

Energy storage technologies: advantages, disadvantages, applications, and economic and environmental perspectives – a comprehensive review

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ABSTRACT

The global transition toward renewable energy sources, due to the intermittent nature of solar and wind power generation, necessitates the development of efficient energy storage systems. This paper provides a comprehensive review of energy storage technologies, including mechanical, electrochemical, chemical, and thermal systems. Comparative analysis indicates that lithium-ion battery systems, with round-trip efficiencies of 78–98% and response times in milliseconds, are the most suitable option for short-term applications, while hydrogen storage systems, with high energy density (120–142 MJ/kg), offer advantages for seasonal and long-term storage [1].

From an economic perspective, the levelized cost of storage for lithium-ion batteries ranges from 600 to 3800 \$/kWh, while for hydrogen systems it varies between 2 and 15 \$/kWh [2]. Environmental assessment reveals that the extraction of raw materials for batteries, such as lithium and cobalt, poses serious challenges, whereas green hydrogen systems, despite lower efficiency (35–50%), have lower carbon footprints over their life cycle [3].

The results indicate that the optimal approach is a hybrid combination of different technologies capable of meeting diverse grid requirements across various time scales.

Keywords: Energy Storage, Lithium-Ion Battery, Hydrogen Storage, Levelized Cost of Storage, Life Cycle Assessment, Renewable Energy Systems

1. INTRODUCTION

Climate change and the depletion of fossil fuel resources have driven the global community toward renewable energy sources. However, the intermittent nature of solar and wind power generation presents a major challenge for reliable and stable electricity supply [4]. Energy storage systems (ESS) have emerged as a key solution to overcome this challenge,

enabling the storage of surplus energy during high production periods and its release during low production or peak demand periods [5].

Over the past decade, significant progress has been made in energy storage technologies. The cost of photovoltaic panels has dropped by over 80%, and along with growing environmental concerns, this has led to substantial investments in this field [1].

However, selecting the appropriate storage technology requires a multi-dimensional assessment including technical, economic, and environmental criteria, since no single technology is optimal across all metrics [2].

This paper systematically reviews various energy storage technologies, their advantages and disadvantages, applications, and economic and environmental perspectives. The structure includes an introduction to the main technologies, comparative performance analysis, economic evaluation, environmental assessment, and future outlook.

2. CLASSIFICATION OF ENERGY STORAGE TECHNOLOGIES

Energy storage systems are classified into four main categories: mechanical, electrochemical, chemical, and thermal [6].

2-1. Mechanical Storage

Pumped Hydro Storage (PHS): Accounting for approximately 96% of global storage capacity, this is the most mature large-scale storage method. Water is pumped to an upper reservoir during surplus energy periods and released through turbines during demand. Capacity depends on water volume and head height, with efficiency ranging from 50% to 90% [1].

Compressed Air Energy Storage (CAES): In this method, compressed air is stored in underground caverns or reservoirs. Efficiency ranges from 41% to 90%, with response times of 1–15 minutes [6].

Flywheel Energy Storage: Energy is stored kinetically in a rotating rotor. High efficiency (70–96%) and long life (10^4 – 10^7 cycles) are advantages, but capital costs are high [4].

2-2. Electrochemical Storage (Batteries)

Lithium-Ion Batteries: With an energy density of 60–300 Wh/kg and efficiency of 78–98%, these are the most popular choice for short-term applications. Their millisecond response time makes them ideal for grid frequency regulation [2].

Lead-Acid Batteries: Despite low energy density (10–50 Wh/kg) and limited cycle life (250–2000 cycles), they are still used in specific applications due to low cost [6].

Flow Batteries (Vanadium Redox): With long cycle life (800–16,000 cycles) and scalability, they are suitable for long-duration storage, although energy density is low (10–50 Wh/kg) [3].

2-3. Chemical Storage (Hydrogen)

Hydrogen, with high energy density (800 Wh/kg) and near-zero self-discharge, is a suitable option for seasonal and long-term storage. However, low cycle efficiency (20–50%) and high infrastructure costs are major challenges [3].

2-4. Thermal Storage

Phase-change materials with energy densities of 80–250 Wh/kg are suitable for heating and cooling applications in buildings and industrial processes [6].

3. COMPARATIVE PERFORMANCE ANALYSIS

Table 1 provides a comprehensive comparison of different energy storage technologies based on key performance indicators. As observed, each technology has its own strengths and weaknesses, and the selection depends on the specific application.

Table 1: Performance comparison of energy storage technologies [1]

Technology	Energy Density (Wh/kg)	Efficiency (%)	Cycle Life	Response Time
PHS	0.2 – 1.5	50 – 90	$10^4 - 6 * 10^4$	Seconds-minutes
CAES	3 – 60	41 – 90	$10^4 - 3 * 10^4$	1-15 minutes
Flywheel	5 – 200	70 – 96	$10^4 - 10^7$	Milliseconds
Li-ion	300 – 60	78 – 98	$250 - 10^4$	Milliseconds
Lead-acid	10 – 50	60 – 90	250 – 2000	Milliseconds
Flow	10 – 50	60 – 90	$- 1.6 - 10^4$ 800	Seconds-minutes
Hydrogen	800	20 – 50	1000	Seconds-minutes
Supercapacitor	1 – 50	65 - 99	$10^4 - 10^6$	Milliseconds

Table 2: Comparative analysis of energy storage systems in terms of power and cost [2]

Technology	Energy Density	Power Density	Efficiency	Cost	Main Application
Li-ion	High	Medium	90 – 95 %	Medium	Portable electronics, EVs, Grid
Lead-acid	Low	Low	70 – 80 %	Low	UPS, Grid, Automotive
Supercapacitor	Low	Very high	95 %	High	Regenerative braking, Power quality
Hydrogen	Low	Low	35 – 55 %	High	Vehicle fuel, Grid storage

4. APPLICATIONS OF ENERGY STORAGE TECHNOLOGIES

Energy storage systems play a vital role in a wide range of applications [5]:

Renewable Energy Integration: Storing surplus energy from solar and wind farms and releasing it during low generation periods.

Frequency Regulation and Grid Stability: Lithium-ion batteries with millisecond response are ideal for instantaneous grid frequency regulation.

Demand Side Management: Storing energy during off-peak hours and consuming during peak hours reduces electricity costs.

Emergency Power Supply: UPS and backup systems for critical facilities such as hospitals and data centers.

Transportation Applications: Electric and hybrid vehicles utilize high-energy-density batteries.

Microgrids: A combination of different storage technologies in microgrids enables sustainable energy supply for remote areas.

5. ECONOMIC PERSPECTIVE

5-1. Levelized Cost of Storage (LCOS)

Levelized cost of storage is the primary metric for comparing the economics of different technologies. Table 3 shows LCOS values for various technologies [2].

Table 3: Levelized cost of storage (LCOS) for different technologies [2]

Technology	Rated Power (MW)	Efficiency (%)	Lifetime (years)	LCOS (\$/kWh)
PHS	110 – 1000	42 – 54	20 – 40	2 – 120
CAES	30 – 5000	70 – 87	40 – 60	5 – 100
Thermal	0.1 – 300	30 – 60	20 – 30	3 – 60
Lead-acid	0 – 40	63 – 90	5 – 15	50 – 400
Li-ion	0 – 100	75 – 97	14 – 16	600 – 3800
Flywheel	0.25 – 20	90 – 95	15 – 20	1000 – 14000
Hydrogen	<58.5	20 – 66	20	2 – 15

Based on these data, hydrogen and pumped hydro systems have the lowest LCOS, while lithium-ion batteries and flywheels have higher costs. However, these figures are highly dependent on local conditions, project scale, and energy prices [3].

5-2. Economic Analysis Based on Discharge Duration

Research indicates a complementary relationship between different storage technologies. Lithium-ion batteries are more economical for short-term storage (several hours to one day) with high efficiency (85–95%), while hydrogen systems, despite lower efficiency (35–50%),

are more suitable for long-term and seasonal storage due to lower large-scale energy storage costs [2].

6. ENVIRONMENTAL PERSPECTIVE

6-1. Life Cycle Assessment (LCA)

Life cycle assessment examines environmental impacts at all stages, from raw material extraction to recycling. Studies show that both batteries and hydrogen systems face specific environmental challenges [3].

Lithium-Ion Batteries: Extraction of lithium, cobalt, and nickel involves serious environmental impacts including high water consumption, soil degradation, and pollution. However, advances in recycling technology can significantly reduce these impacts [3].

Green Hydrogen Systems: Hydrogen production via electrolysis using renewable electricity has very low carbon emissions. However, environmental impacts related to storage infrastructure construction and fuel cells exist [3].

6-2. Carbon Footprint Comparison

Research indicates that green hydrogen systems have lower carbon emissions over their life cycle compared to lithium-ion batteries, provided that the electricity used for electrolysis comes from renewable sources. However, the low round-trip efficiency of hydrogen implies a need for more primary energy to deliver the same final electricity [3].

7. RESULTS AND CONCLUSION

A comprehensive review of energy storage technologies reveals that no single technology can meet all requirements, and the optimal selection depends on a hybrid combination of different technologies. Key findings are summarized below:

1. Technology Complementarity: Lithium-ion batteries with high efficiency and fast response are suitable for short-term storage and grid frequency regulation, while hydrogen systems with high energy density and negligible self-discharge are advantageous for long-term and seasonal storage [1,3].

2. Economic Challenges: High upfront capital costs for many technologies, especially lithium-ion batteries and hydrogen systems, remain a major barrier. However, with technological progress and increasing scale, costs are expected to decrease by up to 40% by 2030 [2].

3. Environmental Considerations: Raw material extraction for batteries and infrastructure construction for hydrogen entail environmental impacts. Developing recycling technologies and using renewable energy in production processes are key to mitigating these impacts [3].

4. Future Outlook: Research indicates that the energy storage field is experiencing rapid growth, with the number of scientific publications reaching 2,522 by 2024. Emerging topics include sodium-ion batteries, nanostructured materials, and AI applications in storage system optimization [7].

Future research should focus on developing intelligent hybrid systems, improving recycling technologies, and reducing dependence on critical raw materials. Additionally, establishing standardized frameworks for integrated economic and environmental assessment will aid in selecting appropriate technologies [8].

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