Review of Energy Storage Systems

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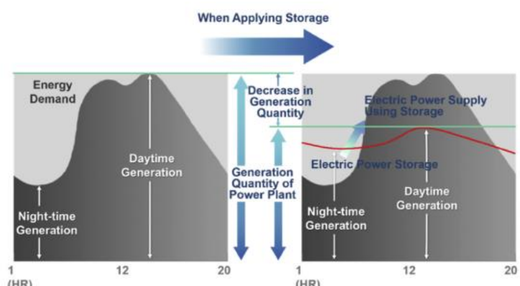
Overview

- Overview of Energy Storage
- Review of Energy Storage Systems (ESS)
- Performance Measures
- Present RFB Technologies

Energy Storage Systems (ESS)

- Why the need for ESS?
  - Renewable energy sources like Solar and Wind can be intermittent and unpredictable
  - Energy Storage Systems can provide load-levelling and can improve grid stability [Cho J, et al., PECS 2015]



Redrawn by [Cho J, et al, PECS '15] from [Yang Z, et al, CR '11]

Energy Storage Systems

- Review of Energy Storage Sytems from [Kyriakopoulos G, Arabatzis G, RSER '15] and [Guarnieri M, et al., RSER '15]
- Mechanical Energy Storage (MES)
- Thermal Energy Storage (TES)
- Electrochemical Double Layer Capacitor [EDLC]
- Electrochemical Energy Storage [ECES]

Performance Measures

- Top Power (MW)
- Top Energy (MW-h)
- Energy Density (W-h/kg)
- Discharge Time (seconds, minutes, hours)
- Response Time (seconds, minutes, hours)

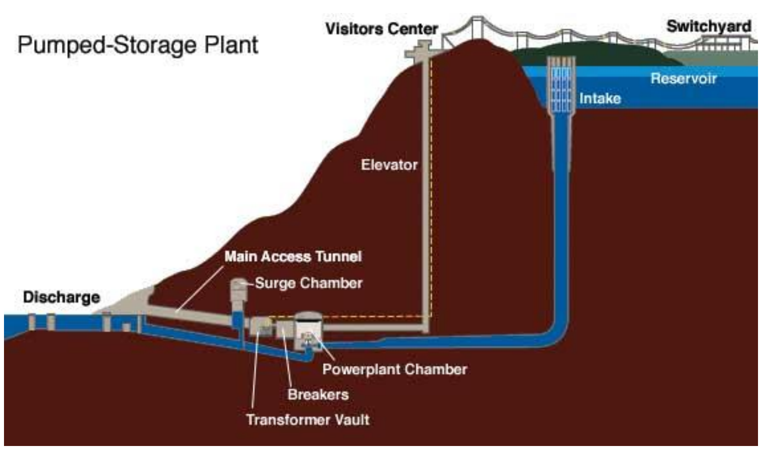
Performance Measures

- Round-trip Efficiency (%)
  - Ratio of energy put-in vs. energy retrieved from storage
- Cycle Life / Lifetime
- Capital Cost
  - Power (PHP/kW)
  - Energy (PHP/kW-h)

Mechanical Energy Storage (MES)

- Pumped Hydro Storage (PHS)
- Compressed Air Energy Storage (CAES)
- Flywheel Energy Storage (FES)

Pumped Hydro Storage (PHS)



Source: Image taken from http://www.tva.gov/power/pumpstorart.htm,
Public Domain, https://commons.wikimedia.org/w/index.php?curid=2740079

Pumped Hydro Storage (PHS)

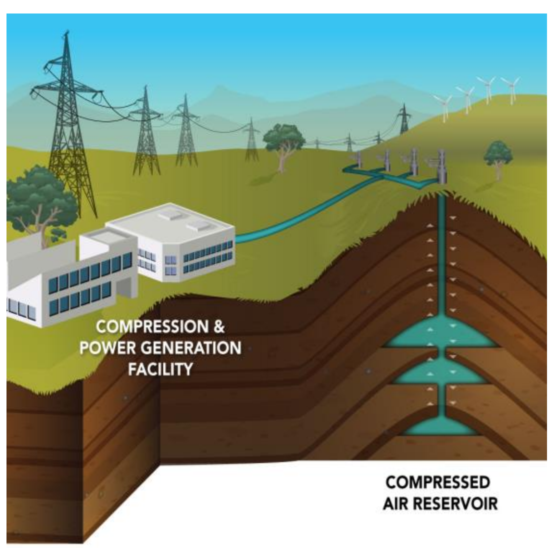
Parameter	Remarks
Typical Operation	Potential energy used: Two reservoirs located at different elevations; water is pumped to the higher reservoir during off-peak hours and discharged to the lower reservoir during peak hours
Output | Capacity	10MW to GW
Efficiency	65-85%
Energy Density	0.5 – 1.5 W-h/kg
Cap. Cost | Lifetime	80-200 $ / kW-h | 30-60 yrs
Advantages	Commercial maturity, high energy and power capacity, least cost for large-scale power, long life.
Disadvantages	Location limited, long lead-time (>10 years), requires special sites

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067, Modified currencies to use USD.

Compressed Air Energy Storage

During power generation air is compressed in the reservoir.

Compressed air is heated and expanded to drive turbines that generate power.



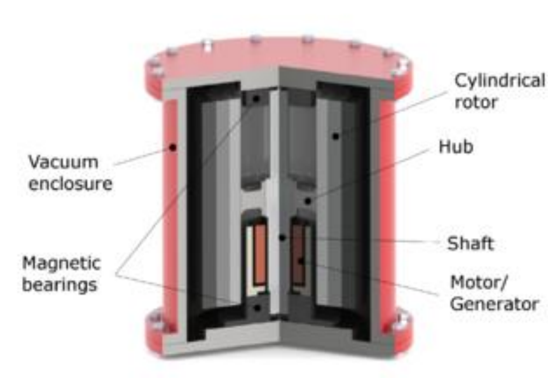
Source: Image taken from http://caes.pnnl.gov/images/Base_v4-02.jpg

Compressed Air Energy Storage (CAES)

Parameter	Remarks
Typical Operation	High and low pressure turbines used, air compressor operating in geological cavities of underground rock or salt cavern, air-pressure: 4-8MPa
Output | Capacity	100 MW to GW
Efficiency	50-89%
Energy Density	30-60 W-h/kg
Cap. Cost | Lifetime	Approx. 200-1400 $/kW-h | 20-60 years
Advantages	Developed technology, high energy and power capacity, long-life.
Disadvantages	Requires special geological sites, high capital cost, long construction time, need for gas fuel input.

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067, Modified currencies to use USD.

Flywheel Energy Storage (FES)



Source: By Pjrensburg - a rendering from a solid-works model, edited to include labels, in png format. Previously published: 2012-04-29, CC BY-SA 3.0

Flywheel spins during power generation. Energy is stored as kinetic energy (angular momentum).

Energy is released through rotational inertial during peak hours.

Flywheel Energy Storage (FES)

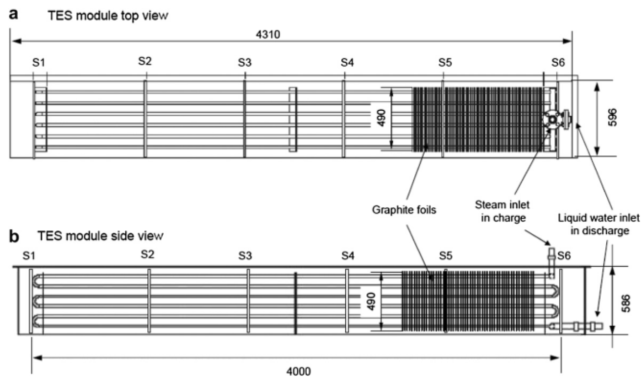
Parameter	Remarks
Typical Operation	Energy stored as angular momentum of a spinning mass during off-peak hours; energy released during peak hours
Output | Capacity	Approx. 0-250 kW
Efficiency	> 90%
Energy Density	30 W-h/kg
Cap. Cost | Lifetime	Approx. 260 $/kW, 3600 $/kw-h | Approx. 15-20 years
Advantages	Portability, can be scaled to different power and energy requirements.
Disadvantages	Technology is still under research, MW capabilities still under development.

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067, Modified currencies to use USD.

Thermal Energy Storage (TES)

- Energy can be used to heat (High-temperature TES) or cool (Low-temperature TES) a thermal storage medium
- Example thermal storage mediums: Water, Salt Hydrates

Example: High-Temperature TES



Concentrating Solar Power (CSP) plants heat up thermal storage medium. Water is heated and turned to steam using the thermal storage medium to drive turbines.

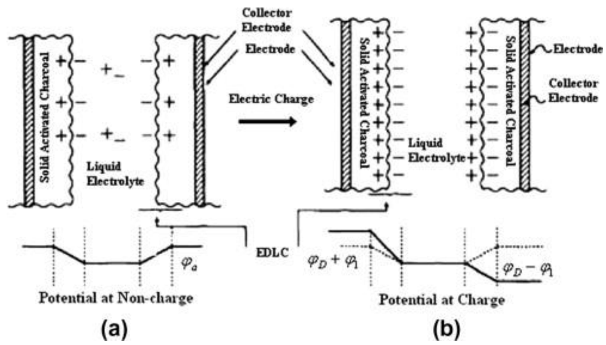
Source: E. Oro, A. Gil, A. de Gracia, D. Boer, L.F. Cabeza, Comparative life cycle assessment of thermal energy storage systems for solar power plants. Renewable Energy 2012;44:166-173.

Thermal Energy Storage (TES)

Parameter	Remarks
Typical Operation	Water in Water Tanks: 110 °C, Acquifers and ground storage: 50 °C, Concrete: 400 °C Salt Hydrates: 30-80 °C
Output | Capacity	Approx. 0-300 MW
Efficiency	30-60%
Energy Density	80-250 W-h/kg
Cap. Cost | Lifetime	Approx. 130-200$/kW 2-30$/kW-h| 5-40 yrs.
Advantages	Depends on thermal storage medium: for water, low cost, when using salt hydrates, high storage density
Disadvantages	Depends on thermal storage medium: for water, significant heat loss over time, for salt hydrates, high capital cost

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067. Modified currencies to use USD.

Electrochemical Double Layer Capacitor (EDLC)



EDLCs are also known as Ultracapacitors or Supercapacitors have very high capacitances.
The porous material increases effective area and the distance between the plates are made significantly small.
[Sharma P, Bhatti TS, ECM '10]

Electrochemical Double Layer Capacitor (EDLC)

Parameter	Remarks
Typical Operation	Used for fast services such as sag compensation, already tested in electric buses (capabuses). [Guarnieri M, et al, RSER 2015]
Output | Capacity	100MW | 10 kW-h
Efficiency	95%
Energy Density	10-30 W-h/kg
Cap. Cost | Lifetime	4,600$/kW-h | 500,000 cycles
Advantages	High efficiency, high charge and discharge rates, virtually maintenance free.
Disadvantages	Costly for large-scale energy storage applications.

Source: Guarnieri M, Alotto P, Moro F. Redox flow batteries for the storage of renewable energy: A review. Renewable and Sustainable Energy Reviews 2014(29):325-335.

Electrochemical-based EES

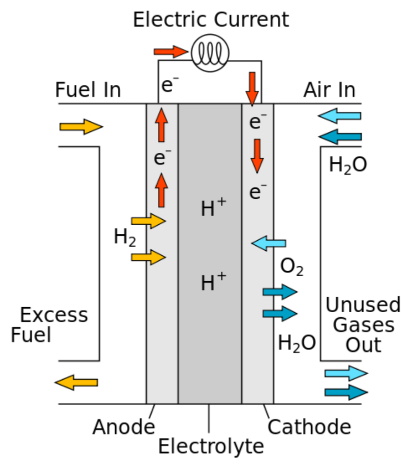
- Hydrogen-based Energy Storage Systems (HESS)
- Lead-Acid Batteries
- Li-Ion Batteries
- Na-S Batteries
- Redox Flow Batteries

Hydrogen-based Energy Storage System (HESS)

Electrolyzer unit converts electrical energy input from off-peak hours to hydrogen.

Hydrogen is combined with oxygen to convert stored chemical energy to electrical energy during peak-hours.

[Ding Y, et al., PNS '09]



Source: By R.Dervisoglu - Own work, based on http://en.wikipedia.org/wiki/File:Solid_oxide_fuel_cell.svg, Public Domain

Hydrogen-based Energy Storage System (HESS)

Parameter	Remarks
Typical Operation	Uses Hydrogen Fuel Cells
Output | Capacity	Approx. 0-50MW
Efficiency	69% [Gonzalez EL, et al., IHHE '15], 20-50% [Ding Y, et al., PNS '09]
Energy Density	0.6-1.2 kW-h/kg
Cap. Cost | Lifetime	> 10,000 $/kW | 5-15 years, almost zero self discharge
Advantages	High energy density, can implement systems on a wide range of capacities, independent system charge rate, discharge rate, and capacities
Disadvantages	High cost, low roundtrip efficiency

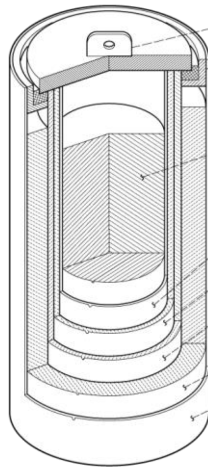
Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067. Modified currencies to use USD.

Lead-Acid Batteries

Parameter	Remarks
Typical Operation	Lead Acid Batteries in different configurations
Output | Capacity	0-40 MW
Efficiency	70-90%
Energy Density	30-50W
Cap. Cost | Lifetime	200-400$/kW, 200-260/kW-h | 3-15 yrs.
Advantages	Mature technology, cost reduction via increased scale of production
Disadvantages	Pb is toxic, limited applicability for large-scale EES due to higher power applications involved

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067. Modified currencies to use USD.

Na-S Batteries



Source: By NaS_battery.jpg: This image was made by NASA John Glenn Research Center. derivative work: Quibik (talk) - NaS_battery.jpg, Public Domain

Na-S Batteries

Parameter	Remarks
Typical Operation	Na as anode, S as cathode, beta-alumina Al2O3 as solid electrolyte and separator. [Cho J, et al., PECS 2015] Cell operated at high temperatures (300-500^{o}C).
Output | Capacity	0-8MW
Efficiency	75-90%
Energy Density	150-240 W-h/kg
Cap. Cost | Lifetime	300-500$/kw-h | 5-15 yrs.
Advantages	High energy and power density, high efficiency and life-cycle, mature technology.
Disadvantages	Highly-corrosive behavior, necessity for extra safety precautions, high initial cost.

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067. Modified currencies to use USD.

Li-ion Batteries

Parameter	Remarks
Typical Operation	Widespread use in portable electronics devices, but still faces several challenges for large-scale energy storage. [Cho J, et al., PECS 2015]
Output | Capacity	0.1 MW
Efficiency	85-98%
Energy Density	75-200 W-h/kg
Cap. Cost | Lifetime	300-500$/kW-h | 5-15 yrs.
Advantages	High energy and power density, long life, and high efficiency. Mature technology for portable devices.
Disadvantages	High cost, necessity for protective system against cell degradation and thermal run-away due to electrolyte decomposition, requires sophisticated management.

Source: G.L. Kyriakopoulos, G.Arabatzis. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067. Modified currencies to use USD.

Thank you!

Redox Flow Batteries to be presented
by Dr. Nathaniel Dugos

Table 1
Best performance and typical figures of main energy storage systems.

Technology	Top power [MW]	Top energy [MW h]	Energy density [W h/kg]	Discharge time	Response time	Round-trip efficiency	Cycle life $\times 10^3$	Capital cost [k$/kW]	Capital cost [$/kW h]	Capital cost [$/MW h/cycles]
PHES	3000	10^4	0.3	10^1 h	min	70–85%	20	0.4–5.6	10–350	0.5–3
CAES:										
Underground	300	10^3	10–30	10^0–10^1 h	min	60–	30	1.7	130–550	4–18
Aboveground	50	10^2	–	10^1 h	min	75%	> 10	2.2	430	43
TES	20	10^1	70	h	min	–	10	–	5,000	500
FES:										
Commercial	20	5	11–30	min	ms	85%	10^1–10^2	2.3	2,400	25–200
Lab	400	1	1.6	s	ms	–	–	–	–	–
SMES:										
Under development	100	10^1–10^3	–	min	ms	90–95%	10	2	> 10,000	1000
Lab	400	10	1.2	s	ms	–	–	–	–	–
EDLC	100	10^{-2}	10–30	s	ms	95%	500	–	4,600	10
ECES:										
Advanced lead-acid	10–40	10^0–10^1	25–50	10^0 h	ms	75–85%	3	4.6	130	150
Sodium-sulfur	34	10^1	150–120	10^0 h	s	85–90%	4.3–6	3.5	550	90–130
Sodium-nickel-chlorine[a]	1	6	95–120	10^0 h	s	85%	3–4	3.5	650	150–200
Lithium-ion	16	20	100–200	10^0 h	ms	95%	4–8	3–4	600	150–200
Electrolyzer/fuel cells	1	> 10	800–1300	> 10^0 h	ms	35–45%	50	17	> 10,000	200
Redox flow battery	2–100	6–120	10–50	10^0–10^1 h	ms	85%	> > 13	3.2	900	< < 70

–Means not applicable or unknown.

[a] Data courtesy of FIAMM S.p.A.—Zebra-Sonick (Italy).

Source: Guarnieri M, Alotto P, Moro F. Redox flow batteries for the storage of renewable energy: A review. Renewable and Sustainable Energy Reviews 2014(29):325-335.

Table 2
Design and operating features of main energy storage systems.

Technology	Scalability	Flexibility	W–W h Independency	Environmental impact	Safeness issue
PHES	Good	Low	Yes	High	High
CAES:					
Underground	Low	Low	Yes	High	High
Aboveground	Low	Low	Yes	Low	High
TES	Low	Low	Yes	Mild	Mild
FES:					
Commercial	High	Good	Yes	Low	Mild
Lab	Low	Low	Yes	Low	Mild
SMES:					
Under development	Good	Low	No	Low	Low
Lab	Good	Low	No	Low	Low
EDLC	Low	Low	No	Low	Mild
ECES:					
Advanced lead-acid	Good	Good	No	Low	Low
Sodium-sulfur	Good	Good	No	Low	Mild
Sodium-nickel-chlorine[a]	Good	Good	No	Low	Mild
Lithium-ion	High	Good	No	Low	Low
Electrolyzer/fuel cells	High	High	Yes	Low	Mild
Redox flow battery	High	High	Yes	Low	Low

[a] Data courtesy of FIAMM S.p.A.—Zebra-Sonick (Italy).

Source: Guarnieri M, Alotto P, Moro F. Redox flow batteries for the storage of renewable energy: A review. Renewable and Sustainable Energy Reviews 2014(29):325-335.

References

Kyriakopoulos GL, Arabatzis G. Electrical Energy Storage Systems in Electricity Generation: Energy Policies, Innovative Technologies, and Regulatory Regimes. Renewable and Sustainable Energy Reviews 2016;56:1044–1067.

Guarnieriri M, Alotto P, Moro F. Redox flow batteries for the storage of renewable energy: A review. Renewable and Sustainable Energy Reviews 2014(29):325-335.

Yang Z, Zhang J, Kintner-Meyer MCW, Lu X, Choi D, Lemmon JP, et al. Electrochemical energy storage for Green grid. Chem Rev 011:3577-613

Cho J, Jeong S, Kim Y. Commercial and research battery technologies for electrical energy storage applications. Prog Energy Combust Sci 2015;48:84–101.

Oro, A. Gil, A. de Gracia, D. Boer, L.F. Cabeza, Comparative life cycle assessment of thermal energy storage systems for solar power plants. Renewable Energy 2012;44:166-173.

González EL, Llerena FI, Pérez MS, Iglesias FR, Macho JG. Energy evaluation of a solar hydrogen storage facility: comparison with other electrical energy storage technologies. Int J Hydrog Energy 2015;40(15):5518–25.

Sharma P, Bhatti TS. A review on electrochemical double-layer capacitors. Energy Conversion and Management 2010;51(12):2901–12.