,3 + 32.6	12.4 %	26 %
UK	10.6 5.9 + 3 + 1.7	5.6 %	22 %
France	11.6 7.6 + 0 + 4.0	4.0 %	12 %
Italy	24.5 8.1 + 0 + 16.4	9.7 %	8 %
USA	67.7 60 + 0 + 7.7	3.7 %	6 %
China	83.6 75.3 + 0 + 8.3	2.5 %	6 %

Share of RES in Europe in 2012 and targets for 2020:

Turkey: 6.6% (present, without small hydro)

Turkey: 20% (target for 2020)

(GW)* On-shore Wind + off-shore Wind + Solar

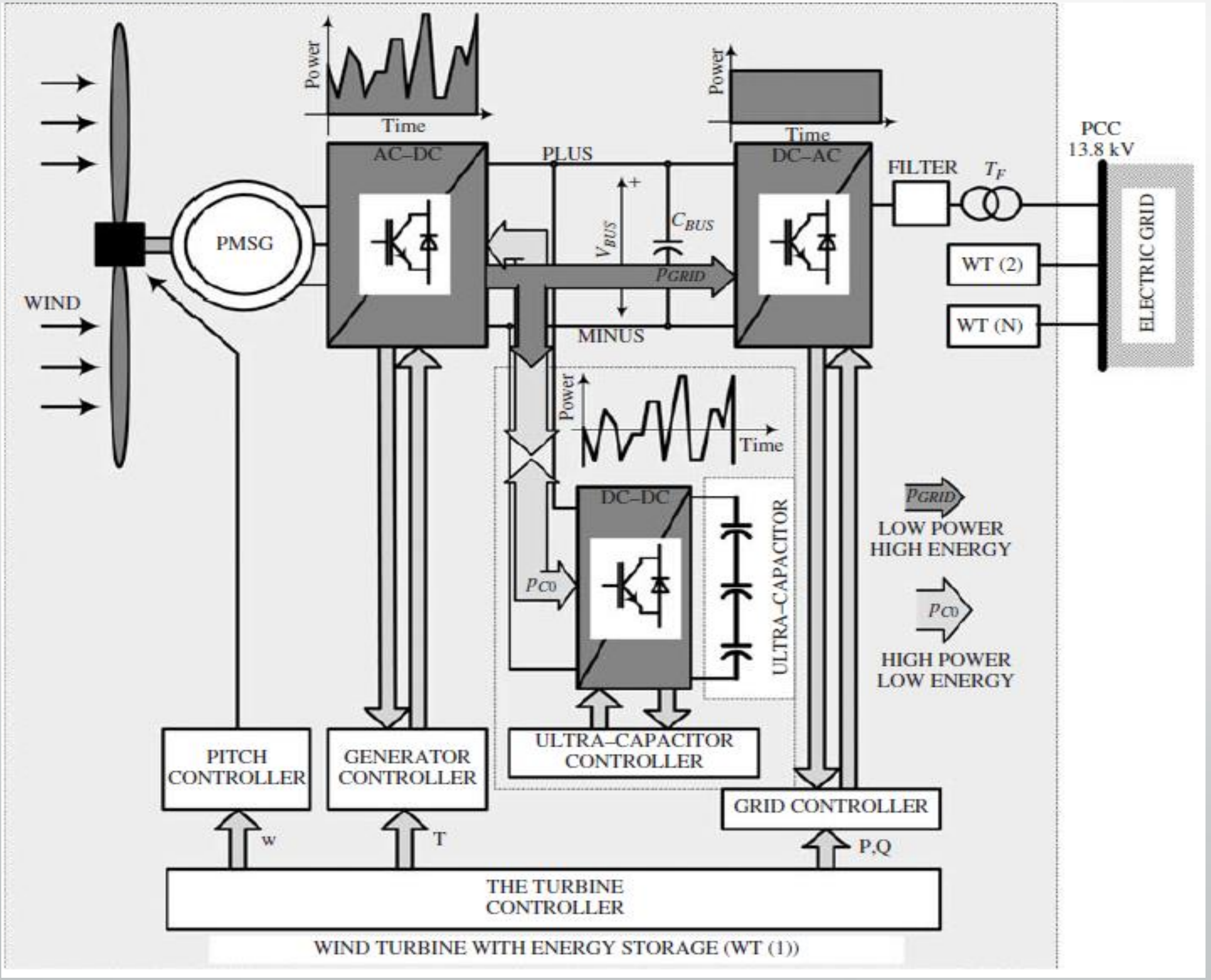
Sources :

EUROBSERVER, EREC, GWEC, IEA, REE, GOV.UK,

AGEE, RTE, RenewableEnergyWorld, Gov.cn

Impact of Renewable Energy Penetration

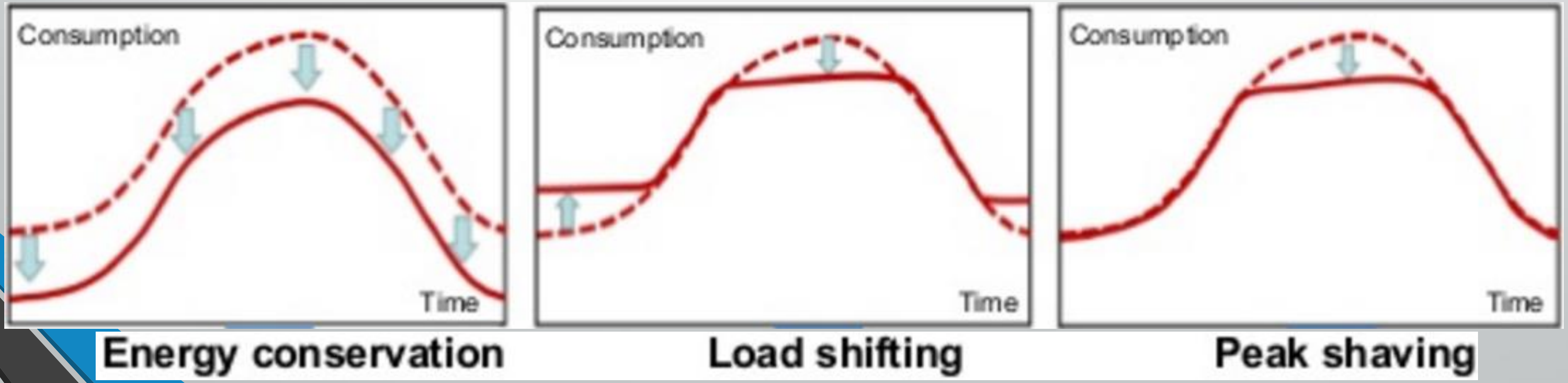
Initial solution:



New Challenges with The Smart Grid Concept

- Natural effects (passing cloud or wind speed variations) cause voltage and frequency fluctuations:
  - Active-Reactive power control is required → Requires Energy Storage System (ESS)
- Generation profile differs from load profile:
  - Load shifting is required → Requires Energy Storage System (ESS)
- Specific generation of a PV system is maximum at noon:
  - Power management is required → Requires Energy Storage System (ESS)

    (Peak shaving)



New Challenges with The Smart Grid Concept

•Largely interconnected network >> complex and less secure power system operation

•Power generation and transmission facilities - unable to meet these new demands

•Recent developments and advances in energy storage and power electronics technologies make them important.

• Large-scale implementation of energy storage is considered to be the key for enabling higher penetration (>20%) of renewable and variable generation sources, such as wind and solar.

• Energy storage is also expected to contribute to more efficient and reliable grid operation, as well as to reduced emissions.

Microgrids

- Stability issues are more prevalent in microgrids than in a large electric grid because power and energy ratings are much lower.
- Analysis of stability issues in AC microgrids follow the same concepts than in the main grid:
  - Voltage and frequency values need both to be regulated through active and reactive power control.
  - If sources are traditional generators with an AC output and are connected directly without power electronic interfaces, stability is controlled through the machine shaft's torque and speed control.
- In DC systems there is no reactive power interactions, which seems to suggest that there are no stability issues. System control seems to be oriented to voltage regulation only.

Installed Energy Storage Applications

- System storage (e.g., pumped-storage plants, CAES, large-scale battery storage
  - Currently 22 GW of pumped-storage in the U.S.

- Renewable energy support (e.g., energy storage combined with wind plant, etc.)

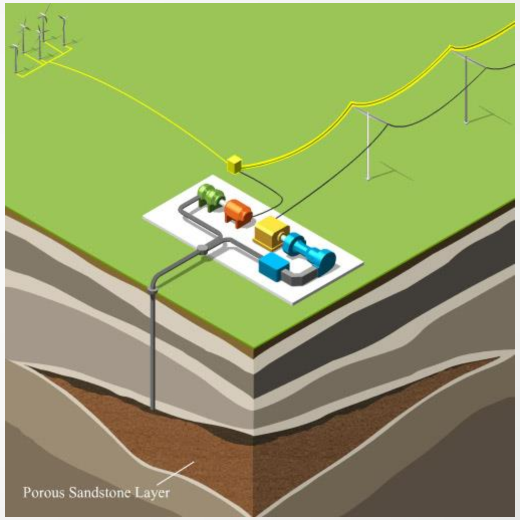
- Distributed energy storage (demand-side storage, customer installations, PHEV & EV batteries, etc.)

Requirements for Energy Storage

- Energy density
- High power output
- Cycle efficiency
- Cycling capability
- Operating lifetime
- Capital cost

Energy Storage Technologies

- Pumped Hydro Energy Storage Systems
- Flywheel Energy Storage Systems
- Compressed Air Energy Storage Systems
- Lead-acid (L/A) batteries
  - Flooded L/A batteries
  - Valve-regulated lead-acid (VRLA) batteries
- Sodium-sulfur (NaS) batteries
- Nickel cadmium (Ni/Cd) batteries
- Lithium-ion (Li-ion) batteries
- Flow Batteries
  - Sodium bromide sodium polysulfide
  - Zinc bromine (Zn/Br)
  - Vanadium-redox (V-redox)
- Hydrogen Based Energy Storage Systems
- Superconducting Magnetic Energy Storage (SMES) Systems
- Supercapacitors



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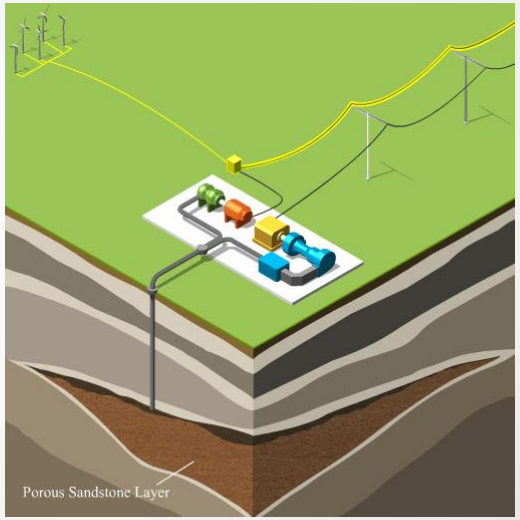
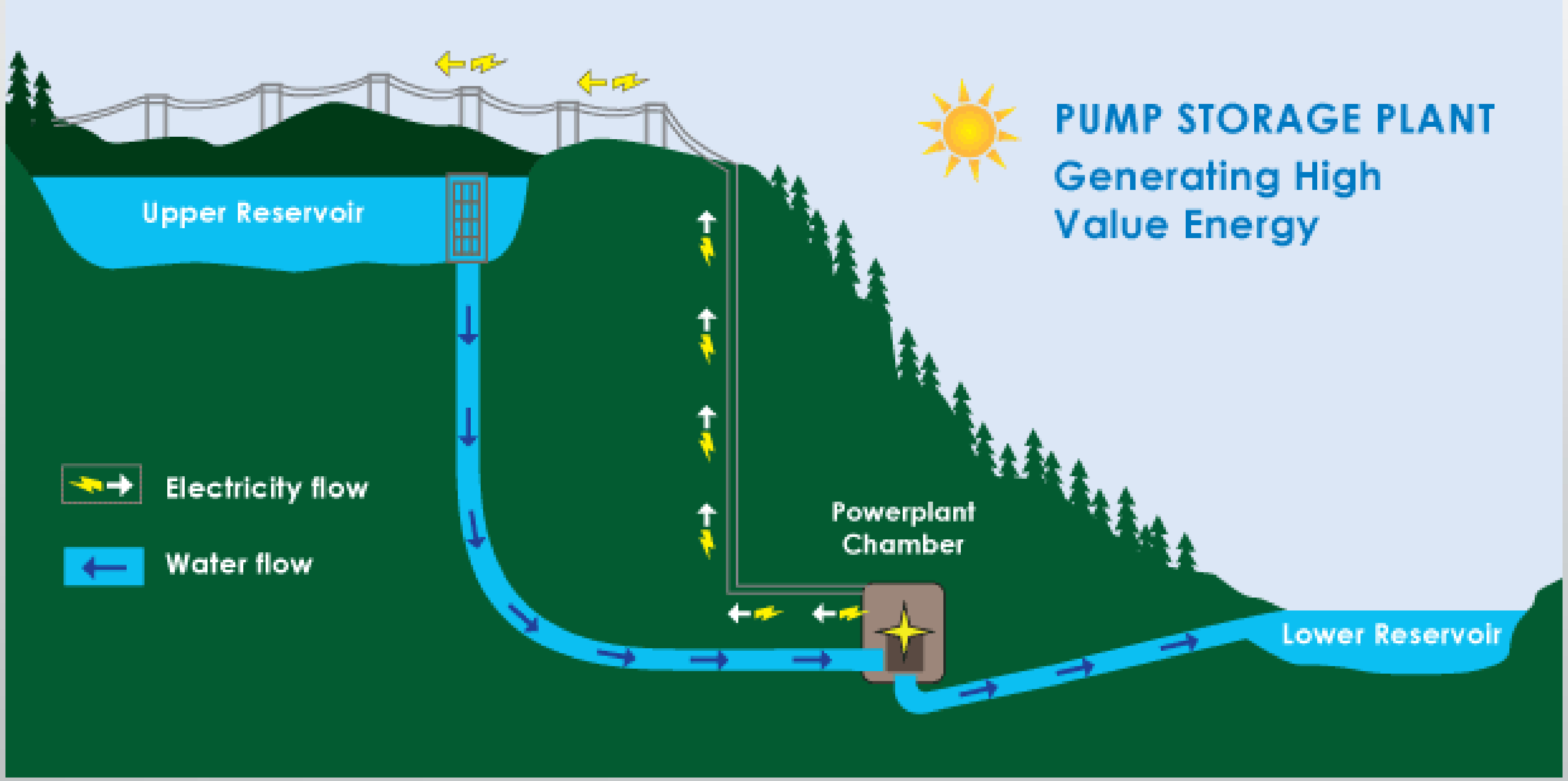


Pumped Hydro Energy Storage Systems

- Its operating principle is based on gravitational potential energy of water.
- It is a large scale energy storage system.
- Power demand is low → Water is pumped to upper reservoir.
- Power demand is high → Water flows down form upper reservoir to lower one.



Source:http://www.upsbatterycenter.com/

Pumped Hydro Energy Storage Systems

- Energy capacity is related with stored water volume (capacity of reservoir).
- Can operate for several days.
- Commonly used in high power applications.
- Fast response time (< 1 min.)
- Round trip efficiency is 65-75%.
- Investment cost is 500-1500 €/kW and 10-20 €/kWh.

Source: www.powermag.com

Pumped Hydro Energy Storage Systems

- Run-of-river hydro storage is key research area.
- Limited by location!

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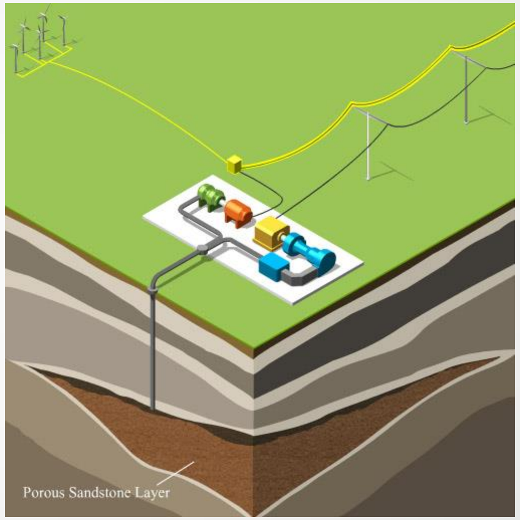
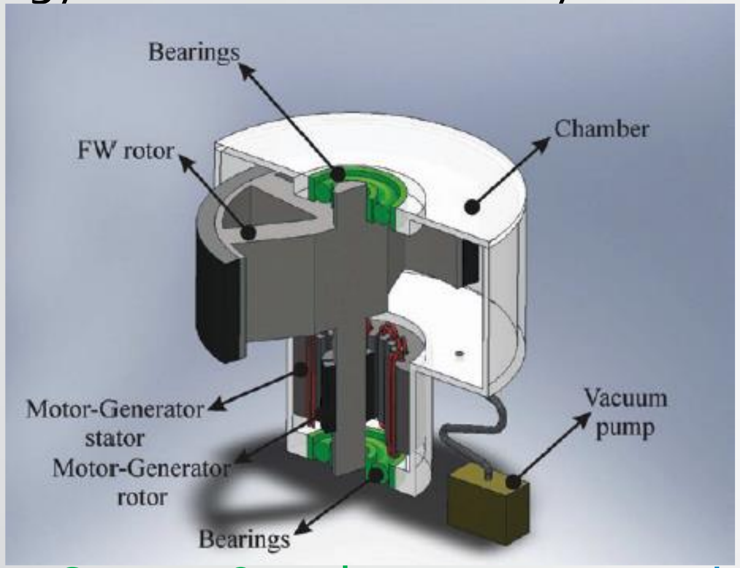
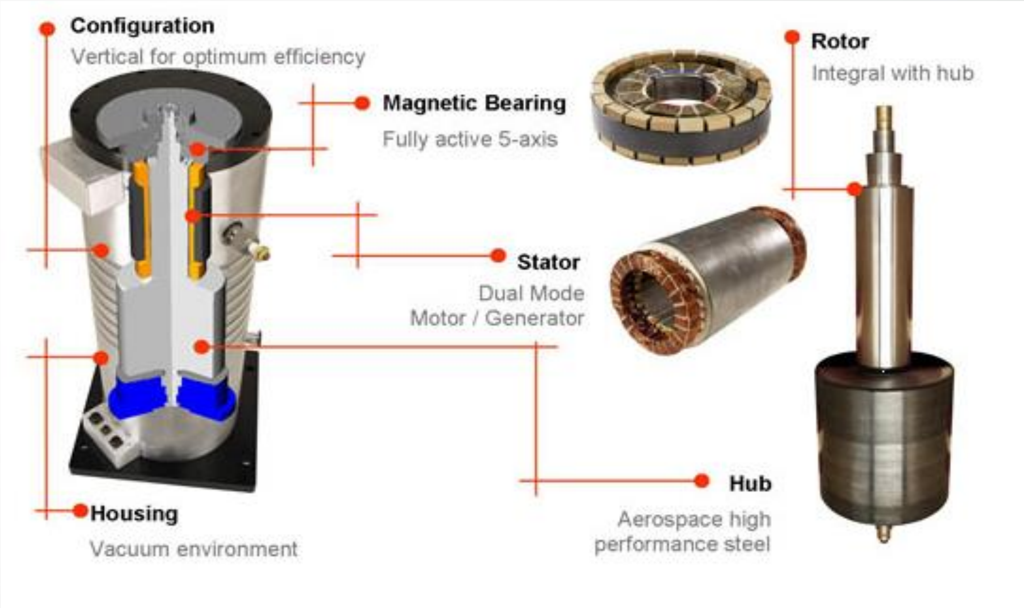


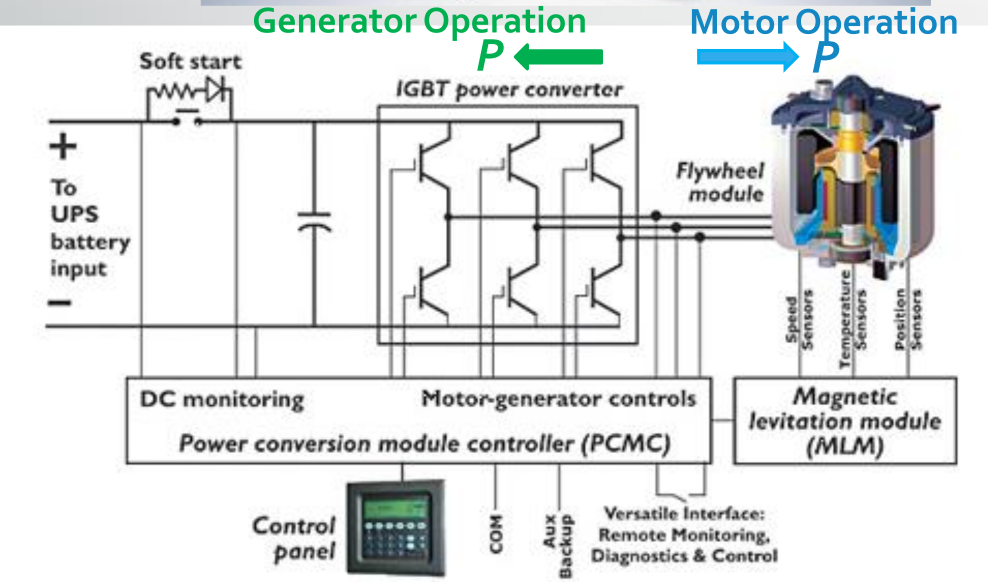
Flywheels Energy Storage Systems

- Energy is stored mechanically (in a rotating disc)

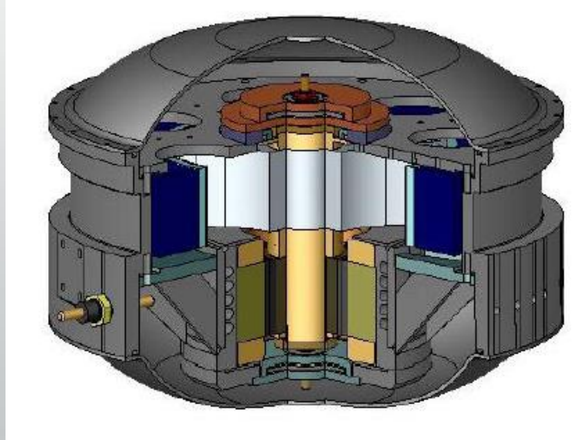




http://www.vyconenergy.com



http://www.pentadyne.com



Flywheels Energy Systems

Flywheel Energy Storage Systems

- Stored energy depends on the moment of inertia of the rotor and the square of the rotational velocity of the flywheel.
- Produce 100-2000 kW for 5-50 seconds.
- High efficiency (~90%)
- Long cycle life,
- Freedom from depth of discharge,
- High power and energy densities,
- Wide operating temperatures,
- High self discharge rate (20% per hour),
- Not suitable for long term energy storage applications
- Best for high-power, low energy applications.
- Key research areas:
  - Materials development
  - Cost reduction
  - Improved manufacture techniques

Flywheels can help with grid angular stability and voltage support.

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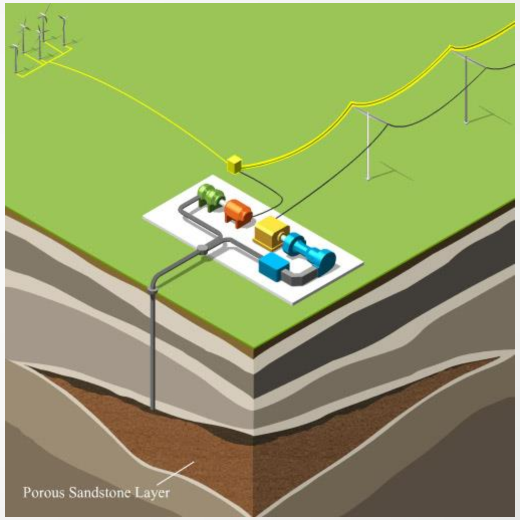
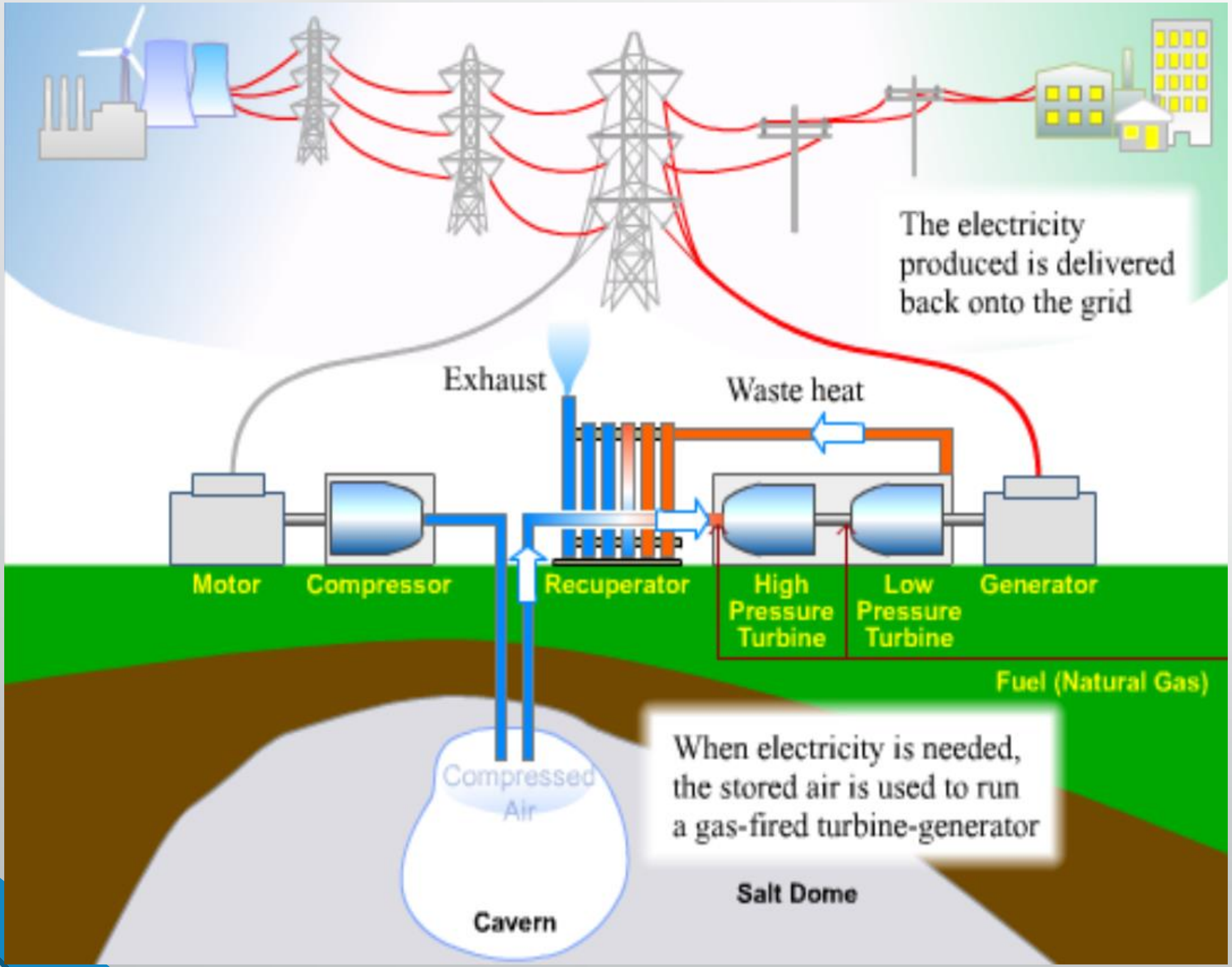


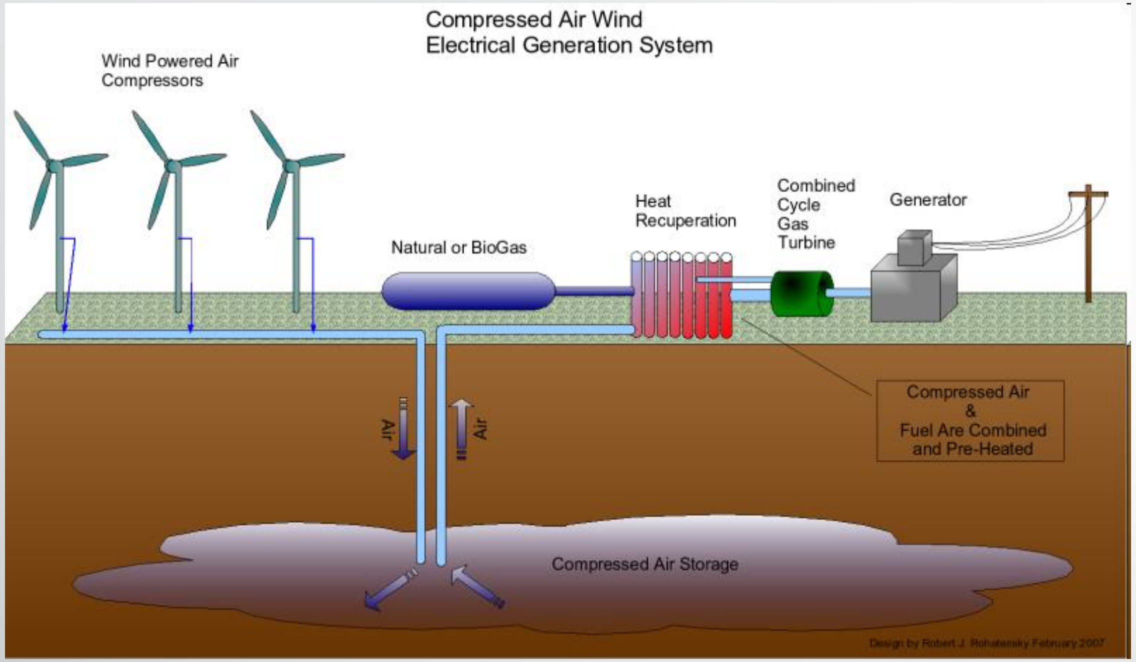
Compressed Air Energy Storage Systems (CAES)



Source: http://www.oenergetice.cz

- Usually combined with gas turbines.
- Air is stored in cavern at low demand times and used through high and low pressure turbines and converted to kinetic energy at high demand times.

Compressed Air Energy Storage Systems (CAES)



Source: http://www.shpegs.org/cawegs.html

- CAES has been operating for over 20 years:
  - Huntorf, Germany: 290 MW (1978)
  - McIntosh, Alabama: 110 MW (1991)
  - Iowa Stored Energy Park: 2700 MW (2011) (conjunction with large wind farm)
- But not so common!

Compressed Air Energy Storage Systems (CAES)

- Heat exchangers are key components.
- Enables wind to supply quick, reliable energy.
- Large storage: smoothens daily variability
- Ramps quickly: smoothens hourly variability
- Efficiency is about 70%.
- More cost-effective than batteries at GWh scale
- Low self-discharge rate,
- So, suitable for long term storage applications.
- Suitable locations are required.

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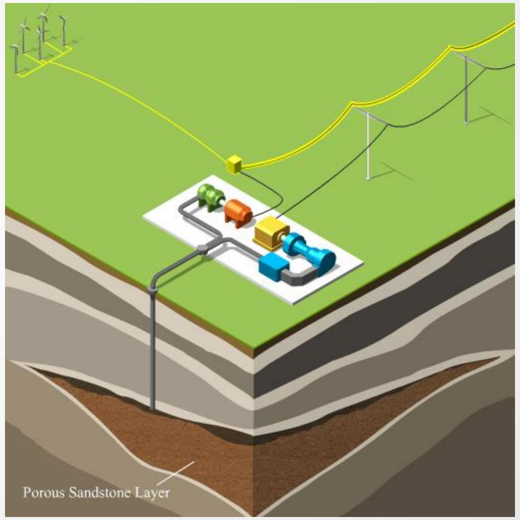
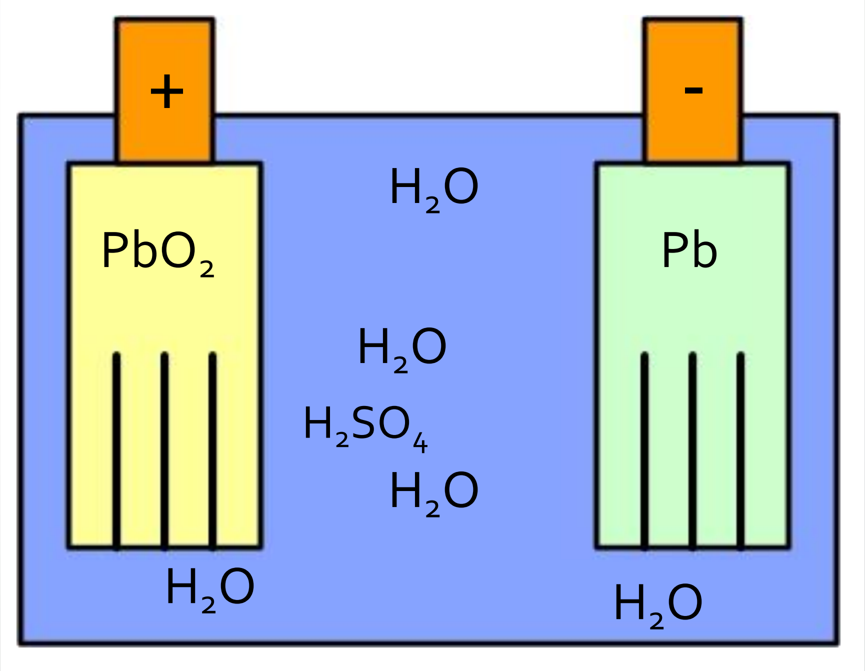


Lead-Acid Batteries

- Mature technology (invented in 1859)
- Low cost,
- Energy efficiency is about 80%.
- Two mayor types (flooded batteries and VRLA batteries)
- Cell voltage is about 2 V, therefore, series and parallel connection is used.

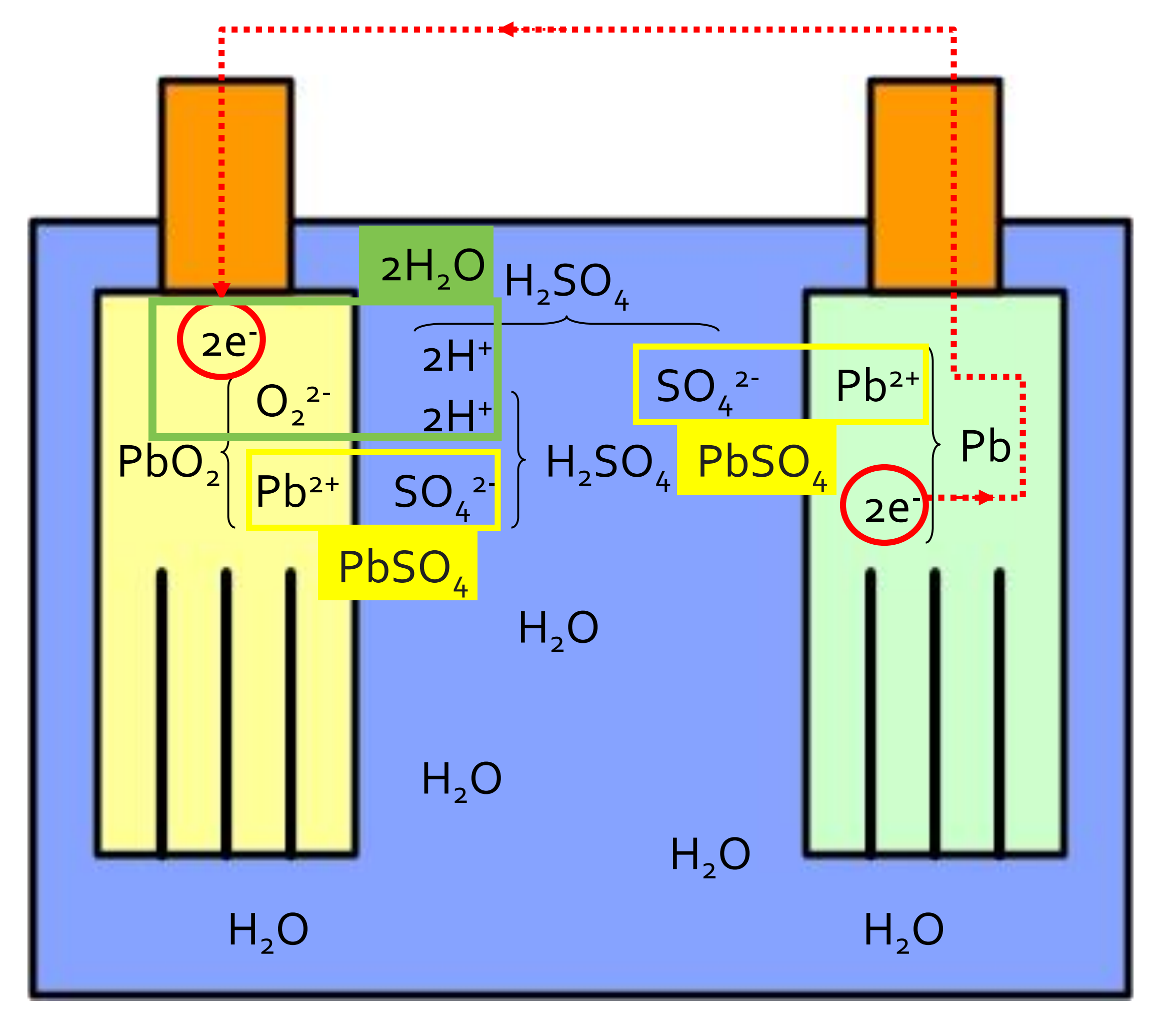


- Positive electrode: Lead dioxide (PbO_2)
- Negative electrode: Lead (Pb)
- Electrolyte: Solution of sulfuric acid (H_2SO_4) and water (H_2O)

Lead-Acid Batteries

- Electrode plates sulfatation affects battery life.
- To avoid accelerating the sulfatation process,
  - batteries need to be fully charged after every discharge
  - they must be kept charged at a float voltage higher than the nominal voltage. (float voltage is between 2.08 V/Cell and 2.27 V/cell).
  - they should not be discharged below 1.75 V/cell.

Chemical reaction (discharge)



Lead-Acid Batteries

- Cycle life is about 1200-1800 cycles and highly depending on depth of discharge and operating temperature.
- Battery temperature exceeding 77°F (25°C) will decrease expected life by approximately 50% for each 18°F (10°C) increase in average temperature. [Tyco Electronics IR125 Product Manual]

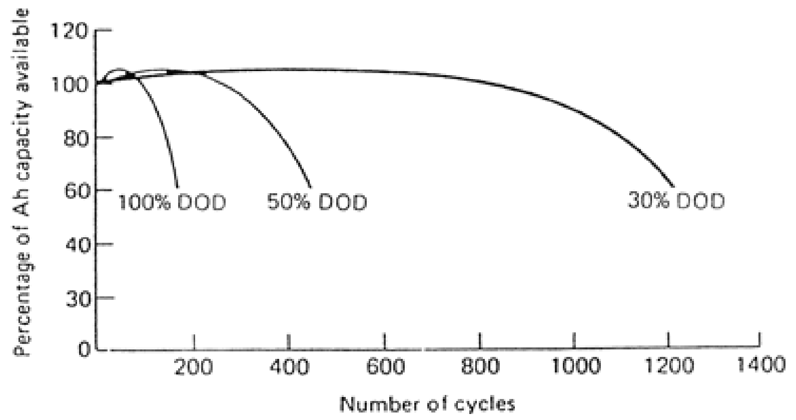
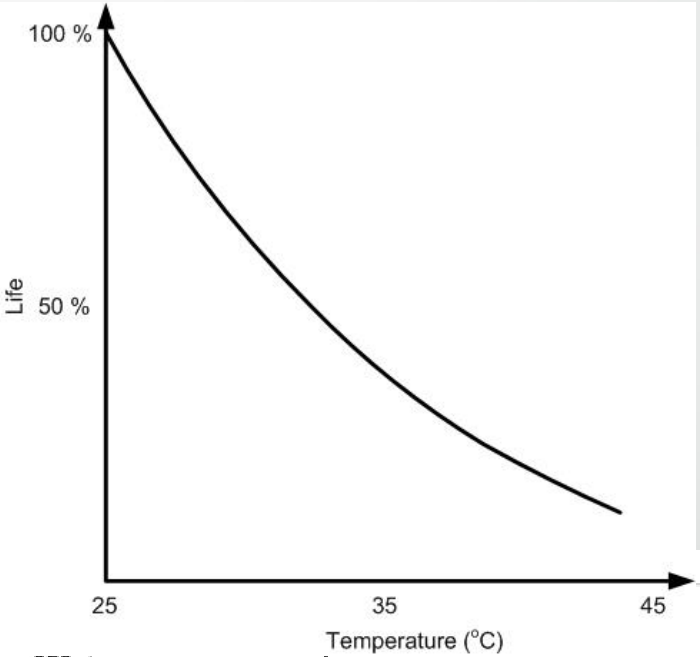
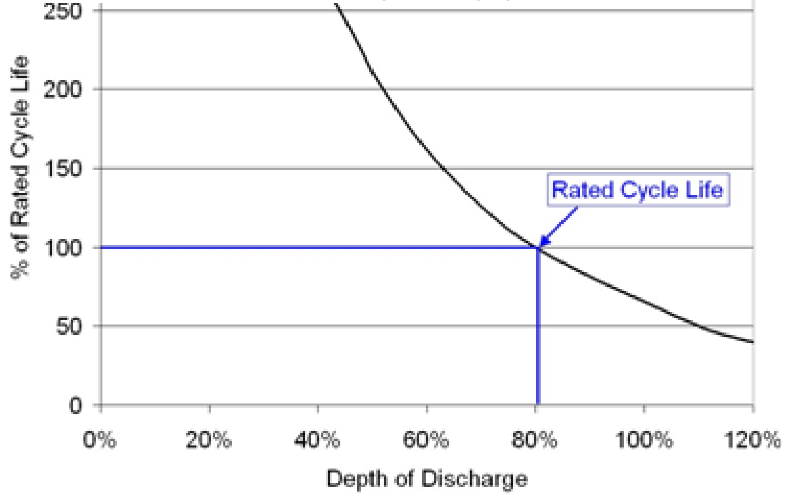


Figure 2-53 Cycle Service Life of a Gel Cell Lead-Acid Battery in Relation to Depth of Discharge (20°C)

Linden, Handbook of Batteries





Lead-Acid Batteries

- Low self-discharge rate (<0.1%, therefore, suitable technology for storing energy for long periods).
- Specific energy and specific power density values are low (30Wh/kg and 180 W/kg).
- Lead carbon electrodes are used to improve the energy and power densities.
- Low charge current.

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- Flywheel Energy Storage Systems
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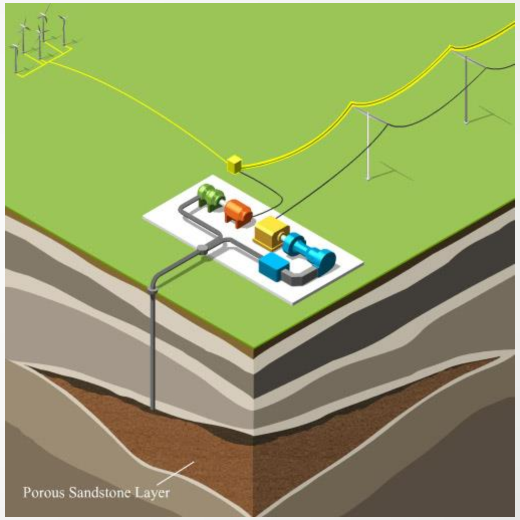
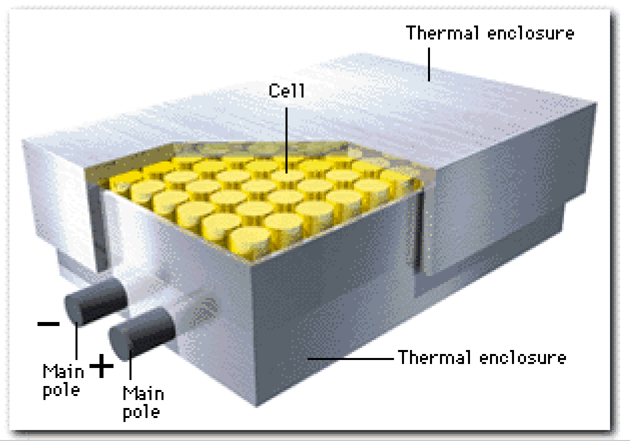


Sodium-Sulfur (NaS) Batteries

- Relatively recent technology,
- Most promising options for high power energy storage,
- High operation temperature (~350 °C)
- Relatively high energy density (151 kWh/m^3)
- High efficiency (85%),
- Relatively high cycle life (4000-5000)
- No self-discharge,
- Low maintenance,
- Highly recyclable



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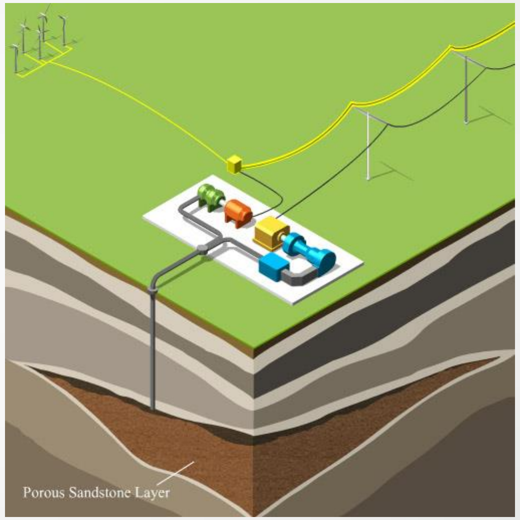
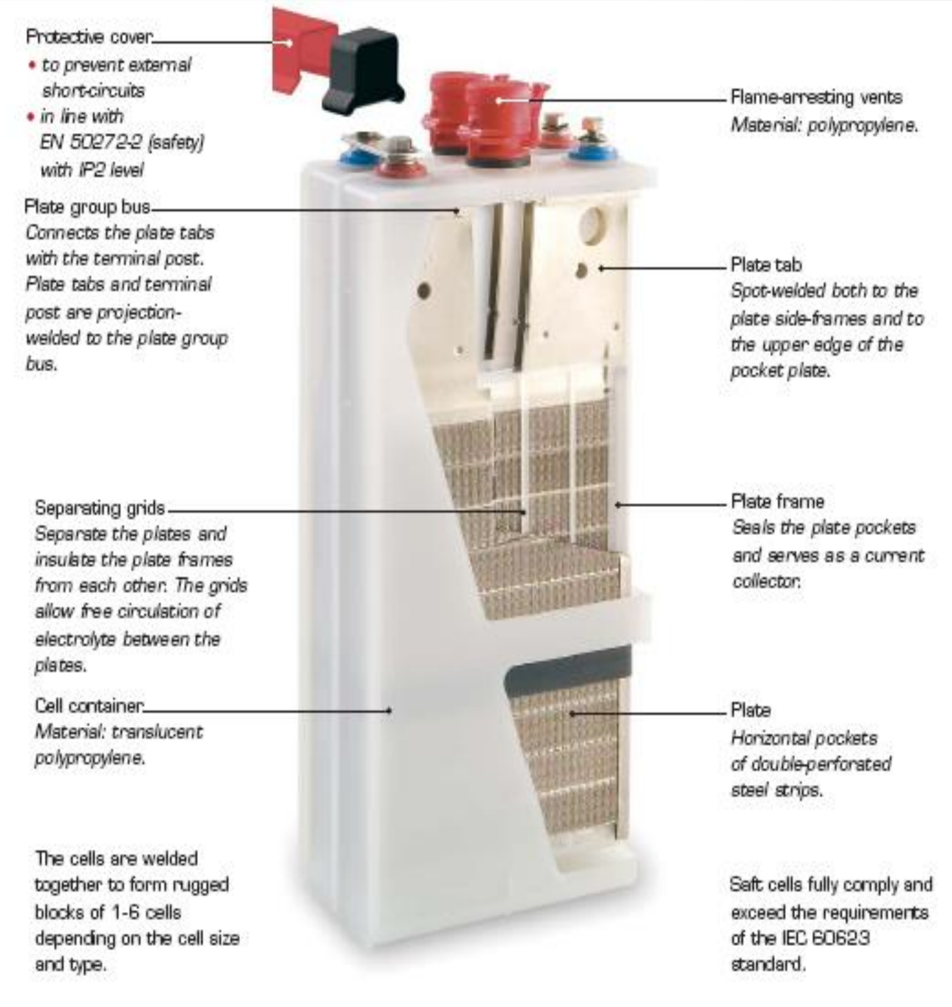


Nickel Cadmium (Ni/Cd) Batteries

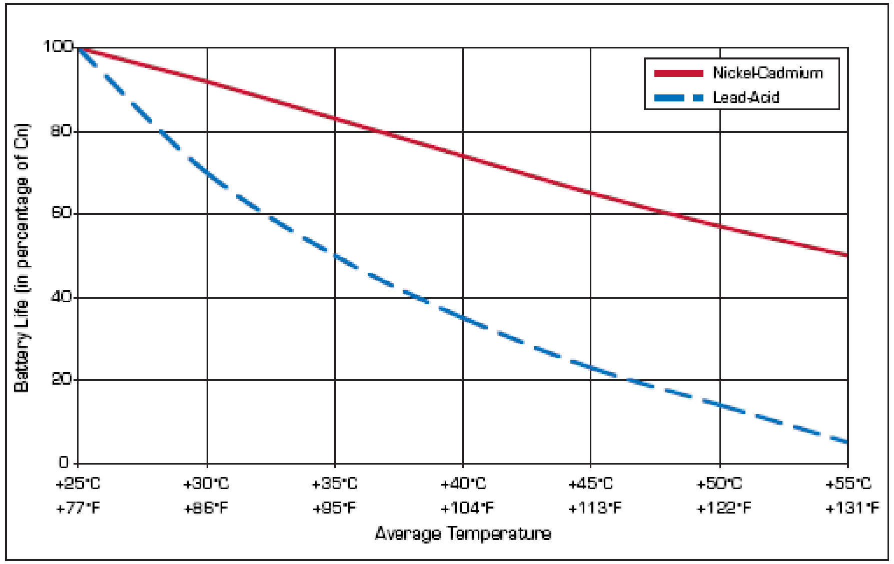
- Negative electrode: Cadmium (Cd)
- Positive electrode: nickel oxyhydroxide (NiO(OH))
- Electrolyte: Potassium hydroxide (KOH) solution
- Float voltage is about 1.4 V,
- Nominal voltage 1.2 V,
- Minimum voltage is about 1 V,
- Two forms (sealed form for portable applications and flooded form for general industrial applications),



Nickel Cadmium (Ni/Cd) Batteries

- Better performance at high temperatures
- Relatively high cycle life (3500), but it is highly dependent on depth of discharge (DoD) (50.000 cycles for 10% DoD)
- Low maintenance,
- High cost (about 10X lead-acid),
- Memory effect,
- Cadmium and nickel are highly toxic.

Figure 22: Battery life at elevated temperatures



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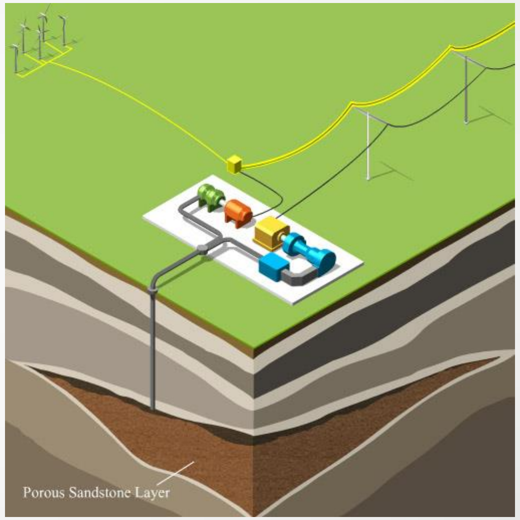
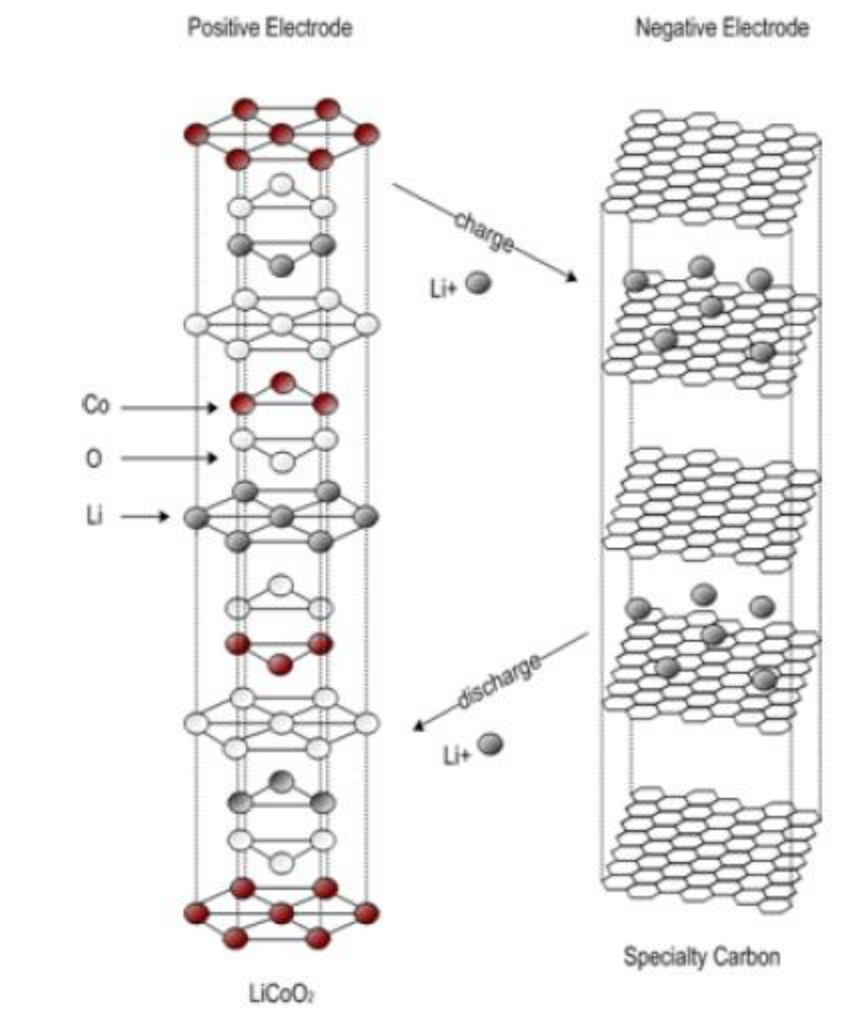


Lithium-Ion (Li-ion) Batteries

- Positive electrode: Lithiated form of a transition metal oxide (lithium cobalt oxide-$LiCoO_2$ or lithium manganese oxide $LiMn_2O_4$)

- Negative electrode: Carbon (C),
  usually graphite (C_6)

- Electrolyte: solid lithium-salt electrolytes
  ($LiPF_6$, $LiBF_4$, or $LiClO_4$)
  and organic solvents (ether)

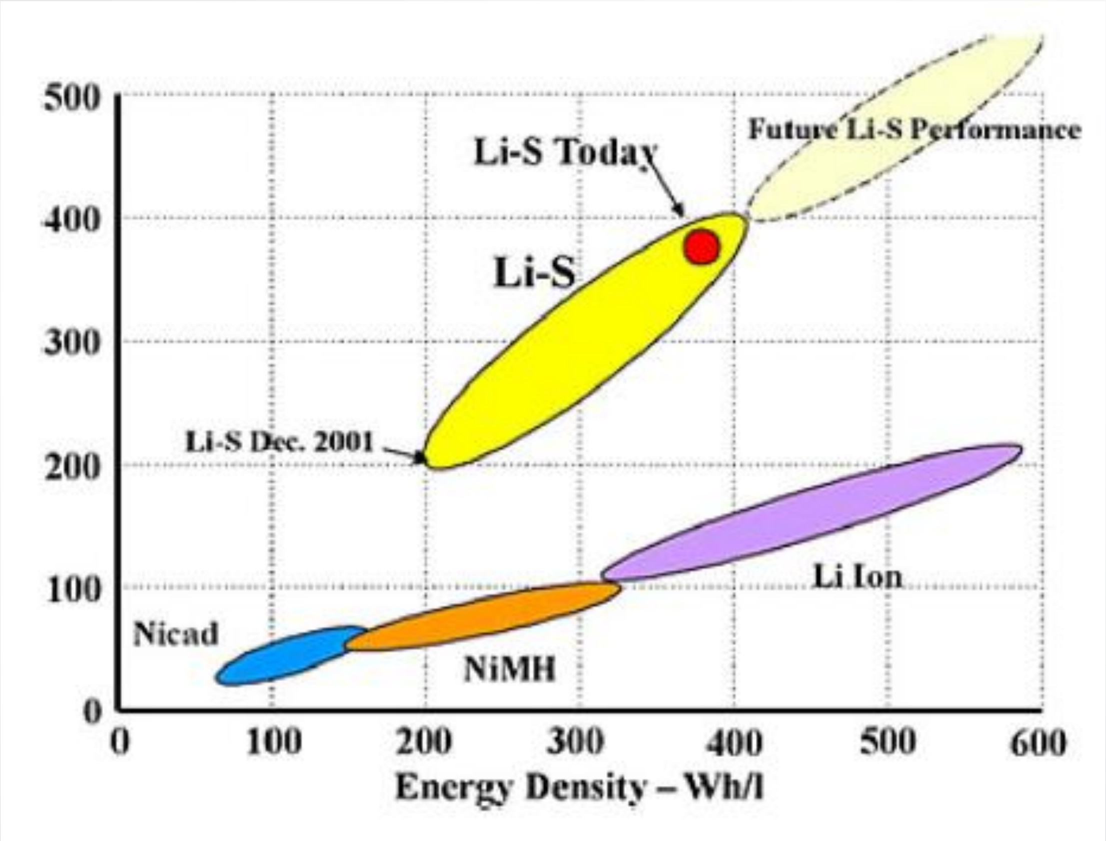


http://www.fer.hr/_download/repository/Li-ION.pdf

Lithium-Ion (Li-ion) Batteries

- Less sensitive to high temperatures (specially with solid electrolytes)
- Lighter (compare Li and C with Pb)
- High efficiency (80%)
- High cost,
- High energy and high specific energy density (170-300 Wh/l and 75-125 Wh/kg),
- Fast charge and discharge capability,
- High cycle life (3500 cycles) but it depends on DoD (not useful for back-up applications)
- High daily self-discharge rate (1-5%),
- Maintaining safe voltage and temperature is required (fragile).

Lithium-Ion (Li-ion) Batteries



Future prospects

Comparison of Battery Technologies

	Lead-Acid	Ni-Cd	Ni-MH	Li-ion
Cell voltage (V)	2	1.2	1.2	3.6
Specific energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific power (W/kg)	< 300	150 – 300	< 200	100 – 1000
Energy density (kWh/m^3)	25-60	25	70-100	80-200
Power density (MW/m^3)	< 0.6	0.125	1.5 – 4	0.4 – 2
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	> 1 min	1 min-8 hr	> 1 min	10 s-1 h
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75 - 90	75	81	99

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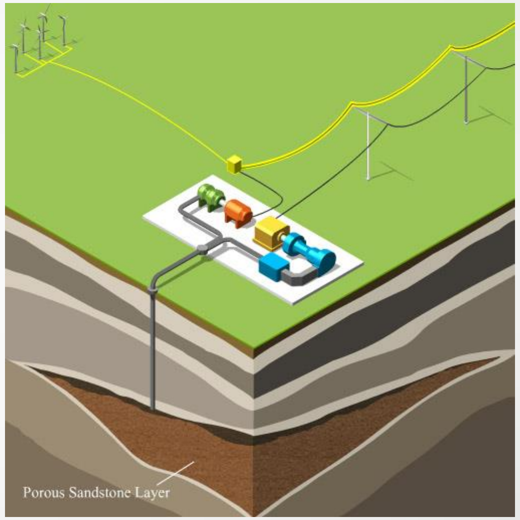
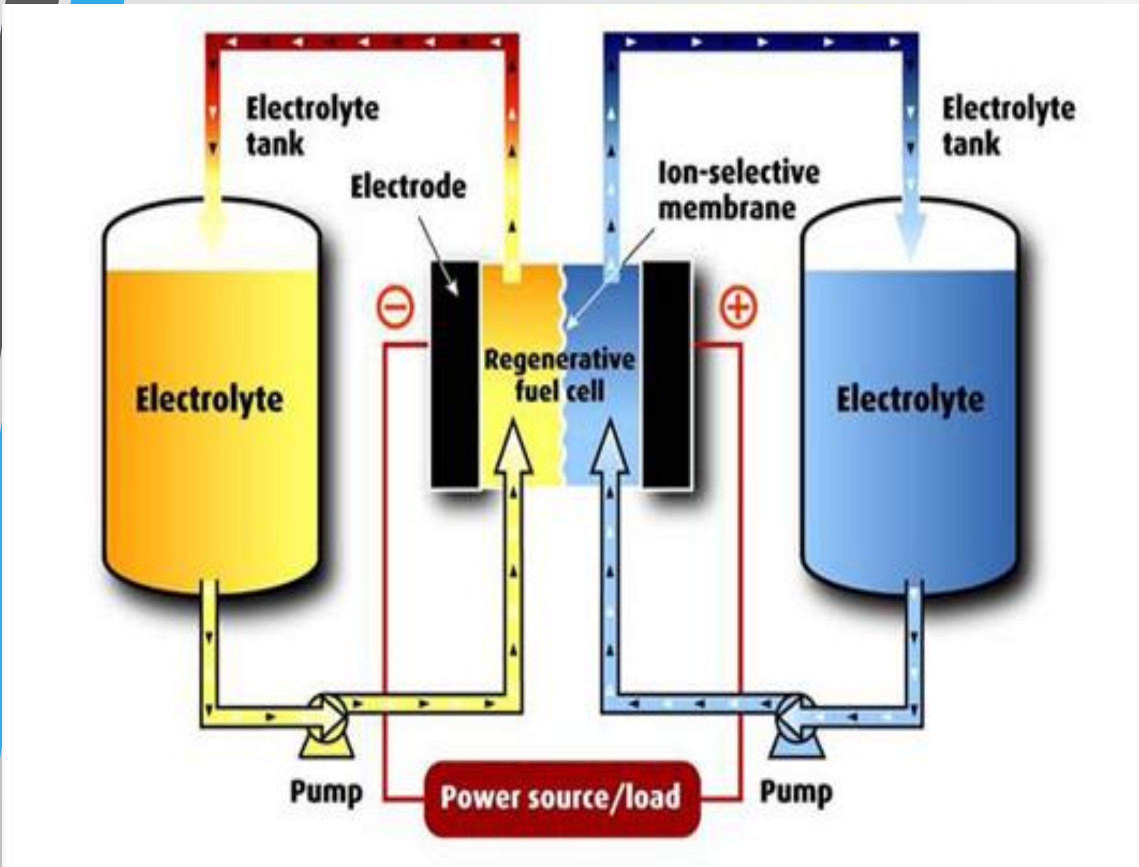
- Lithium-ion (Li-ion) batteries
- **Flow Batteries**
  - Sodium bromide sodium polysulfide
  - Zinc bromine (Zn/Br)
  - Vanadium-redox (V-redox)
- Hydrogen Based Energy Storage Systems
- Superconducting Magnetic Energy Storage (SMES) Systems
- Supercapacitors



Flow Batteries

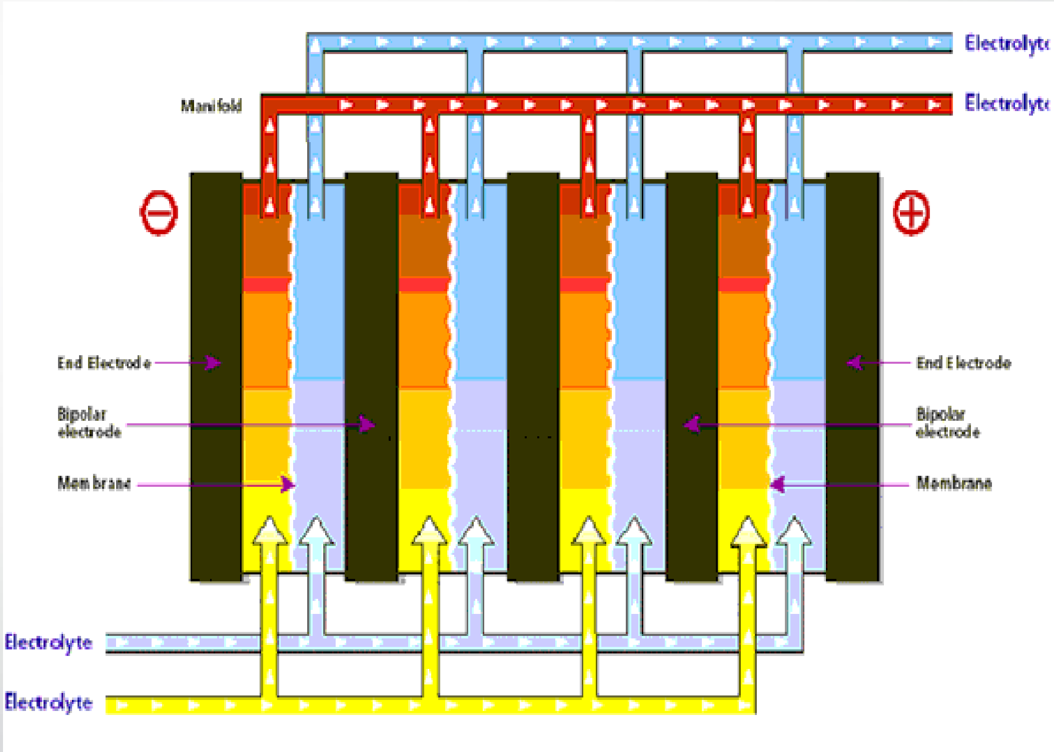


- It compose of
  - two electrolyte liquids in separate tanks,
  - an electrochemical cell.
- In the electrochemical cell, a membrane is held between two electrodes.
- Electrolytes are pumped through the electrochemical cell and ion exchange occurs through the membrane.
- Today, three types of flow batteries are commercially available in the market:
  - **Vanadium redox battery,**
  - **Polysulphide bromide battery,**
  - **Zinc bromine battery.**

Flow Batteries

Flow Battery Cell Stack

- Array or "stack" of individual cells in series
- Each cell consists of
  - bipolar plate
  - 2 electrodes
  - membrane separator



Flow Batteries

Advantages

- Rapidly charged by replacing the electrolyte liquid (like refilling fuel tanks of ICE).
- No daily "off periods" - always on
- Power and energy capacity can be sized independently of one another (Energy capacity is related with electrolyte volume, power is related with electrode area.)
- Long cycle life,
- Operates at any SOC without life impact
- Efficient over 100% DOD range
- Very low self-discharge rate
- Quick response,
- Closed loop no emissions

  – no disposal issues

Disadvantages

- Low energy storage density = big footprint
- Complicated than standard batteries,
- Relatively high operating cost
- Not mobile

Energy Storage Technologies

- Pumped Hydro Energy Storage Systems
- Flywheel Energy Storage Systems
- Compressed Air Energy Storage Systems
- Lead-acid (L/A) batteries
  - Flooded L/A batteries
  - Valve-regulated lead-acid (VRLA) batteries
- Sodium-sulfur (NaS) batteries
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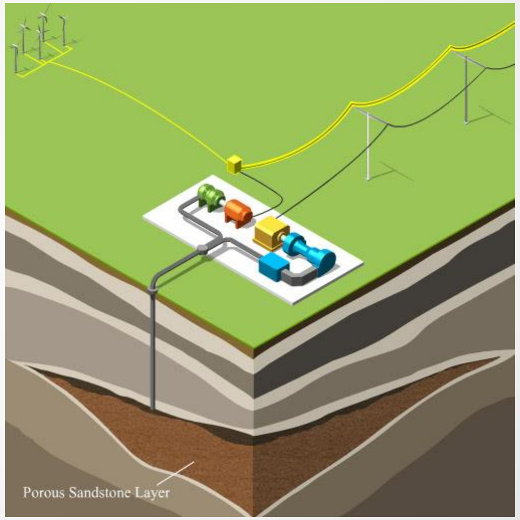
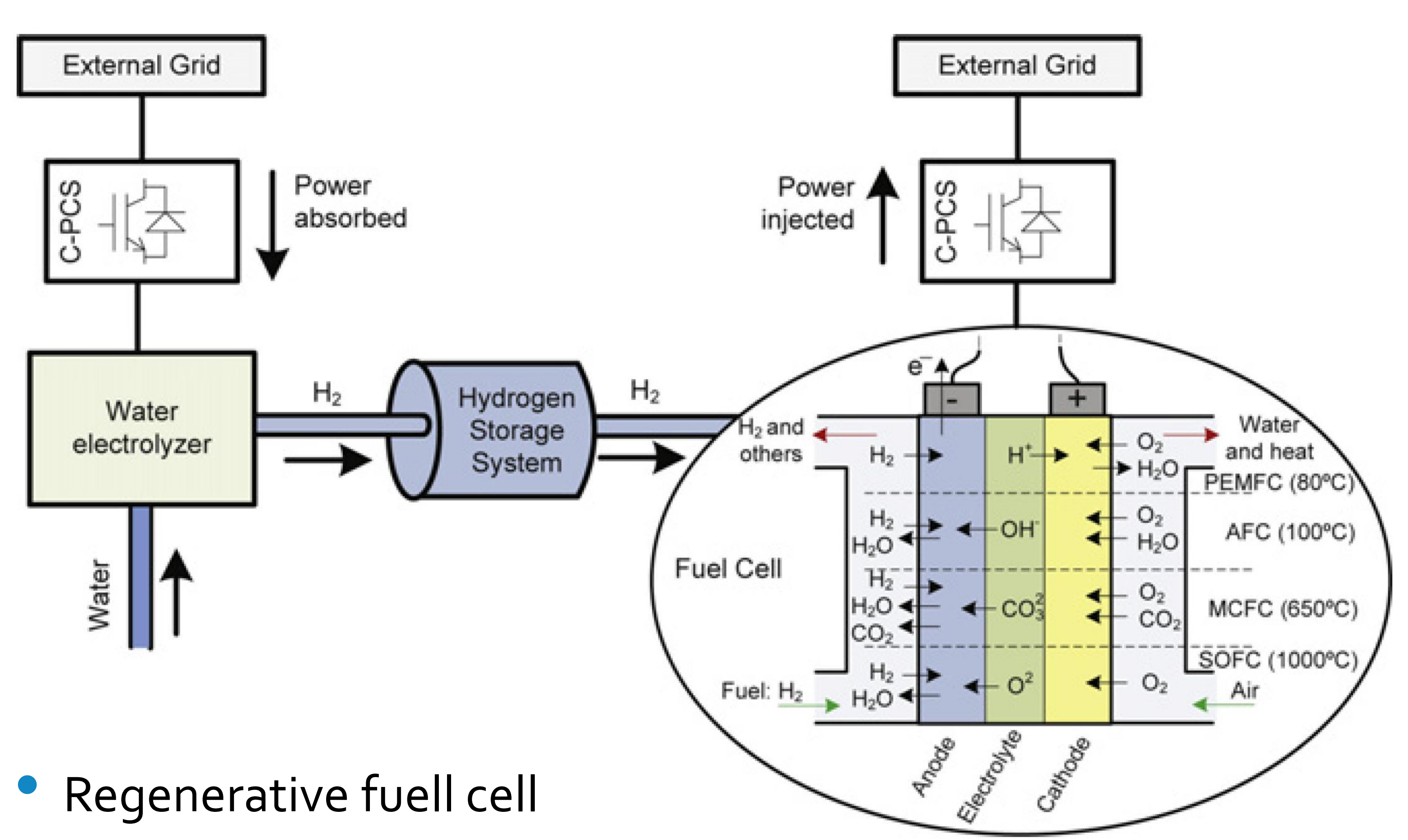


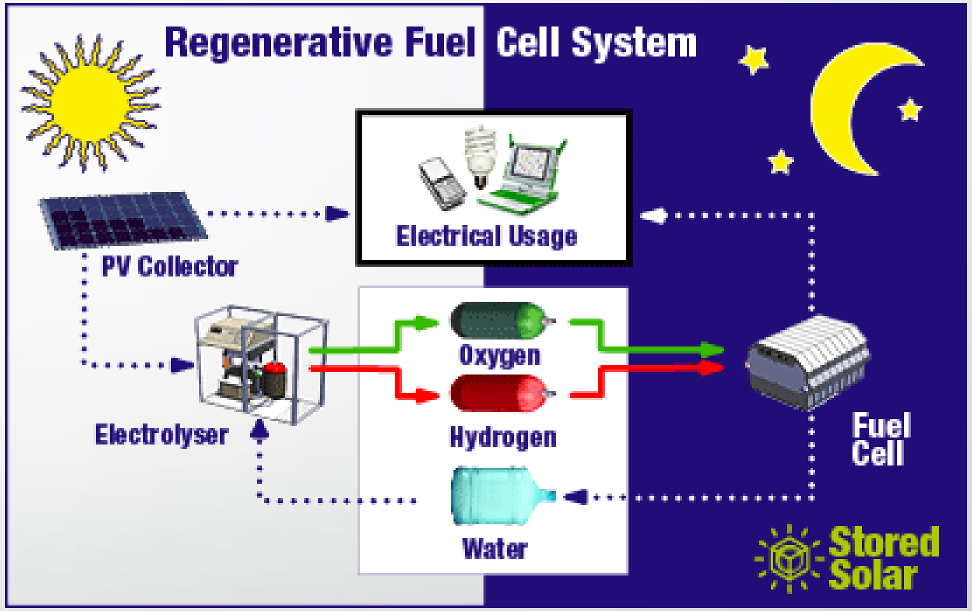
Hydrogen Based Energy Storage Systems



- Regenerative fuell cell

Hydrogen Based Energy Storage Systems

- Energy is stored in form of hydrogen.
- System is composed of electrolyzer, hydrogen tank, fuel cell and power converters.
- Different type of electrolyzers such as alkaline electrolyzers or Polymer Electrolyte Membrane (PEM) electrolyzers.
- Types of fuel cell:
    - Polymer Electrolyte Membrane Fuel Cell (PEMFC),
    - Alkaline Fuel Cell (AFC),
    - Molten Carbonate Fuel Cell (MCFC),
    - Solid Oxide Fuel Cell (SOFC)



Hydrogen Based Energy Storage Systems

- Good dynamic behavior,
- Energy capacity can be sized,
- Modular structure eases the high power high energy applications.
- Very low self-discharge
- Long life and life cycle (>15 years and 20.000 cycles)
- Low efficiency (~42% because of electrolyzer and fuel cell efficiencies (60% and 70%, respectively)

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- Flywheel Energy Storage Systems
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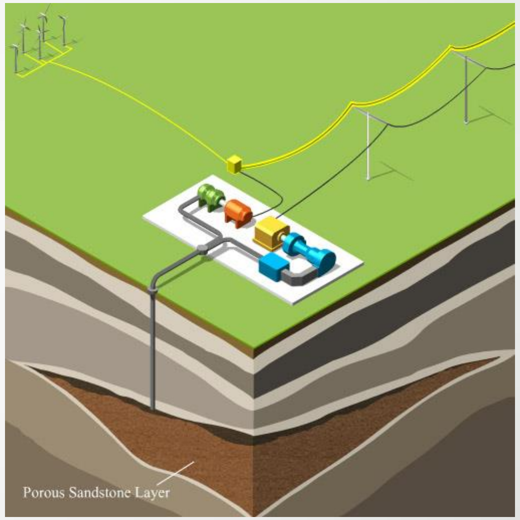
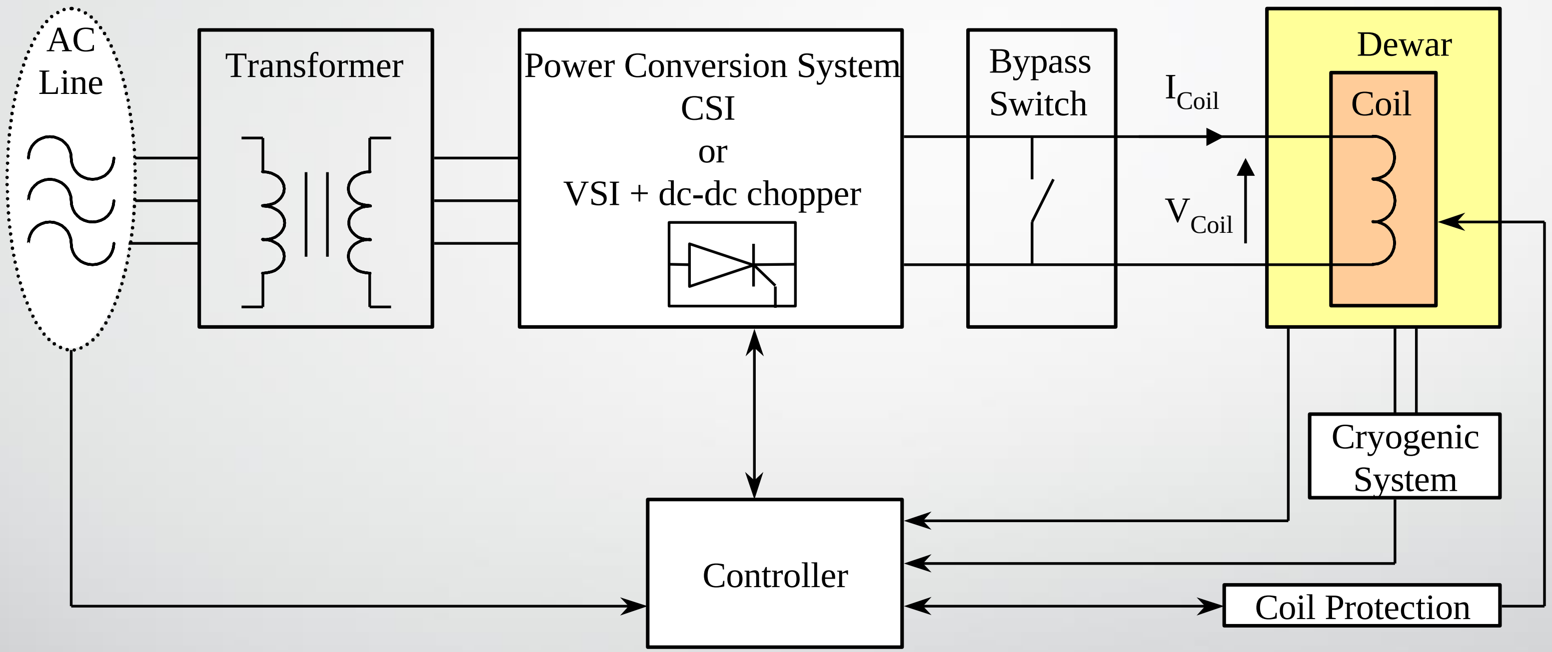
- **Superconducting Magnetic Energy Storage (SMES)**
- Supercapacitors



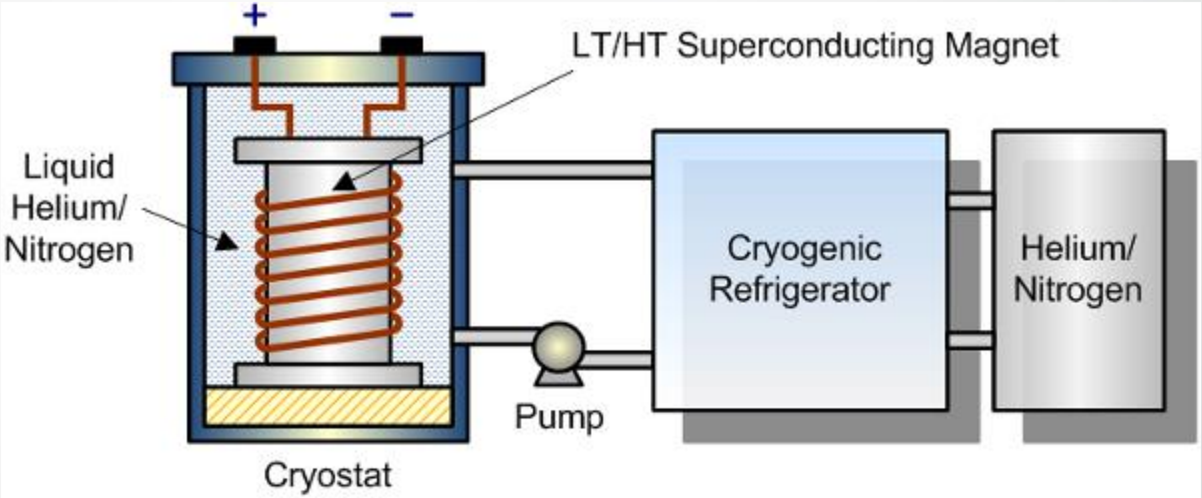
Superconducting Magnetic Energy Storage (SMES) Systems



- Relatively recent technology (1970)
- Based on storing energy in a magnetic field.

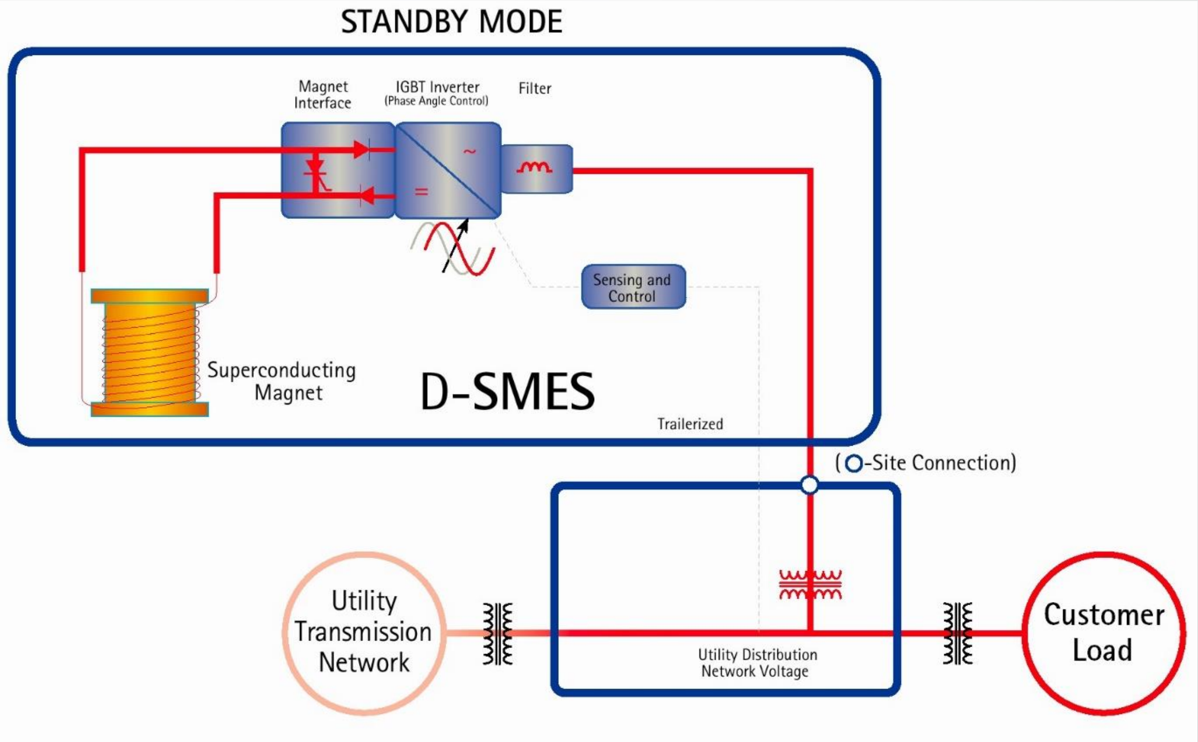
Superconducting Magnetic Energy Storage (SMES) Systems

- $W = 0.5LI^2$
- Thus, inductance design is important.
- High temperature coils – around 70 K
- Low temperature coils – around 5 K
- Cooling system is also core component.
- It consumes energy.
- Efficiency is about 90%.



Superconducting Magnetic Energy Storage (SMES) Systems

- Very fast response (MW/millisecond) (it can inject or absorb very large amount of energy in very short time).
- Energy capacities are around 100kWh .
- Very long life cycle (tens of thousands cycles),
- Very high cost.



Superconducting Magnetic Energy Storage (SMES) Systems

- Potential applications:
  - load leveling,
  - frequency support (spinning reserve) during loss of generation,
  - enhancing transient and dynamic stability,
  - dynamic voltage support (VAR compensation),
  - improving power quality,
  - increasing transmission line capacity, thus enhancing overall security and reliability of power systems.
- Further development continues in power conversion systems and control schemes, evaluation of design and cost factors, and analyses for various SMES system applications.

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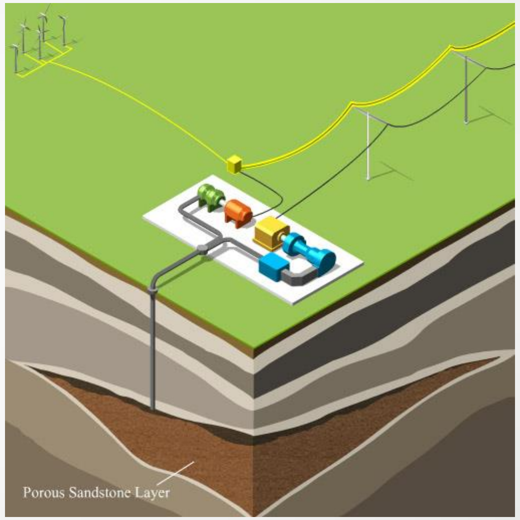
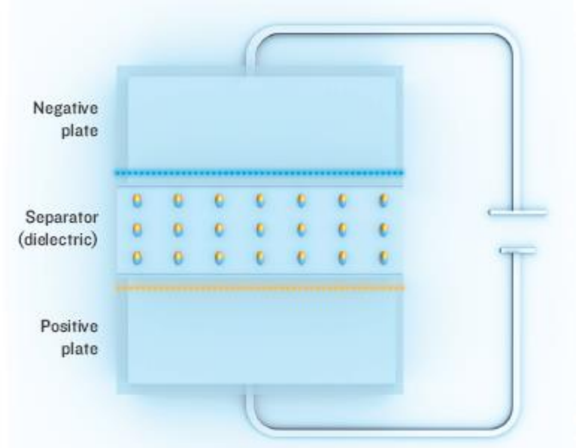
- Superconducting Magnetic Energy Storage (SMES) Systems
- **Supercapacitors**



Supercapacitors (Ultracapacitors)

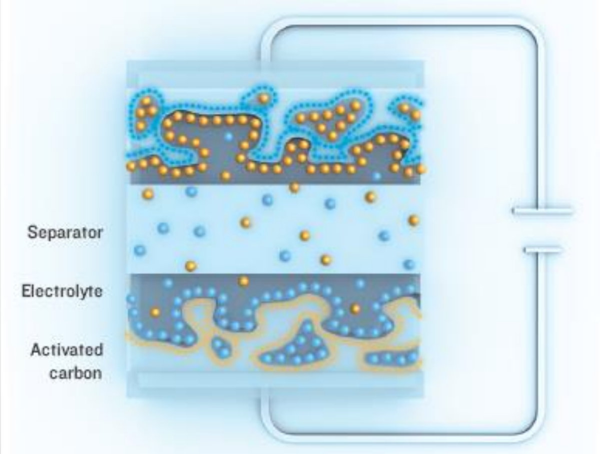
- Supercapacitors technology: construction

Traditional standard capacitor



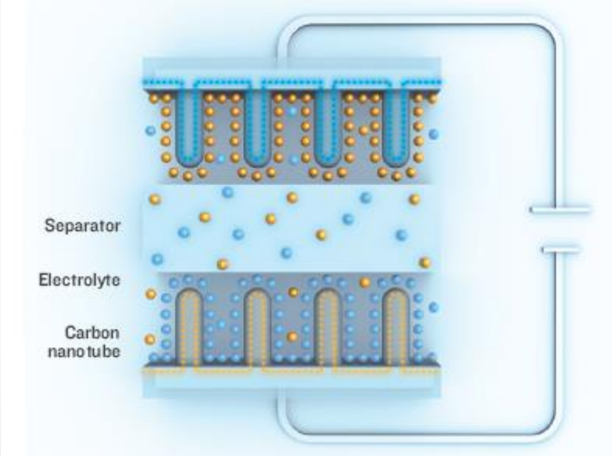
The charge of ultracapacitors, IEEE Spectrum Nov. 2007

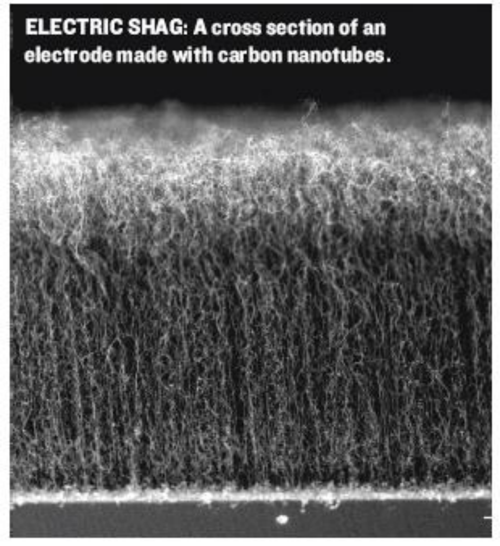
Double layer capacitor (ultracapacitor)



$$C = \varepsilon \frac{A}{d}$$

Ultracapacitor with carbon nano-tubes electrodes





- Key principle: area is increased and distance is decreased
- There are some similarities with batteries but there are no reactions here.

Supercapacitors (Ultracapacitors)

- Some typical Maxwell's ultracapacitor packages:

C =	650	1200	1500	2000	2600	3000 F
ESRac =	0.6	0.44	0.35	0.26	0.21	0.20 mΩ
ESRdc =	0.8	0.58	0.47	0.35	0.31	0.30 mΩ
τ =	0.52	0.696	0.705	0.700	0.806	0.900 s
I_{rms} =	105	110	115	125	130	150+ A_{rms}

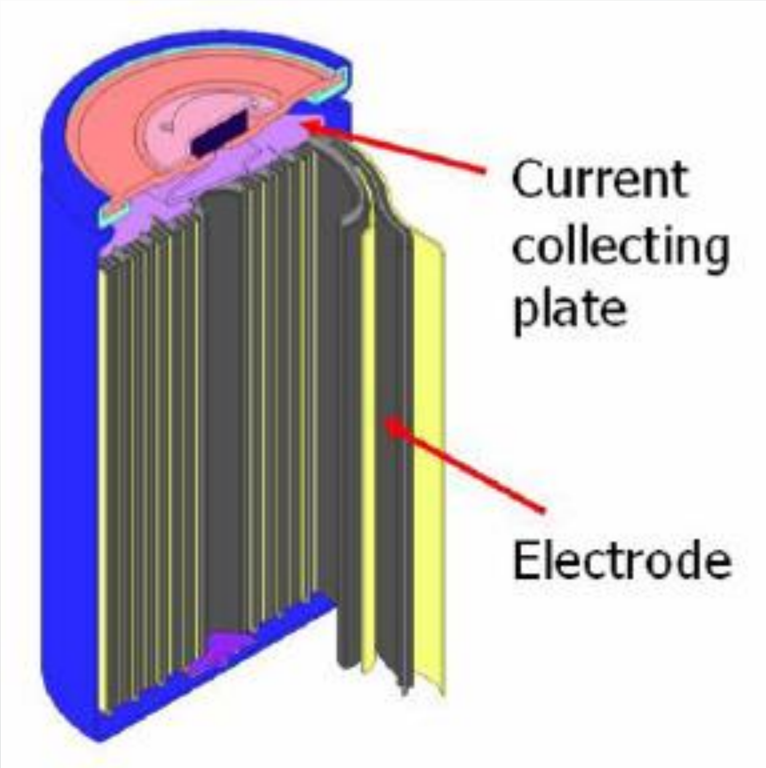
www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf

- At 2.7 V, a BCAP2000 capacitor can store more than 7000 J in the volume of a soda can.

- In comparison a 1.5 mF, 500 V electrolytic capacitor can store less than 200 J in the same volume.

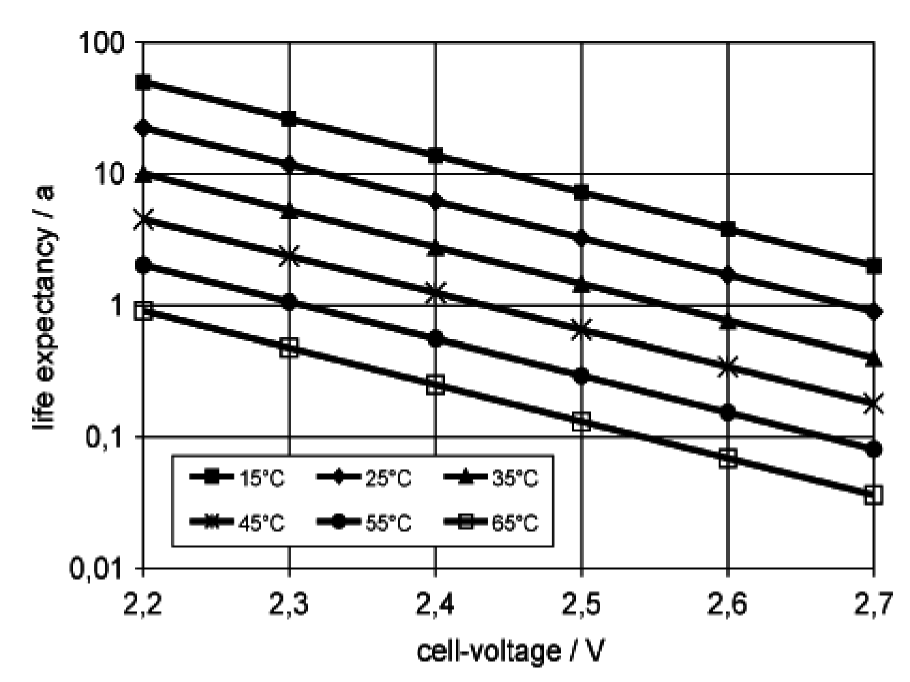
Supercapacitors

- Very low equivalent resistance and therefore, very short time constants and fast response
- High power density (10X higher than the batteries).
- Efficiency is about 75-80%,
- Cycle life is 50,000-100,000.
- High specific power density -- 2000-5000 W/kg
- High power density -- 20,000-30,000 W/m^3



Supercapacitors

- High self-discharge rate (20% of rated capacity in 12 hours),
- Low specific energy density -- 2-5Wh/kg,
- Low energy density values -- 10,000Wh/ m^3 ,
- High cost,
- Aging effect because of degrading materials with time
- Aging is also influenced by temperature and cell voltage
- The supercapacitor systems are useful for short time applications.



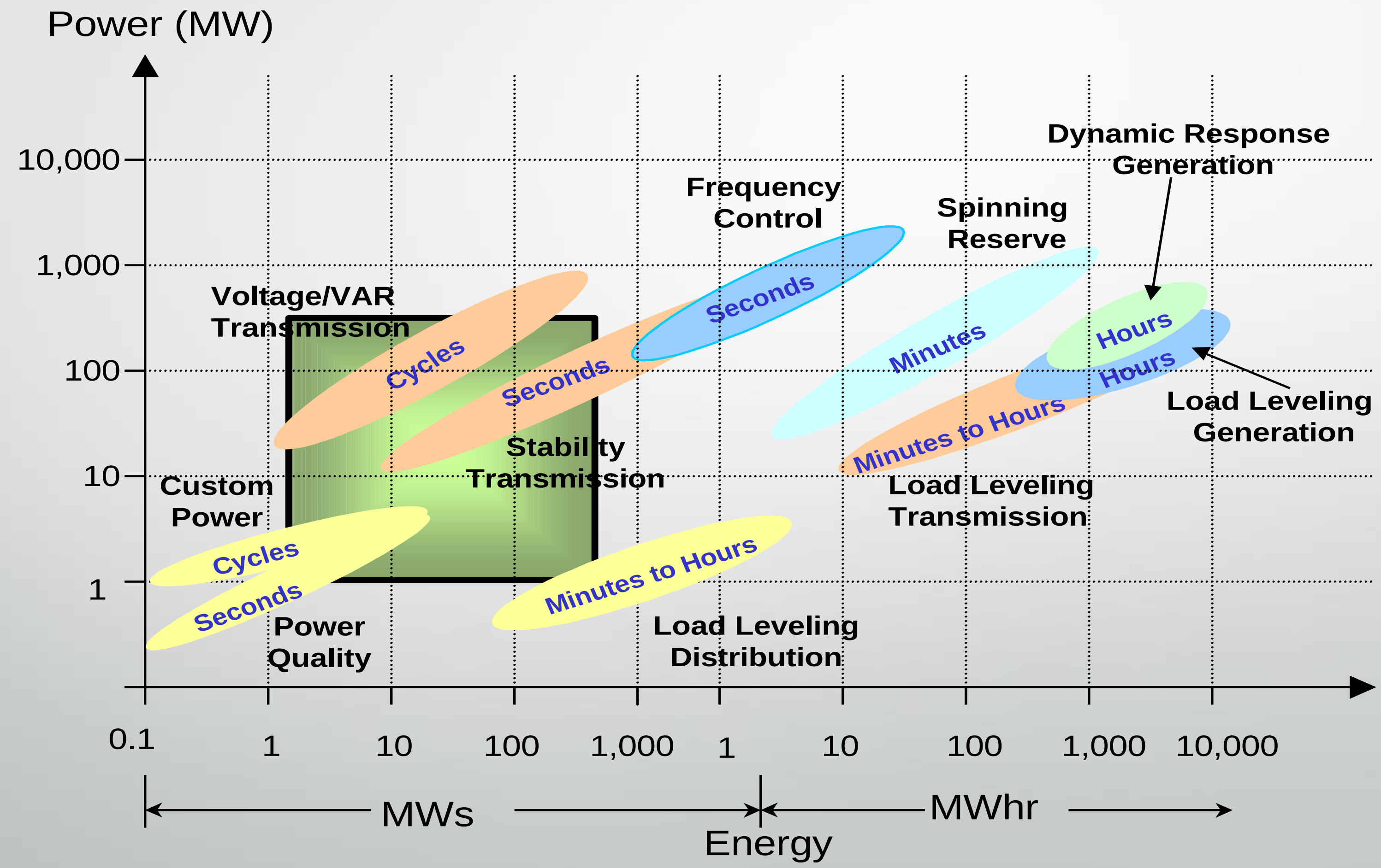
Linzen, et al., “Analysis and Evaluation of Charge-Balancing Circuits on Performance, Reliability, and Lifetime of Supercapacitor Systems”

Power vs. energy delivery profile technologies

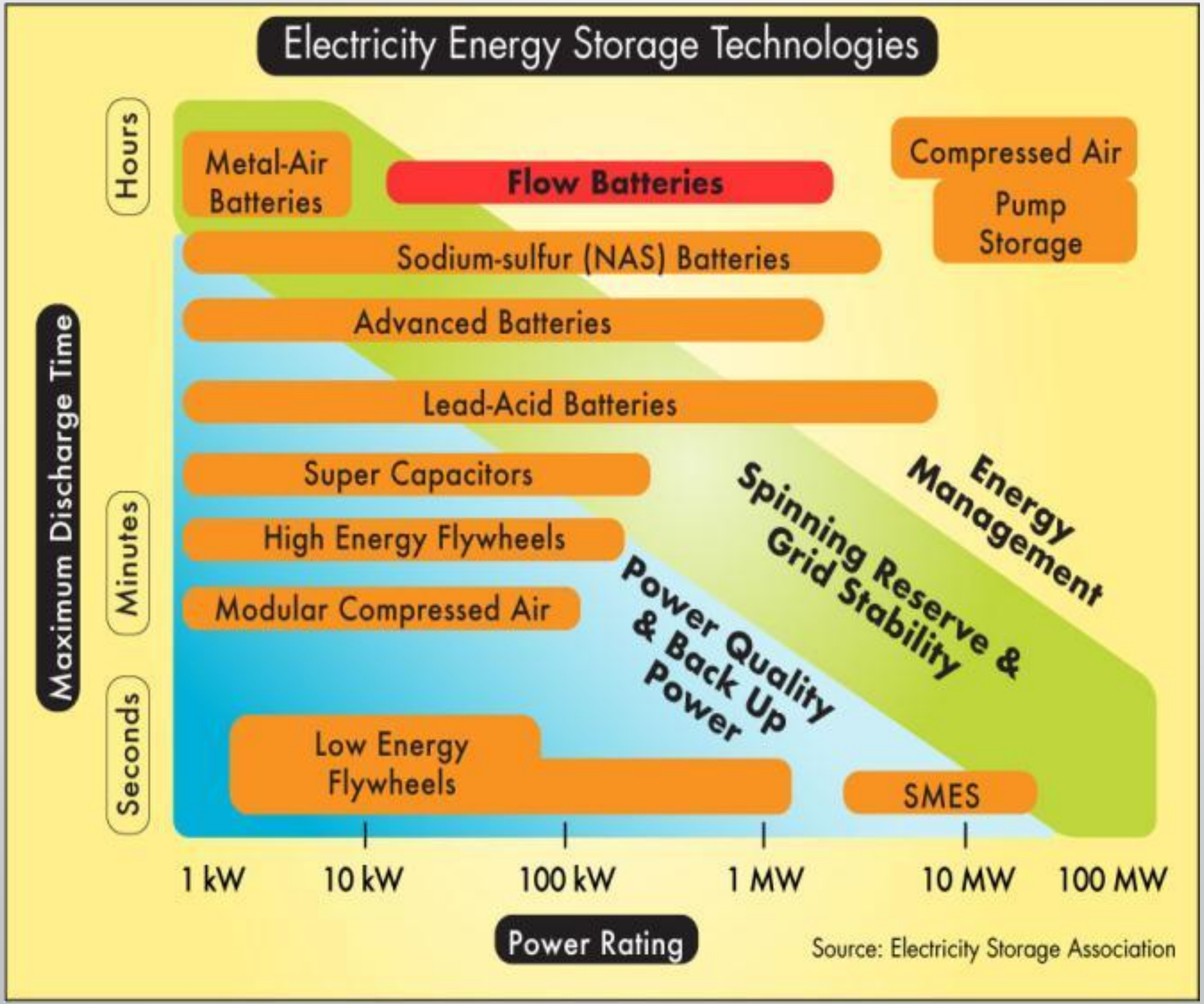
	Lead-Acid	Ni-Cd	Ni-MH	Li-ion
Cell voltage (V)	2	1.2	1.2	3.6
Specific energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific power (W/kg)	< 300	150 – 300	< 200	100 – 1000
Energy density (kWh/m^3)	25-60	25	70-100	80-200
Power density (MW/m^3)	< 0.6	0.125	1.5 – 4	0.4 – 2
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	> 1 min	1 min-8 hr	> 1 min	10 s-1 h
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75 - 90	75	81	99

	Flywheel	Ultracapacitor
System power ratings (kW)	2 – 500	5 – 1000
Specific energy (Wh/kg)	15 – 150	0.5 – 4
Specific power (W/kg)	900 - 20000	50 – 3000
Energy density (kWh/m^3)	6 – 100	0.8 – 4
Power density (MW/m^3)	0.3 – 40	0.3 – 1
Maximum cycles	> 100 000	> 100 000
Discharge time range	4 - 60 s	1 – 60 s
Life expectancy (hours)	175 000	100 000
Cost ($/kW)	300	500
Efficiency (%)	90 – 93	90 – 95

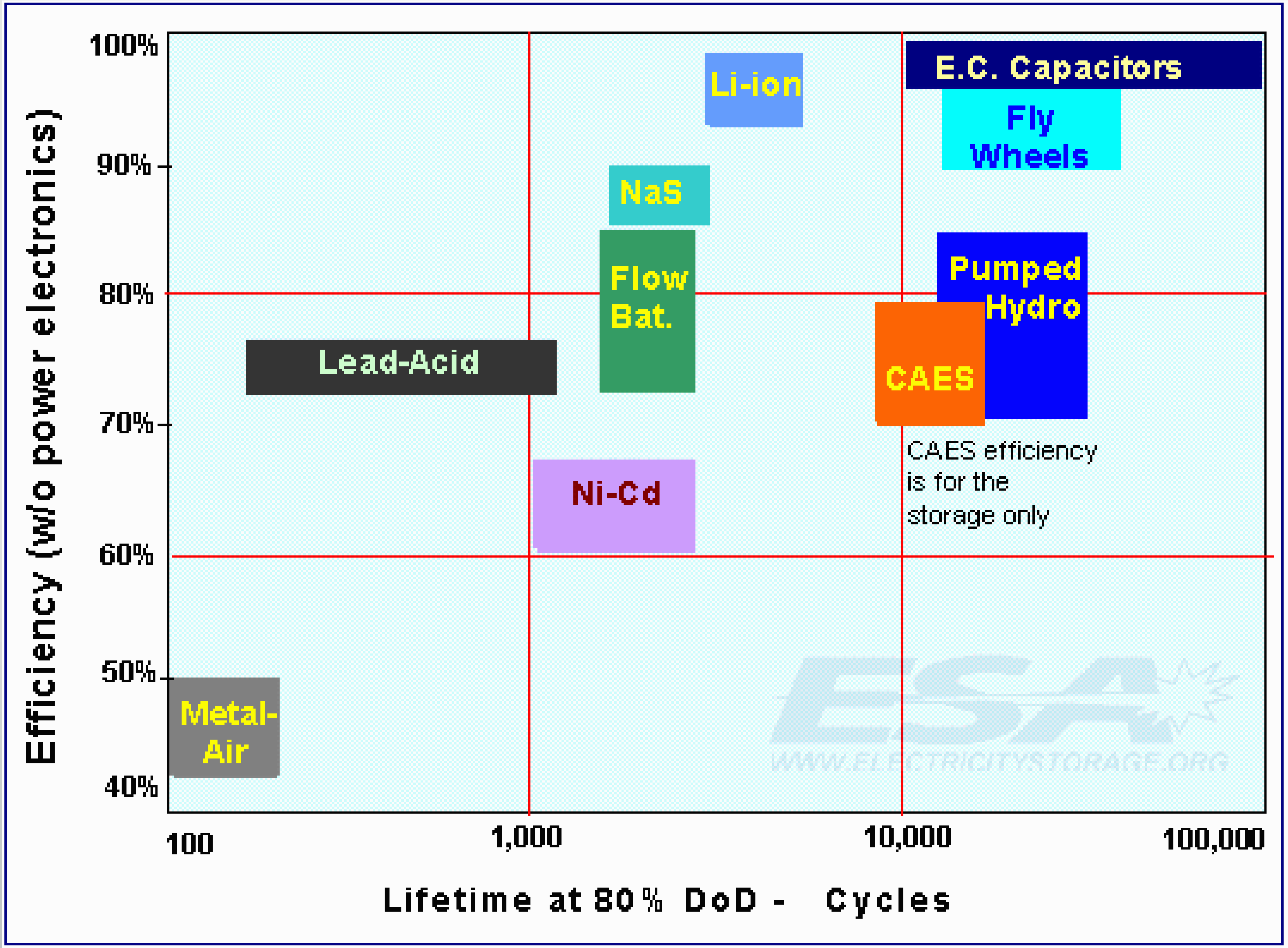
Storage Requirement of Power Quality and Stability Issues



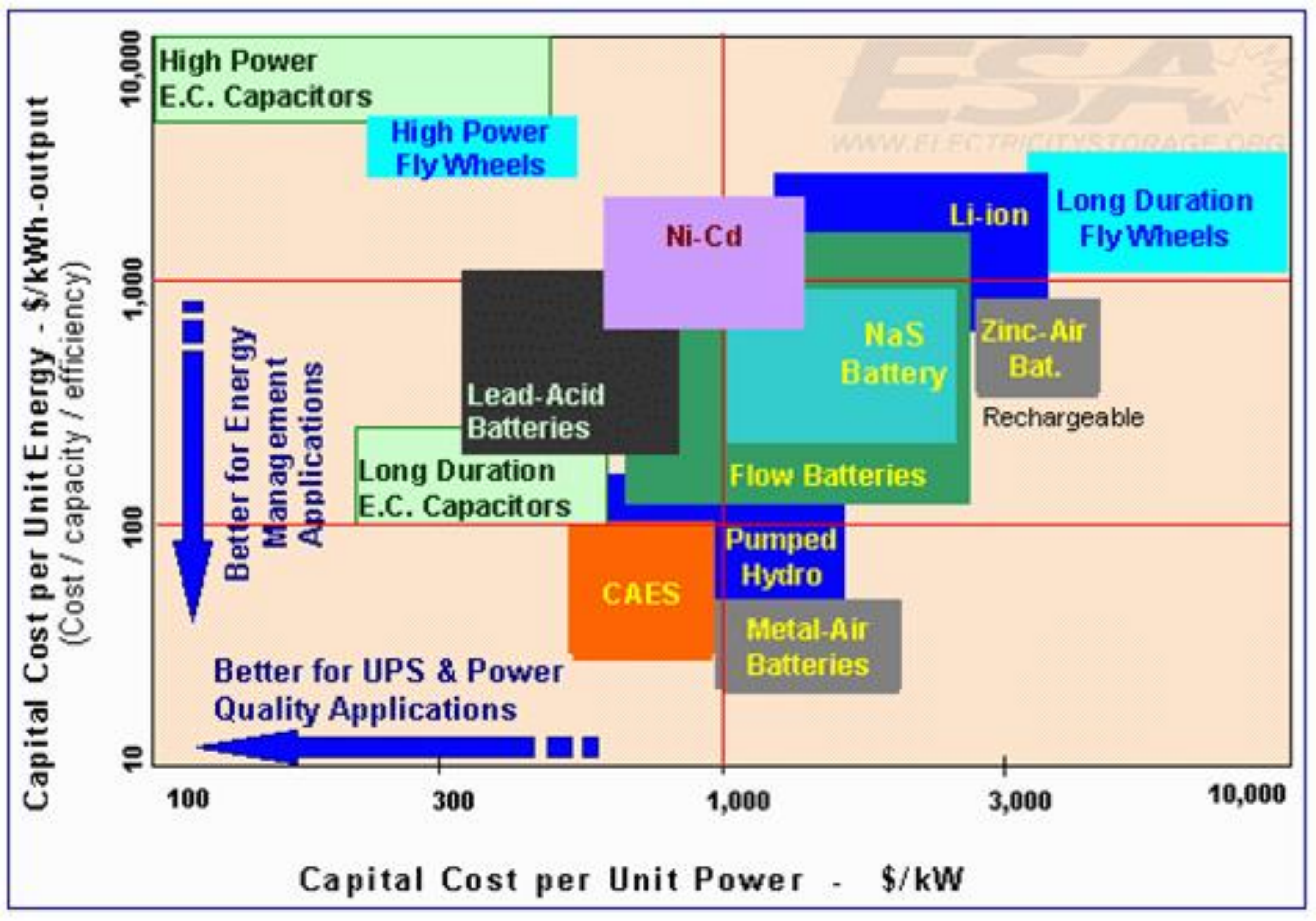
Summary of Energy Storage Technologies



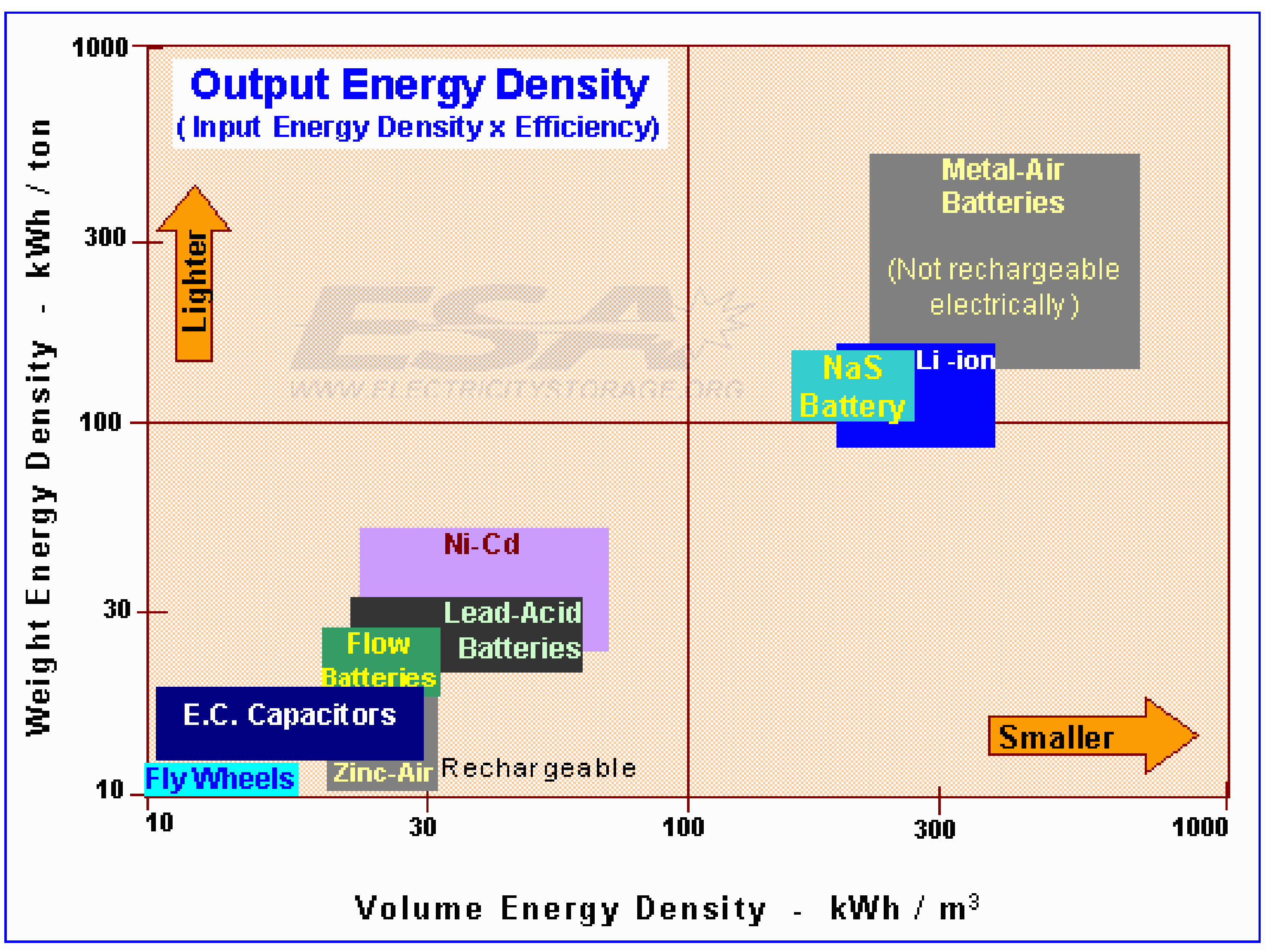
Cycle Efficiency of Energy Storage Technologies



Energy Storage Capital Costs Requirements



Size and Weight of Energy Storage



Applications of Energy Storage Technologies

Source ASA

Storage Technologies	Main Advantages (Relative to others)	Disadvantages (Relative to others)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement	■	■■■■
Compressed Air	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel	■	■■■■
Flow Batteries: Regenesys, Vanadium Redox, Zinc Bromine	High Capacity, Independent Power and Energy Ratings	Low Energy Density	■■■	■■■■
Metal-Air Batteries	Very High Energy Density	Electric Charging is Difficult	■	■■■■
Sodium Sulfur (NAS) Battery	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	■■■■	■■■■
Li-ion Batteries	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit.	■■■■	■■
Ni-Cad Batteries	High Power & Energy Densities, Efficiency		■■■■	■■■
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	■■■■	■■
Lead-Acid Batteries	Low Capital Cost	Limited Cycle Life when Deeply Discharged	■■■■	■■
Flywheels	High Power	Low Energy density	■■■■	■
SMES, DSMES	High Power	Low Energy Density, High Production Cost	■■■■	■
Double Layer Capacitors (SuperCapacitors)	Long Cycle Life, High Efficiency	Low Energy Density	■■■■	■■■

Supports to The Grid

1. Bulk Energy Services
   a) Electric Energy Time-Shift (Arbitrage)
   b) Electric Supply Capacity
2. Ancillary Services
   a) Frequency Regulation and Response
   b) Spinning, Non-Spinning, and Supplemental Reserves
   c) Voltage Support
   d) Ramping and Load Following
   e) Black Start
3. Transmission Infrastructure Services
   a) Transmission Upgrade Deferral
   b) Transmission Congestion Relief
4. Distribution Infrastructure Services
   a) Distribution Upgrade Deferral
   b) Improvement of Power Quality/ Voltage Support
   c) Mitigation of System Outages
   d) Integration of Distributed Renewable Generation
5. Customer Energy Management Services
   a) Maintain Power Quality
   b) Ensure Power Reliability – Uninterruptible Power Supply
   c) Retail Electric Energy Time-Shift
   d) Demand Management

Supports to The Grid

Bulk Energy Services

- Electric Energy Time-Shift (Arbitrage)
- Electric Supply Capacity

Ancillary Services

- Frequency Regulation and Response
- Spinning, Non-Spinning, and Supplemental Reserves
- Voltage Support
- Ramping and Load Following
- Black Start

Transmission Infrastructure Services

- Transmission Upgrade Deferral
- Transmission Congestion Relief

Distribution Infrastructure Services

- Distribution Upgrade Deferral
- Improvement of Power Quality/ Voltage Support
- Mitigation of System Outages
- Integration of Distributed Renewable Generation

Customer Energy Management Services

- Maintain Power Quality
- Ensure Power Reliability – Uninterruptible Power Supply
- Retail Electric Energy Time-Shift
- Demand Management

Supply/Demand Balance, Ancillary Services Requirements

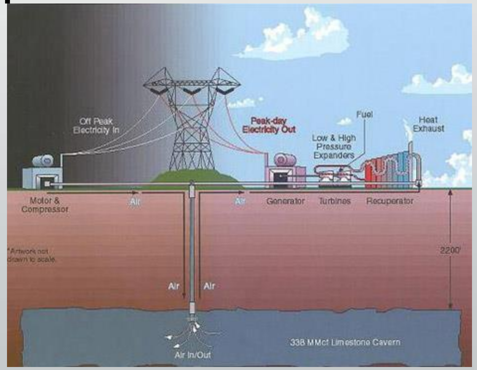
- Short-term storage (seconds to minutes)
  - For services such as frequency regulation, reactive power supply and voltage support
    - Requires fast/secure communications for automatic control
  - For contingency reserves (e.g., spinning reserve)
    - Requires communication to verify the requirement to operate and to confirm the available capacity

- Longer term storage (minutes to hours)
  - Energy/price arbitrage, load following and ramping
  - Scheduling of charging and discharging requires information on current value of energy and the expected future value of energy (may include value of capacity and energy)
  - Information on constraints on total capacity, ramping, and total energy limits of the storage system

Energy Storage Technologies - Different Applications

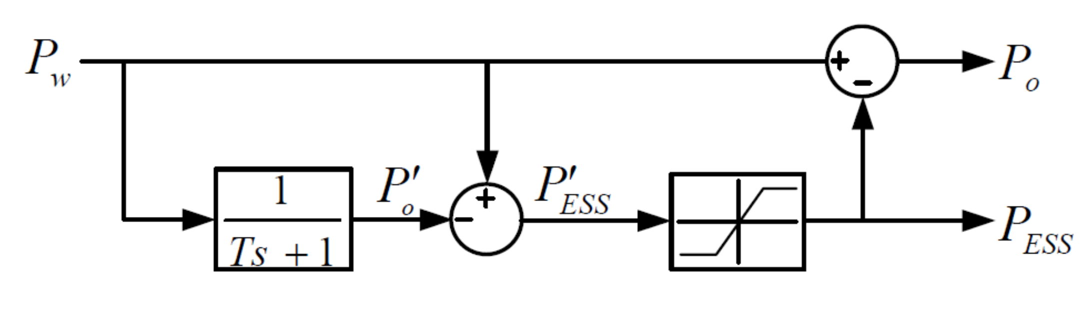
- Flywheels, super-capacitors, SMES, and other storage technologies with the short-term power output (minute time scale)
  - Regulation service
  - Spinning reserve, etc.

- NaS batteries, flow batteries, hydrogen fuel cells, CAES, pumped storage can provide several hours of full capacity:
  - Load shifting
  - Electricity generation



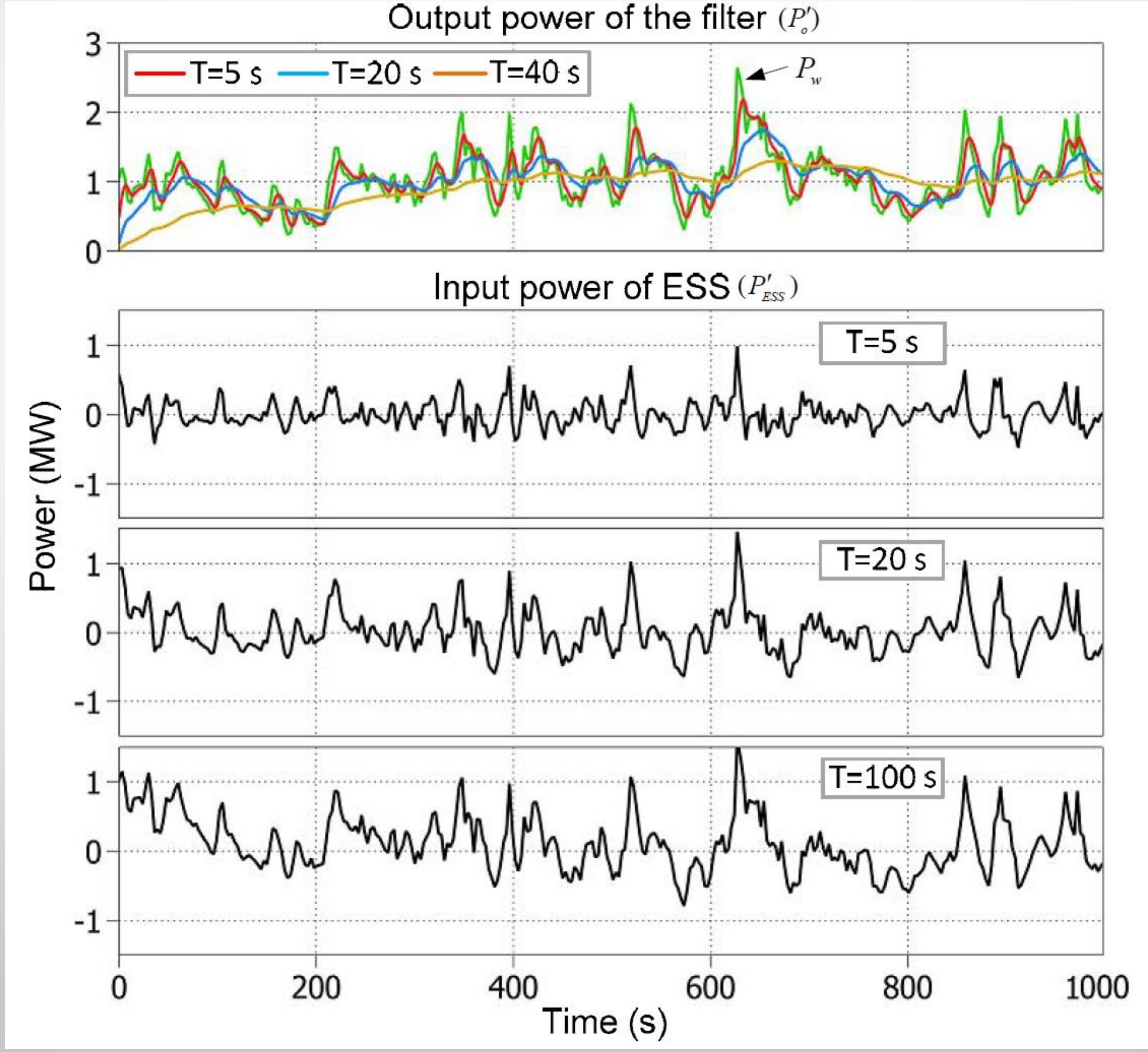
Control of Energy Storage Systems

- The controller determines the power reference for the energy storage systems.
- The first order low pass filter based controllers which can be implemented easily and suitable for real time applications are commonly used as controller.
- The larger values of *T* (time constant) provide smoother power, but the required storage system capacity also increase.

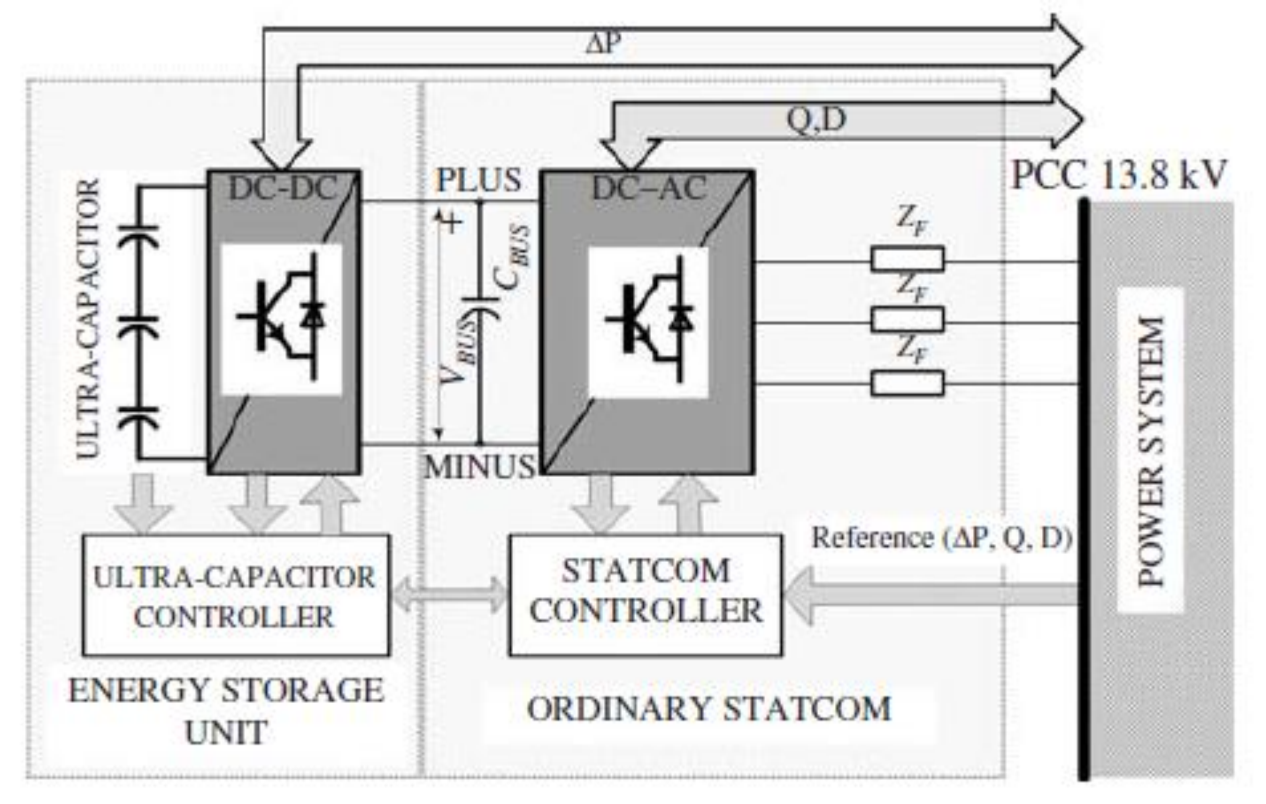


Control of Energy Storage Systems

- Impact of the first order low pass filter based control system



Combination with Other Technologies



- STATCOM+ESS → Active and reactive power support to the grid

THANKS…