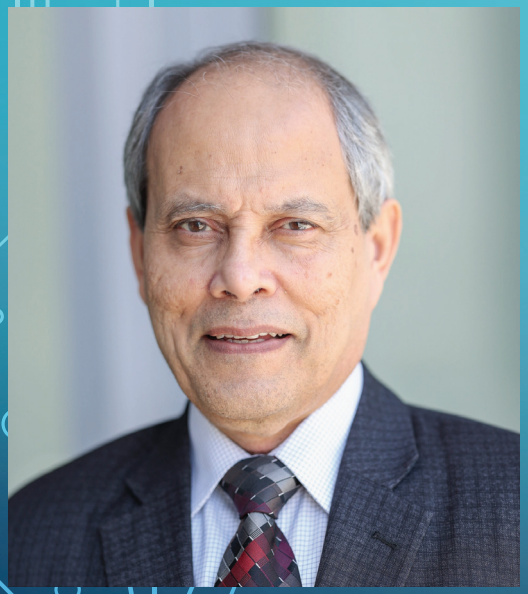
A Brief Overview of Energy Storage Systems and Their Application-Based Classification



Pumped Storage and New Energy Storage Forum

Keynote Speech
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2023 IEEE President

Need For Energy Storage

Energy storage is critical in power systems for several reasons:

- Balancing Supply and Demand
- Mitigating Intermittency of Renewable Energy Sources
- Peak Load Management
- Grid Stability and Reliability
- Energy Arbitrage

Need For Energy Storage - 2

- Resilience and Backup Power
- Transmission and Distribution Support
- Microgrids and Off-Grid Applications
- Energy Efficiency
- Ancillary Services (frequency control, spinning reserves, and energy trading)
- Decarbonization

A Few Energy Storage Systems to Consider

A few selected ESS technologies are:

1. Pumped Hydro Storage (PHS) Systems
2. Compressed Air Energy Storage Systems (CAES)
3. Flywheel Energy Storage Systems
4. Battery Energy Storage Systems (BESS)

Pumped Hydro Storage (PHS) Systems

- Pumped hydro storage (PHS) is one of the most widely used mechanical energy storage systems.
- PHS accounts for over 94% of the world's installed energy storage capacity.
- Stores electrical energy by using the potential energy of water.
- During low-demand hours, the water is pumped and stored in an upper reservoir.
- When the demand is high, this stored water is released and converted into electrical power with good efficiency (around 70 to 85%).

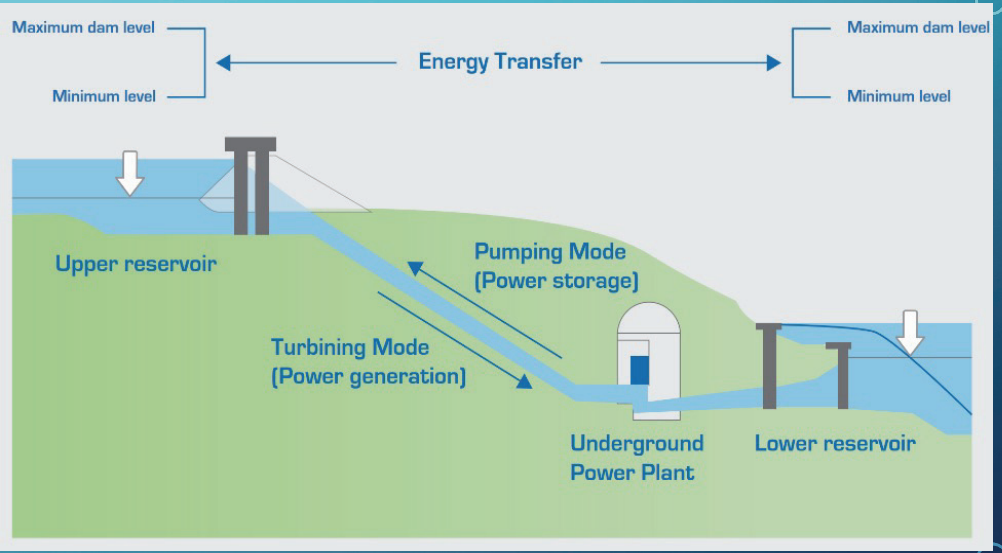

Figure 4: Charging and discharging principle of pumped hydro storage (PHS).

[Image Source: https://ease-storage.eu/energy-storage/technologies/]

Hebei Fengning (China) Pumped Storage Station

Net Generation Capacity: 3,600 MW

(Under Construction, will be largest in the world)

Source: https://en.powerchina.cn/2025-05/06/c_817026.htm

Guangdong Huizhou (China) Pumped Storage Station

Net Generation Capacity: 2,400 MW

It has eight units with a single unit capacity of 330 MW.

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world
https://baike.baidu.com/item/惠州抽水蓄能电站/1680261

Guangdong Meizhou (China) Pumped Storage Station

Net Generation Capacity: 2,400 MW

(Active Capacity 1,200 MW Phase 1

1,200 MW to be added Phase 2

Source: https://en.powerchina.cn/2025-05/06/c_817026.htm

More Photo: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Bath County (Virginia, USA) Pumped Storage Station

Net Generation Capacity: 3,003 MW (largest in the world)

Lower Reservoir Dam is 135 feet high and 2,400 feet long

Upper Reservoir Dam is 460 feet high and 2,200 feet long

Water level fluctuates 105 feet during operation

Source: https://www.dominionenergy.com/about/making-energy/hydroelectric-power-facilities/bath-county-pumped-storage-station

More Photo: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Ludington (Michigan, USA) Pumped Storage Station

Net Generation Capacity: 1,872 MW

It has six units with a single unit capacity of 312 MW.

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Grand Maison (France) Pumped Storage Station

Net Generation Capacity: 1,800 MW

It has 12 units with a single unit capacity of 150 MW

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world
https://www.nsenergybusiness.com/projects/grand-maison-hydroelectric-power-plant/

La Muela (Spain) Pumped Storage Station

Net Generation Capacity: ~1,800 MW (Approximate)

It has 7 units across two stages (3+4 units).

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Dinorwig (United Kingdom) Pumped Storage Station

Net Generation Capacity: ~1800 MW

It has 6 units with single unit capacity of 300 MW.

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Raccoon Mountain (Tennessee, USA) Pumped Storage Station

Net Generation Capacity: 1,652 MW

It has 4 units with single unit capacity of 413 MW.

Source: https://www.enr.com/articles/44302-the-10-largest-pumped-storage-hydropower-plants-in-the-world

Top 25 Countries: Current Storage Systems

Operational		
Country	**Capacity (MW)**	**No. of Plants**
China	31471.45	90
Japan	28064.21	84
United States	24458.55	874
Spain	9600.356	80
Germany	7935.624	81
Italy	7134.617	54
India	6773.29	15
Switzerland	6374.585	24
Austria	6307.564	27
France	5861.845	35
South Korea	4855.443	58
Portugal	3553.605	16
United Kingdom	3253.798	29

Country	**Capacity (MW)**	**No. of Plants**
Ukraine	3174.043	4
Australia	2711.858	53
Taiwan	2608.727	7
Czech Republic	2393.04	16
Russia	2228.925	8
Poland	1926	11
South Africa	1885.01	8
Thailand	1391	3
Belgium	1340.5	11
Luxembourg	1096	1
Bulgaria	1052	3
Indonesia	1040.4	2
R.O.W.	9942.576	167
Total (Apprx.)	**178.44 TW**	**1761**

Source: DOE Global Energy Storage Database (https://gesdb.sandia.gov/)

Top 25 Countries: Future Storage Systems

Upcoming/ Under Construction/ Standby		
Country	**Capacity (MW)**	**No. of Plants**
United States	8283.188	214
Italy	572	1
Austria	300	1
China	267.5	4
Germany	251.2	10
Chile	210	2
South Africa	100	1
South Korea	36.1	2
Canada	28.75	8
United Kingdom	25.4	4
Kazakhstan	25	1
France	16.1	3

Country	**Capacity (MW)**	**No. of Plants**
Australia	5.3	4
Finland	5	2
Netherlands	4.75	2
Rwanda	2.68	1
Ireland	2.5	2
Qatar	2	1
Greece	0.8	1
Mexico	0.39	1
Thailand	0.3	1
R.O.W.	0	0
Total (Apprx.)	**10.14 TW**	**266**

Source: DOE Global Energy Storage Database (https://gesdb.sandia.gov/)

Energy Storage Technology Map

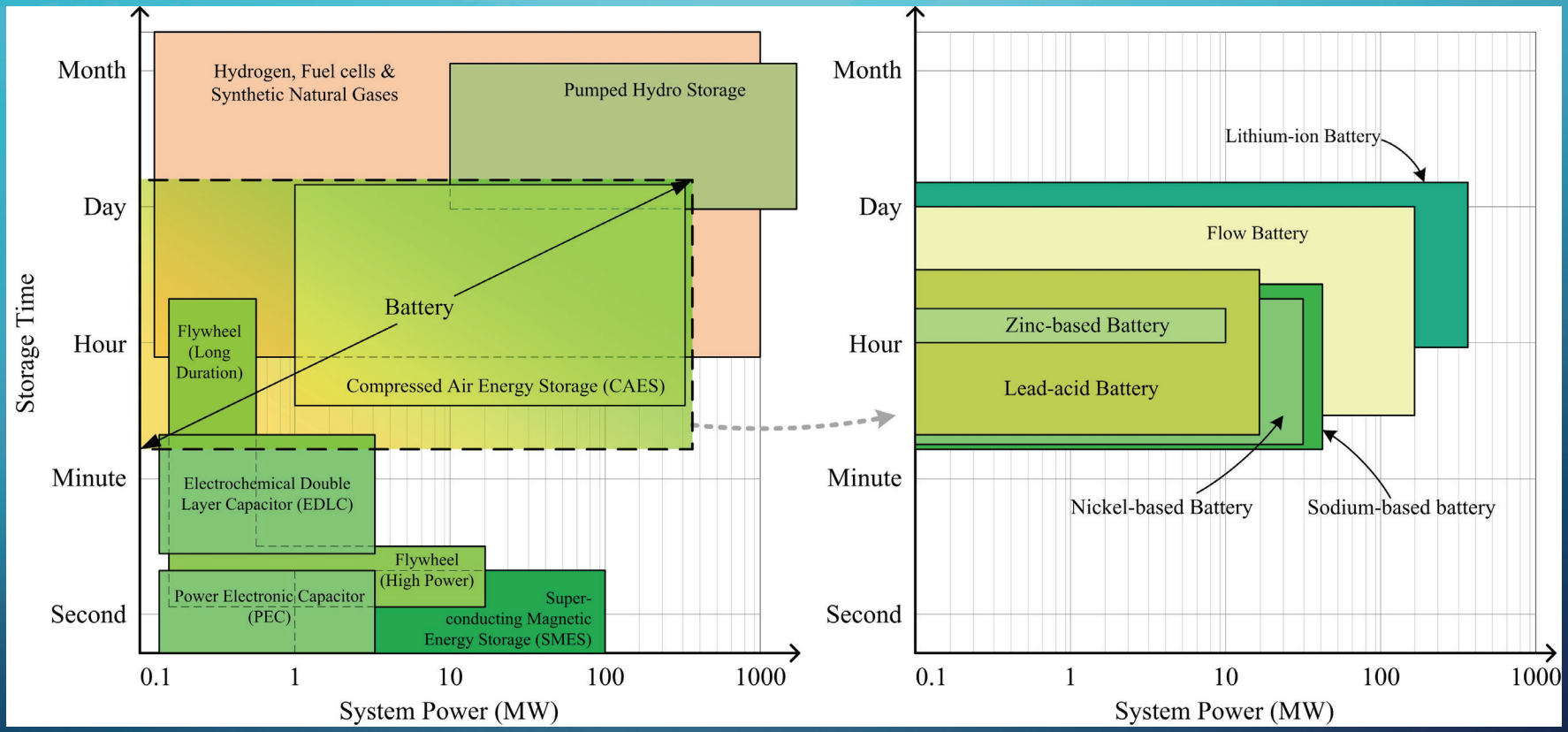

Figure 3: Energy storage technology map: storage time vs system power.

The left part of the figure is adapted from the "Energy Storage Technology Review" by SBC Energy Institute and updated from the current "DOE Global Energy Storage Database" [https://gesdb.sandia.gov/, https://wecanfigurethisout.org/ENERGY/Energy_home.htm].

Suitable Technologies for Energy Storage Applications

Duration		Applications	Examples of Suitable Technologies
Short-term	Millisec. to Minutes	• Frequency regulation • Voltage support • Uninterruptible power supply (UPS) • Black Start support • Renewable smoothing	• Batteries: High power density, fast response (Lithium-Ion such as LFP, LTO, LNMC etc., NaS). • Flywheels: High-power, short-duration variants. • Supercapacitors: Extremely fast charge/ discharge cycles.

Suitable Technologies for Energy Storage Applications - 2

Duration		Applications	Examples of Suitable Technologies
Mid-term	Minutes to Hours	• Load shifting • Peak shaving • Renewable intermittency mitigation • Spinning reserve	• Batteries: Conventional batteries like Lithium-Ion (e.g. LFP, LTO, LNMC etc.), NaS and others for hours-scale storage as well as flow batteries (e.g. VRFB) for scalability & longer-duration storage. • Pumped Hydro: Can support hours of operation depending on reservoir size. • Compressed Air Energy Storage (CAES): Suitable for hours of discharge in certain regions.

Suitable Technologies for Energy Storage Applications - 3

Duration		Applications	Examples of Suitable Technologies
Long-term	Days to Months	• Seasonal energy storage • Grid resilience • Renewable energy backup • Energy price arbitrage	• Hydrogen Energy Storage: Large-scale and long-duration storage in salt caverns or tanks. • Pumped Hydro Storage: Ideal for seasonal storage in regions with appropriate geography. • Power-to-Gas: Converting electricity into synthetic fuels (e.g., methane) for long-term storage. • Thermal Energy Storage: Storing heat in molten salts, rocks, or other materials for months. • Compressed Air Energy Storage (CAES): Suitable for multi-day or seasonal storage in underground caverns.

Thank You