Thermal and electrical storage. Options for coupling with SMR

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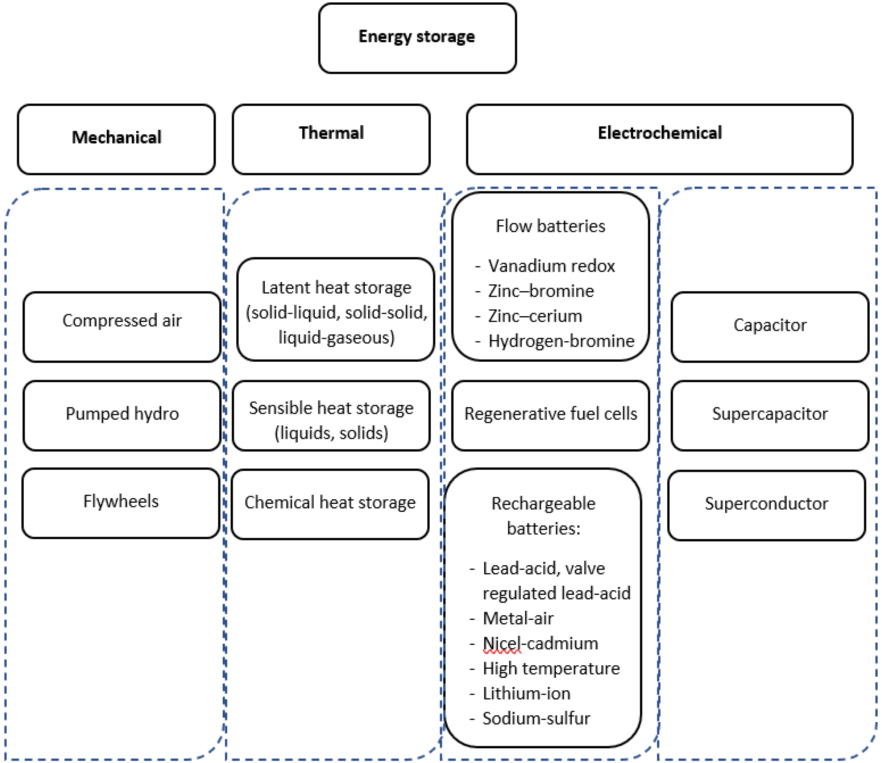
Introduction

ES accumulate and release energy so that the stored energy can later be used for various applications by simply reversing the process

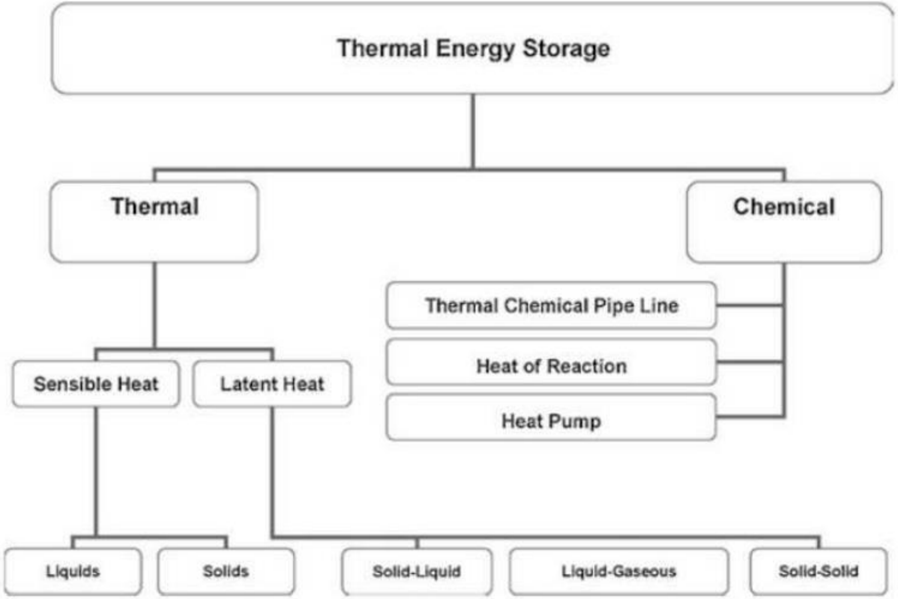
TES, BES, RES and nuclear – key elements of hybrid systems



Thermal Energy Storage – coupling with nuclear

TES technologies in conjunction with nuclear power

- Sensible heat storage. Energy stored as temperature difference in solid or liquid media:
  - Liquid based sensible heat storage
  - Thermocline systems, packed bed thermal storage
  - Hot and cold-water systems, steam accumulators
  - Solid based sensible heat storage (firebricks; concrete; ceramics, graphite, and alloys
  - Underground storage
  - Geothermal heat storage
- Latent heat storage. Energy stored using phase-change materials:
  - Molten salt;
  - Liquid air, cryogenic air energy storage
- Thermochemical energy storage



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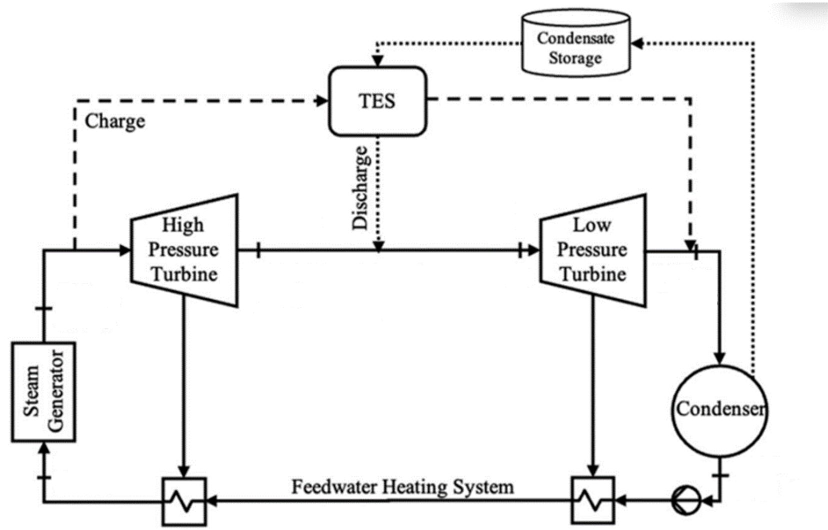
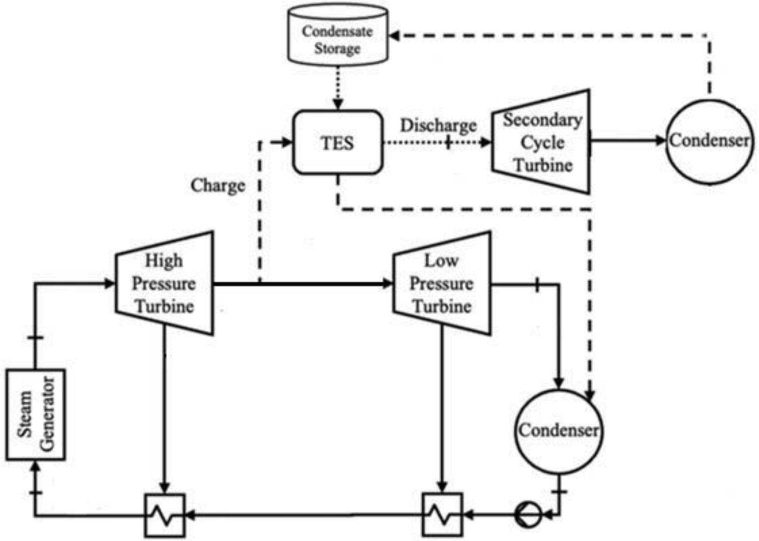
Thermal Energy Storage – coupling with nuclear (examples)

Primary steam Rankine cycle



Secondary steam Rankine cycle



Thermal Energy Storage – comparison

	Sensible heat storage	**Latent heat storage**	**Thermochemical energy storage**
Advantages	Demonstrated large energy capacity (~GWh) Inexpensive media Solid media does not freeze and can achieve >1000°C	Good for isothermal or low delta temperature applications Highly efficient heat-to-power conversion (liquid air) Can provide large energy density with combined sensible and latent heat storage	Large energy densities Small heat losses Potential for long term storage Compact storage system
Challenges	Requires insulation to mitigate heat losses Lower energy density requires larger volumes Thermal oils are of greater environmental concern than molten salts, due to post-use leakage and deposition.	Potential for corrosion For larger delta temperature, may need cascaded systems (adds costs and complexity) Emissions produced during operation (for liquid air) Challenges with PCMs include relatively high costs and narrow operating temperature ranges. Using PCMs to provide energy to a heat engine will typically require a cascaded system with multiple PCMs with different melting points. The use of molten silicon at high temperatures provides challenges with materials containment and heat loss. Phase-change systems must still be well insulated to prevent heat loss and subsequent phase change	Higher complexity Higher capital costs May require storage of gaseous products
Maturity	High	Low	Low
Cost	\$1/MJ – \$10/MJ (system capital cost)	~\$10/MJ – \$100/MJ (system capital cost)	\$10/MJ – \$100/MJ (system capital cost)

Thermal Energy Storage – comparison

	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
Applicability for LWR	Yes (thermal oil, low temperature molten salt)	Yes,	Yes (thermal oil) No (molten salt)	Yes	Yes, but have geographical sensitivity	Yes, only for low temperature molten salt	Yes	Yes
Energy arbitrage	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	compatible
Frequency regulation	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible
Load following	somewhat compatible	incompatible	somewhat compatible	incompatible	incompatible	somewhat compatible	compatible	incompatible
Voltage support	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible

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Thermal Energy Storage – comparison

	Two-tank	Hot/cold water	Thermo-cline	Solid sensible	Under-ground	Molten salt latent	Liquid air	Thermo-chemical
Spinning reserves	compatible	incompatible	compatible	incompatible	incompatible	compatible	compatible	incompatible
Nonspinning and supp reserves	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	somewhat compatible
Black start	incompatible	incompatible	incompatible	incompatible	incompatible	incompatible	compatible	incompatible
Variable supply resource integration	compatible	compatible	compatible	compatible	incompatible	compatible	compatible	compatible
Seasonal storage	incompatible	compatible	incompatible	incompatible	compatible	incompatible	compatible	compatible
Process heat applications	compatible	compatible	compatible	compatible	compatible	compatible	somewhat compatible	incompatible

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Thermal Energy Storage – selection

TES that could be potentially coupled with advanced NPPs:

I. Two tank system with molten salt, molten salt latent heat storage, solid based sensible heat storage

II. Two tank system with low temperature molten salt, two tank system with thermal oil, steam accumulator system, solid based sensible heat storage (concrete)

III. Hot/cold water, underground TES, solid based sensible heat storage, liquid air

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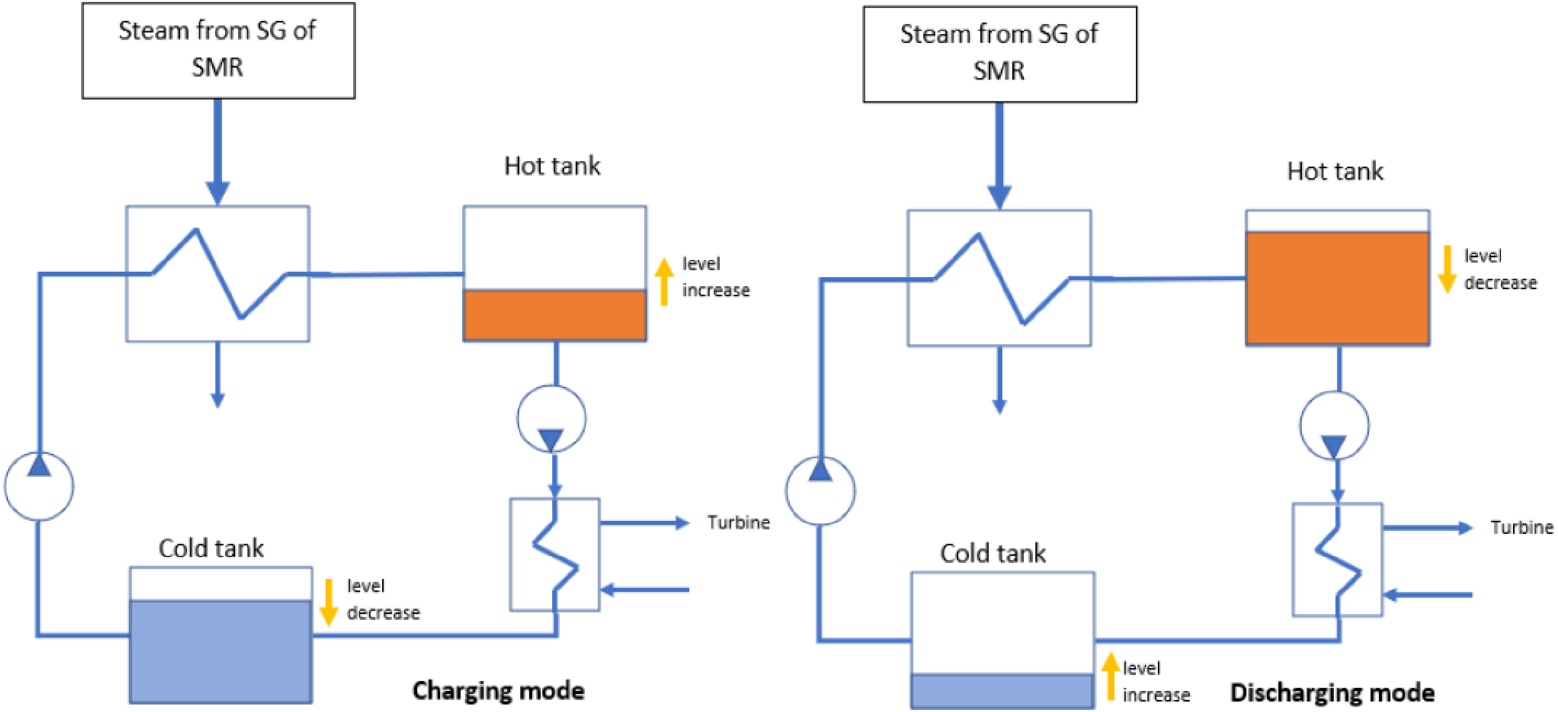
TES simplified architecture with charge and discharge mode



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Thermal Energy Storage – conclusion

When coupled with NPP

- TES could store any excess energy not being used for power production. This energy could later be used to generate heat or electrical power when needed (e.g. for load following, energy arbitrage).
- This would enable NPPs to operate at maximum capacity, without necessity for load following to match the demands of the market.
- It would lead to increase efficiency of NPP and to reduce any mismatches between energy supply and demand.

Gen IV reactors provide higher temperatures to the power cycle relative to LWR

- beneficial for thermal storage because at higher temperatures, less storage material is required to deliver a desired amount of thermal power

In practice, NPP often works at full capacity and does not follow any load variation. The interest is more in the reuse of the thermal energy loss.

TES, as a key technology for energy-system integration, could play an important role in providing flexibility and in particular long-term and seasonal storage

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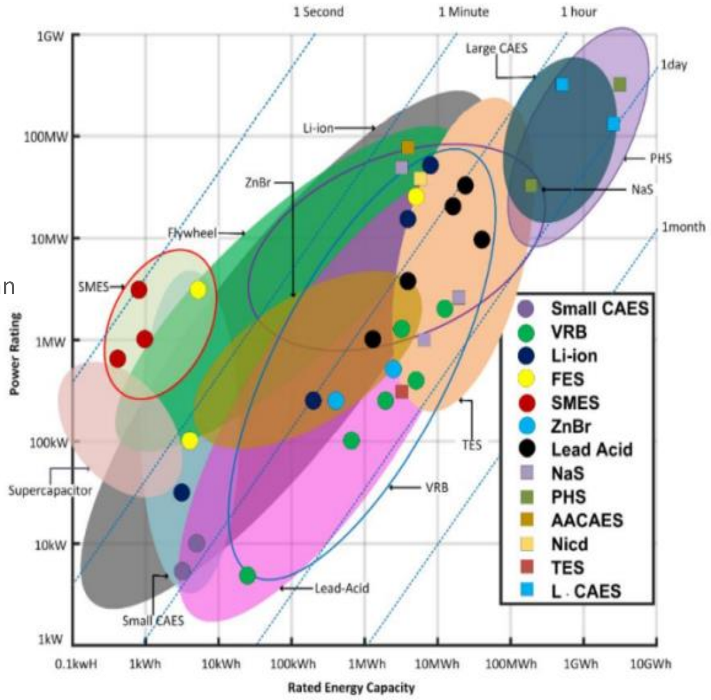
Electrical Energy Storage

- There is a wide variety of electrical energy storage technologies, each with different attributes and intended for different applications. Choosing the "ideal" storage technology depends on:
    - amount of energy or power that needs to be stored,
    - the time for which this stored energy must be stored or released,
    - siting requirements, etc
- Increasing application of BES at NPPs including SMRs is anticipated in near future
- BES could offer a considerable amount of daily flexibility in the electricity system in 2030, but than they would be less able to provide weekly and monthly flexibility
- Lower storage applications
    - BES and capacitors
- Mid capacity applications
    - flow batteries, lead-acid batteries and sodium–sulfur batteries.
- Since SMRs are positioned as mid power range, capacitor/super capacitors are not considered



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Electrical Energy Storage

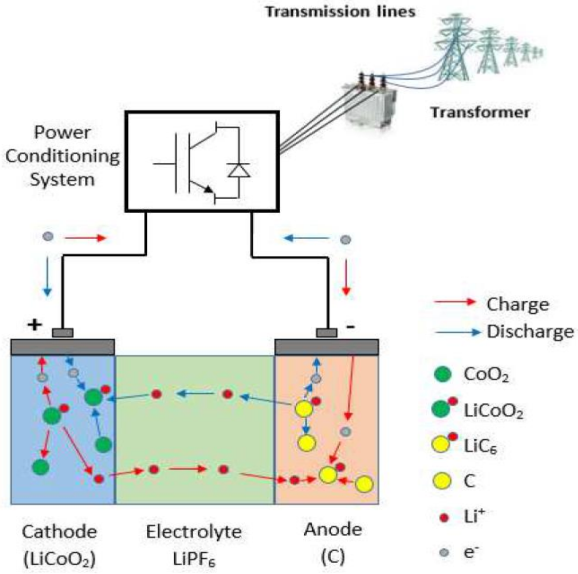
- Batteries

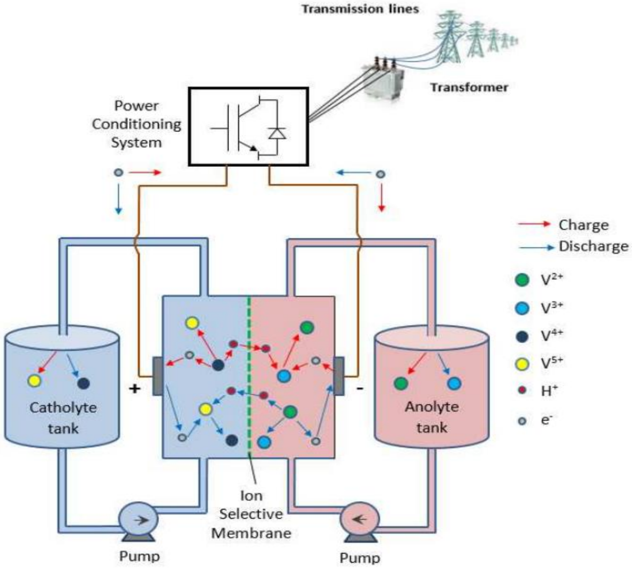
lead-acid, lithium-ion, sodium-sulfur, nickel-cadmium .....

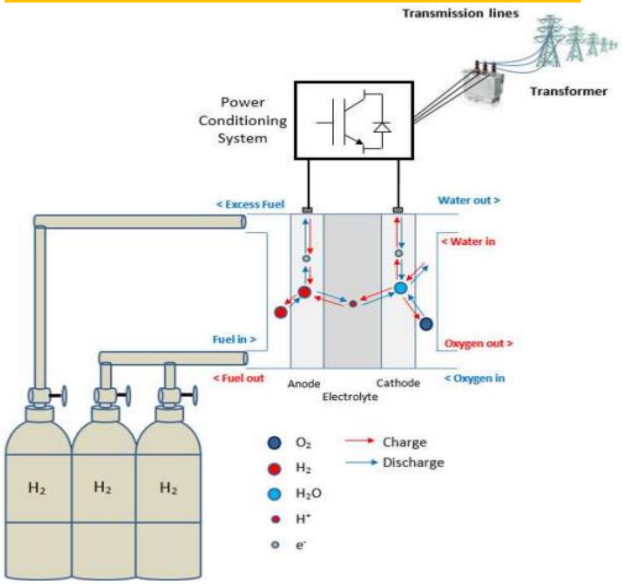
- Flow batteries

vanadium redox, polysulfide bromide, zinc-bromine, metal-air

- Regenerative fuel cells







Electrical Energy Storage – comparison

BES	Advantage	Disadvantage
Lead-acid	Matured technology Low maintenance requirement	Non- environment friendly
Lithium-ion	High energy density; Cycle or round-trip efficiency is a key element in evaluating EES options in power system applications. Lithium-ion batteries have very high efficiency; No memory effect; Low self-discharge	High cost
Sodium-sulfur	High power and energy density; High efficiency; Good temperature stability; Long cycle life	High cost
Nickel cadmium	Matured technology Low maintenance requirement	Toxicity of cadmium requires a complex recycling procedure; Lower energy density

Electrical Energy Storage – comparison

BES	Advantage	Disadvantage
Flow batteries	High power and energy capacity; Fast recharge by replacing exhaust electrolyte; Long-term storage duration, Long life enabled by easy electrolyte replacement; Full discharge capability; Use of non toxic materials; Low temperature operation	The need for moving mechanical parts such as pumping systems that make system miniaturization difficult
Metal-air	Low cost	Non-matured technology
Regenerative fuel cells	Long-term storage duration	Non-matured technology

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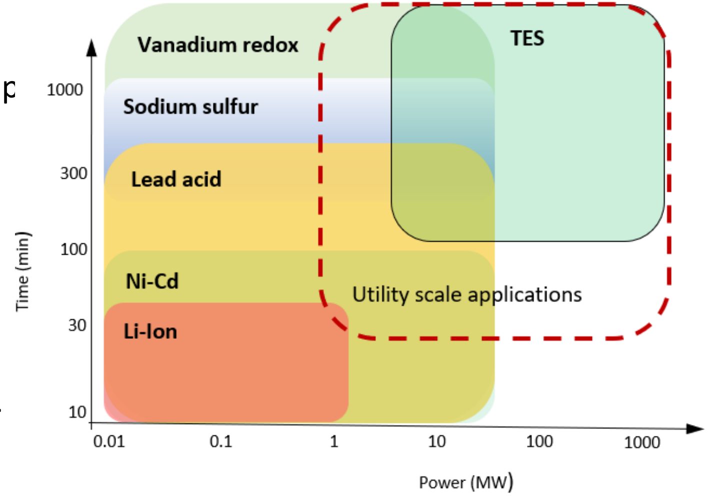
Electrical Energy Storage – selection

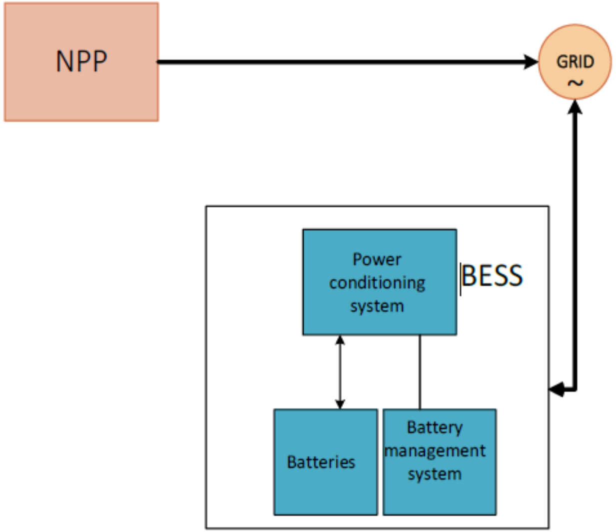
- Selection of the best BES depends on application requirements (power quality, energy management, emergency back-up power, ramping and load following, peak shaving, voltage regulation and control etc)
- Lead-acid, lithium-ion, sodium-sulfur
    - suitable and highly promising for the most of applications (except of seasonal energy storage)
- Vanadium redox, NAS and large-scale (lead–acid, lithium-ion, Ni–Cd) technologies, are applied for energy management purposes, because of their long discharge timescales
- Lithium-ion is likely to replace Ni–Cd in the future, due to toxicity of cadmium and its complicated recycling process



Electrical Energy Storage – selection

TANDEM Modeling

- Lithium-ion
- Lead-acid
- Sodium-sulfur
- Vanadium redox



Parameter	Lead acid	Lithium-ion	NAS	Vanadium redox
Energy Density (kWh/m^3)	25-90	94-500	150-345	10-33
Power Density (kW/m^3)	10-400	56-800	1.3-50	2.5-33
Specific Energy (Wh/kg)	25-50	75-200	100-240	10-30
Specific Power (W/kg)	75-300	150-2000	90-230	166
Rated Energy Capacity (MWh)	0.001-40	0.004-10	0.4-244.8	≤60
Power Rating (MW)	0-40	0-100	10-34	0.03-50
Daily Self-Discharge (%)	0.1-0.4	0.15-0.3	0.05-20	Very small
Operating temperature (°C)	-30 to +50	-20 to +60	300-350	10-40
Nominal cell voltage (V)	2.0-2.35	3.6-4.2	2.1	1.4-1.5
Response Time	Milli-seconds	Milli-seconds	Milli-seconds	Milli-seconds

Conclusion

- The most promising battery technology at 2030-2040 timeline
  - the next generation of Lithium batteries - alternative Li-ion technology with lithium sulphur/air

- Flow batteries (e.g. vanadium redox) could emerge as a breakthrough technology for grid-scale storage
  - do not show degradation of performance for long period and are capable to be sized according to energy storage needs

- Regarding non-matured technologies, it is difficult to predict which concept will be matured at 2035 for grid-scale storage purposes. Researches on next generation batteries:
  - nanobolt Lithium Tungsten batteries; rechargeable Zinc-Manganese oxide battery; Gold nanowire gel, electrolyte batteries, etc.

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