The Princeton Journal of Interdisciplinary Research
ISSN 3069-8200

Evaluating the Most Commercially Viable Energy Storage Technologies

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Abstract

As the global energy sector shifts toward low-carbon systems, energy storage becomes essential for ensuring reliability, flexibility, and long-term sustainability. This study evaluates sixteen energy storage technologies, grouped into four categories: gravity-based, kinetic, electrochemical, and chemical. To assess commercial viability, each technology is examined using a consistent set of seven criteria: Technology Readiness Level (TRL), Life Cycle Assessment (LCA), GreenScore, Geopolitical Score, Depreciation, Cost per Energy ($/Energy), and Cost per Unit ($/Unit). These factors reflect a combination of technical maturity, environmental impact, strategic risk, and economic practicality. Scores were assigned based on published data and comparative analysis, with weights applied to emphasize criteria most relevant to large-scale deployment. Radar plots illustrate the relative strengths of each technology within its category, while a final heatmap offers an overview across all groups. The results confirm the continued market strength of pumped hydro and lithium-ion batteries, largely due to their high readiness levels and low unit costs. However, technologies such as liquid air and ammonia-based systems show promise in areas like sustainability and geopolitical stability. By integrating environmental, technical, and economic dimensions into a unified framework, this study offers a method for comparing a wide range of storage solutions. The findings are intended to inform energy planning, investment decisions, and policy development at a time when scalable and resilient energy storage is more critical than ever. As demand for clean power rises, the diversification and strategic deployment of storage technologies will remain essential to the success of the global energy transition.

Keywords: energy, storage, renewables, battery, sustainability

Introduction

Access to energy is essential to ensure the fundamental functions of our society. Meeting the increasing demand for energy ensures economic expansion and development on all societal axes (Omer, 2008; Hall & Bain, 2008). Access to energy has a cost, and ethical factors such as sustainability are becoming increasingly important (Weidenkaff et al., 2021; Sharpe, 2017). In this context, the ability to store energy is key. In the short term, energy storage can guarantee electrical grid stabilization (Hall & Bain, 2008; Mitali et al., 2022). In the medium and long terms, energy storage is a fundamental factor of resilience for developed economies that need constant access to resources to sustain production and functioning (Rogalev et al., 2022).

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ISSN 3069-8200

Global energy demand continues to rise (Figure 1), shaping how societies think about energy supply, infrastructure, and long-term sustainability (Ritchie & Rosado, 2020). The Kardashev scale, which ranks civilizations by their energy use, highlights this growing dependence on energy as a marker of development. Humanity remains far from Type I, capable of harnessing all the energy available on Earth, However, our trajectory points toward increasing consumption as more sectors electrify and global living standards improve (Kardashev scale, 2025; Zhang et al., 2023).

Figure 1.

Kardashev Scale Projections. Edited from (“Kardashev Scale,” 2025).

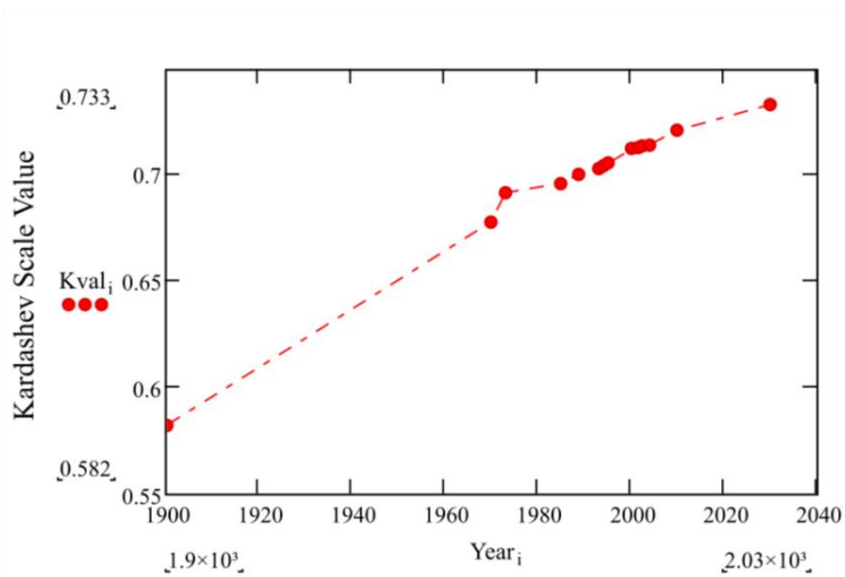
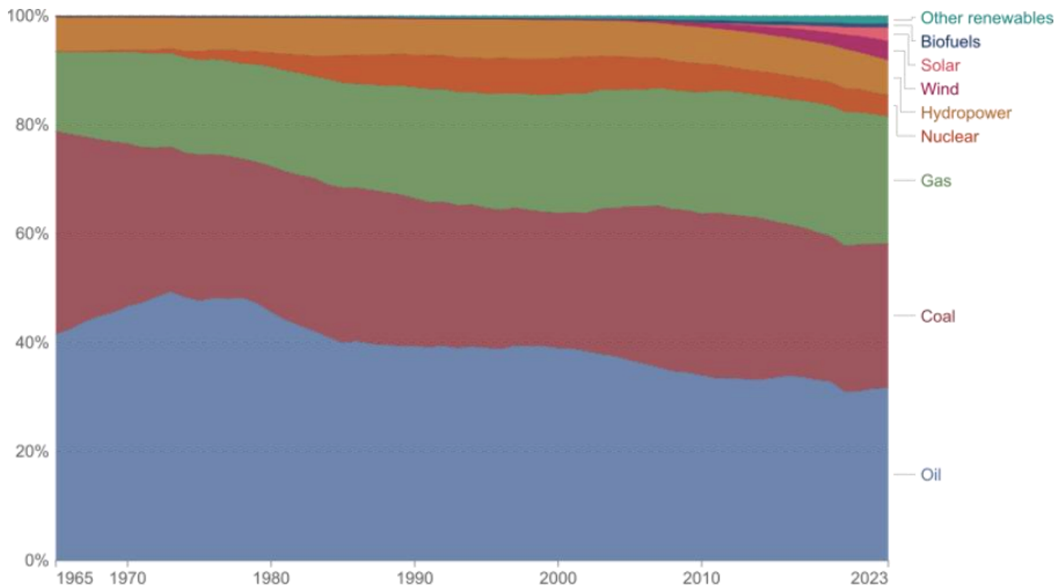


Figure 2.

World energy consumption by source – Edited from (Ritchie & Rosado, 2020).



Despite the growing attention to renewables, the global energy mix remains largely fossil based. As of the most recent data, oil, coal, and natural gas together account for about 80 percent of primary energy use, with oil alone making up roughly 31 percent (Ritchie & Rosado, 2020). Hydropower and nuclear contribute smaller portions, while wind, solar, and other renewables remain a small but fast-growing part of the mix. This imbalance reflects the gap between long-term environmental goals and the realities of existing energy production infrastructure and global energy dependence (Hall & Bain, 2008; Omer, 2008).

Addressing this imbalance requires a shift toward renewable energy sources. Unlike fossil fuels, renewables are sustainable and do not rely on limited resources. However, they are also not consistently reliable. Sunlight and wind are not always available when demand is high, which makes energy storage essential (Mitali et al., 2022; Revankar, 2019).

This need for storage is also closely tied to grid stability. As renewable sources replace conventional power plants, the grid must be able to handle faster fluctuations in both supply and demand (Sabihuddin et al., 2014). No proper leads to instability, overproduction, or energy shortages. Additionally, energy storage adds flexibility and resilience in the face of geopolitical disruptions. (Khan et al., 2023; Mineral Commodity Summaries, 2024).

This report explores energy storage technologies using the NABC framework (Need, Approach, Benefits, and Competitors), and examines why energy storage is necessary, how various systems function, what advantages they offer, and which alternatives were not included in the final selection (UK Energy Storage Roadmap, 2025; EASE, 2025). Understanding these systems is a key step toward building a cleaner, more resilient, and more efficient energy future (Rogalev et al., 2022; Mitali et al., 2022).

Energy storage systems are commonly categorized based on the method they use to store and release energy, regardless of scale or specific application. The four main types are kinetic-based, gravity-based, electrochemical, and chemical systems, were used for classifying the chosen technologies (Kandhasamy et al., 2024. Each type relies on a different physical or chemical process to temporarily hold energy and return it to the grid.

Kinetic-based systems store energy as mechanical motion. In most cases, electricity is used to spin a mass, usually in a low friction environment, and the energy remains stored in that motion until it is needed. At that point, the motion is converted back into electrical energy using a generator or similar device (Olabi et al., 2021; Sabihuddin et al., 2014).

Gravity-based systems store energy by lifting a mass and holding it at an elevated height. The energy is stored as gravitational potential, which is released when the mass is allowed to fall. As it moves downward, its motion drives mechanical components that generate electricity (Li et al., 2024; Tong et al., 2022; Berrada, 2022).

Chemical storage systems involve converting electricity into a chemical fuel. This process creates compounds that store energy in their molecular bonds. These fuels can be stored and later used to produce electricity again, either through combustion or other conversion methods (Revankar, 2019; Ozturk & Dincer, 2021; Tawalbeh et al., 2022).

Electrochemical systems work through chemical reactions that occur inside a storage cell. During charging, electrical energy causes a shift in the chemical state of the materials inside the cell. When discharging, the reaction is reversed, and energy is released in the form of electric current (Rolison & Nazar, 2011; Kim et al., 2019).

The table below lists four representative technologies for each of the four categories. These examples were selected to show the range of systems currently under development or in use, and to give a clearer picture of how this classification applies to real-world technologies.

The Princeton Journal of Interdisciplinary Research
ISSN 3069-8200

Table 1.

List of Selected Energy Storage Technologies for this study.

Tech	Classification
Pumped Hydro Storage (PHS)	Gravity-Based
Solid Mass Gravity Storage (Energy Vault)	Gravity-Based
Gravitricity	Gravity-Based
Rail-Based Gravity Storage (ARES)	Gravity-Based
Compressed Air Energy Storage (CAES)	Kinetic Energy
Liquid Air Energy Storage (LAES)	Kinetic Energy
Flywheel Energy Storage (FES)	Kinetic Energy
Superconducting Magnetic Energy Storage (SMES)	Kinetic Energy
Power-to-Gas (Hydrogen)	Chemical
Ammonia Storage Systems	Chemical
Methanol Fuel Cells	Chemical
Synthetic Methane (Power-to-Methane)	Chemical
Lithium-Ion (Li-ion) Batteries	Electrochemical
Sodium-Ion (Na-ion) Batteries	Electrochemical
Vanadium Redox-Flow Batteries (VRFB)	Electrochemical
Lithium-Air Batteries	Electrochemical

These selected technologies provide a snapshot of the different ways energy can be stored today and in the future. By selecting examples that vary in maturity, scale, and underlying mechanisms, this study sets the stage and provides insight for a comparison of how well each one performs in tangible applications.

Methodology

For this study, we selected a set of evaluation criteria to help assess the commercial potential of different energy storage technologies. These criteria were chosen to reflect a balance between technological maturity, environmental impact, economic cost, and supply chain considerations. After reviewing a wide range of possible factors, we identified seven that are applicable across all systems in a consistent and meaningful way. The criteria used in our analysis includes technology readiness level, life cycle assessment, GreenScore, geopolitical score, depreciation, cost per unit of energy, and cost per unit. Each of these is described in the following section, where we explain the reasoning behind its inclusion and its relevance to real-world energy storage deployment.

Technology Readiness Level (TRL):

Technology Readiness Level (TRL) is a scale that measures how developed a technology is, ranging from early-stage laboratory research (TRL 1) to full-scale commercial deployment (TRL 9). It provides a clear benchmark for assessing whether a technology has been sufficiently tested and validated for widespread use. A high TRL indicates that a system has moved beyond experimental stages and is ready for real-world application.

ISSN 3069-8200

Life Cycle Assessment (LCA):

Life Cycle Assessment (LCA) is a systematic method for evaluating a technology's total environmental impact throughout its life span. This includes the extraction of raw materials, manufacturing processes, usage, and final disposal or recycling. LCA provides critical insight into a technology's hidden environmental costs, allowing for a comprehensive understanding of its sustainability (TRL Assessment, 2025; UK Energy Storage Roadmap, 2025).

GreenScore:

GreenScore is an overall indicator of a technology's environmental benefits and drawbacks. It considers factors such as greenhouse gas emissions, resource consumption, toxicity, and end-of-life recyclability. While closely related to LCA, GreenScore focuses more broadly on how environmentally sustainable a technology remains throughout its operational lifetime and its ability to integrate into clean energy systems (Ortiz et al., 2009; Rostami et al., 2022).

Geopolitical Score:

The Geopolitical Score assesses risks associated with the sourcing of critical materials necessary for a technology's production. It considers the availability, geographic concentration, and political stability of supplier regions. A lower score may signal higher vulnerability to supply chain disruptions, which can impact both the scalability and long-term reliability of a technology Khan et al., 2023; Mineral Commodity Summaries, 2024).

Depreciation:

Depreciation refers to the gradual loss of performance, efficiency, or value of a technology over time. In the context of energy storage, this typically includes reductions in storage capacity, increased maintenance needs, or shortened operational lifespan. Technologies with lower depreciation rates are generally more cost-effective and reliable over the long term (Kumtepeli et al., 2024).

Cost per Energy ($/Energy):

Cost per Energy measures the operational cost of storing or delivering a unit of energy, typically expressed in dollars per kilowatt-hour ($/kWh). It captures the economic efficiency of a technology and is a central metric for determining its competitiveness at scale. Lower $/Energy values are critical for achieving cost-effective commercial deployment (Rostami et al., 2022; Rogalev et al., 2022).

Cost per Unit ($/Unit):

Cost per Unit refers to the upfront capital cost needed to deploy an energy storage system, independent of how much energy it can store or produce over time. It plays a significant role in investment decisions, particularly during early-stage adoption, though it is considered less critical than operational cost when evaluating long-term commercial viability (Sabihuddin et al., 2014; Rostami et al., 2022).

All scores in this study, including TRL, LCA, GreenScore, Geopolitical Score, Depreciation, $/Energy, and $/Unit, were obtained or inferred from existing literature and public data sources. No new LCA, TRL, or original techno-economic assessments were performed by our research group. For each technology, values from different sources were compared and mapped onto a common 1-10 scale to create a consistent scoring framework. These normalized scores were then used to generate the radar plots, where each criteria forms a radical axis and the scores of each technology are connected to form a polygon, allowing visual comparison of trade-offs within each technology group. The same normalized and weighted scores were then used to construct the final heatmap, which summarizes and compares the overall performance of the top technologies across all evaluation criteria.

Results

In this section, we examine in more detail the potential and limitations of the selected energy storage technologies, using the classification criteria introduced earlier. To enable comparison, we first assigned a score to each technology across seven key criteria reflecting environmental, technical, and economic performance. The technologies were then grouped into four categories based on the type of energy resource managed by the system: gravity-based, kinetic, electrochemical, and chemical. Within each group, we analysed and compared the technologies to identify their relative strengths and weaknesses. Based on the weighted scores, we then selected the top-performing technology in each category to represent the group in a final comparative analysis.

To visualize this evaluation, we used radar plots (Figures 3 to 6) to show the performance of each technology across all criteria within its category. We then summarized the top-performing technologies from each group in a heatmap (Figure 7), which presents their normalized weighted scores for direct comparison. Before presenting the results of this comparison, we first explain the rationale behind the scores assigned to each technology and outline the specific features that influenced their evaluation.

Analysis of Gravity-based Storage Technologies

1. Pumped Hydro Storage (PHS)

PHS receives a strong LCA score of 9 because it uses gravity and water flow rather than combustion or chemical reactions, resulting in very low emissions over its lifespan (Rehman et al., 2015; Blakers et al., 2021). However, its need to construct large reservoirs can lead to significant ecological disruption, particularly affecting aquatic ecosystems and land use. Its TRL is a perfect 10, reflecting its long-standing commercial use and technical maturity around the world (Rehman et al., 2015). The GreenScore of 9 aligns with its clean and renewable nature but acknowledges that land and water resource impacts slightly detract from its overall sustainability. A Geopolitical Score of 6 highlights its dependence on specific geographical features such as elevation and access to water, which limits global deployment (Li et al., 2024). Depreciation is rated at 8, since the system is highly durable and can operate for decades, though the initial infrastructure costs are considerable. Its $/Energy score of 4 reflects these large initial capital costs, which make each unit of energy stored relatively expensive (Berrada, 2022). The $/Unit score of 5 supports this, noting that while startup costs are high, the system becomes cost-effective over its very long service life (Rogalev et al., 2022). (Figure 3 – blue area and outline).

2. Solid Mass Gravity Storage (Energy Vault)

Energy Vault earns an LCA score of 7 because it avoids the use of toxic materials or emissions-heavy fuels, but the production and transport of concrete blocks still generate a notable carbon footprint (Tong et al., 2022). With a TRL of 6, the system has been successfully demonstrated in pilot projects, though it has not yet been rolled out commercially at scale (Su, 2025). The GreenScore of 7 reflects this relatively sustainable design, which is simpler and cleaner than many alternatives, though emissions from crane operation and construction materials remain a factor. A Geopolitical Score of 7 recognizes the benefit of relying on abundant and locally sourced materials like concrete, which avoids the need for rare or geopolitically sensitive resources (Sharpe, 2017). Depreciation is rated 8, based on the expectation that these systems will have long lifespans with minimal degradation. Both the $/Energy and $/Unit scores are 5, reflecting that while current costs are moderately high, there is strong potential for cost reduction as the technology matures and scales (Berrada, 2022). (Figure 3 – orange area and outline).

Figure 3.

Radar plot comparing the selected energy storage technologies based on the effect of Gravity exploiting potential energy. Made using Jupyter Notebook.

3. Gravitricity

Gravitricity earns a LCA score of 8 because it relies on raising and lowering heavy weights in disused mine shafts, creating minimal emissions during operation and requiring no toxic materials (Bowoto et al., 2021). That said, the construction or adaptation of shafts and mechanical systems may cause localized environmental impacts. With a TRL of 5, the technology is in early stages, with prototypes developed but not yet deployed commercially. Its GreenScore of 8 is based on its low-impact design and limited material requirements, making it a promising alternative to chemical batteries (Li et al., 2024; Tong et al., 2022). A Geopolitical Score of 6 reflects the fact that this system requires specific site conditions, such as access to deep shafts or mineshafts, which limits deployment flexibility (Li et al., 2024). Depreciation is rated at 7, suggesting a long lifespan and strong durability, though this hasn't been tested at scale. Both the $/Energy and $/Unit scores are 4, indicating that, for now, the technology remains costly and capital-intensive, but may improve significantly with refinement and wider implementation (Berrada, 2022). (Figure 3 – green area and outline).

4. Rail-Based Gravity Storage (ARES)

ARES receives an LCA score of 8 due to its use of relatively clean and recyclable materials like steel rails and heavy loads, with low emissions during operation (Cava et al., 2016). However, the land use required for laying long rail systems can cause ecological or community concerns. The TRL is 6, indicating that the technology is in development, with pilot systems tested but not yet widely commercialized. A GreenScore of 8 reflects the fact that the system runs on electricity and has low operational emissions, though land use challenges prevent a higher score. A Geopolitical Score of 6 shows it is limited by geography, namely, the need for long slopes and open land, which are not always available (Li et al., 2024). The depreciation score of 7 indicates strong durability with minimal component degradation over time. Both $/Energy and $/Unit are rated 5, suggesting that while current costs are high, they are expected to decline as the system is scaled and refined (Berrada, 2022). (**Figure 3** – red area and outline).

Analysis of Kinetic Energy Storage Technologies

1. Compressed Air Energy Storage (CAES)

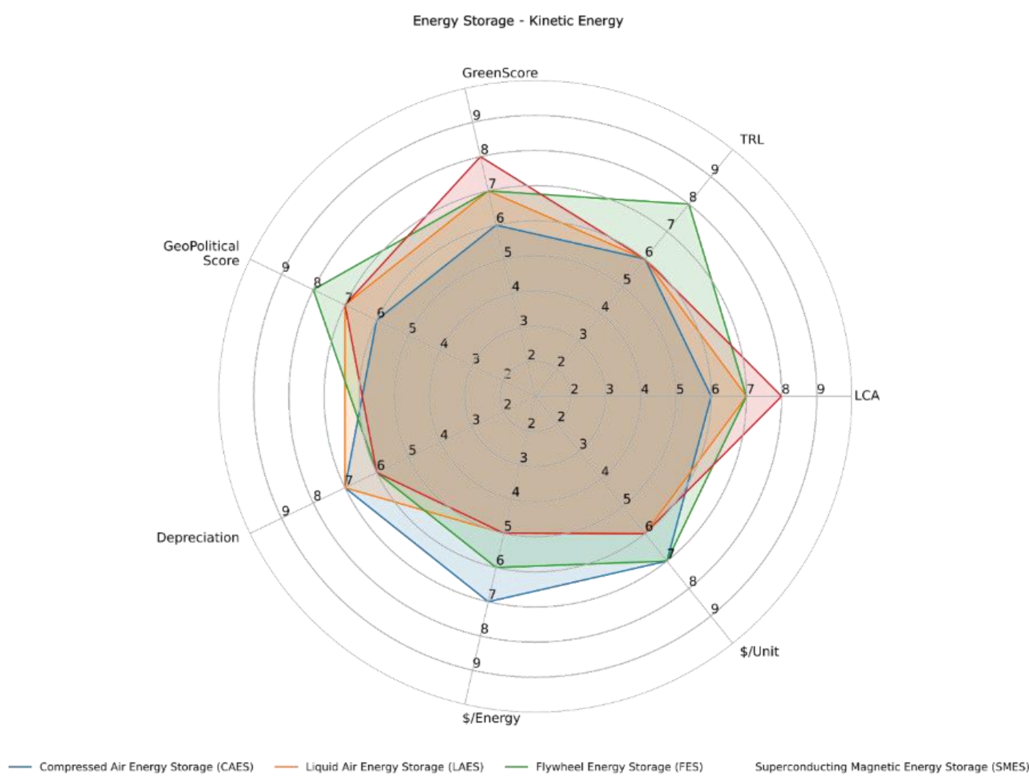
CAES earns an LCA score of 7 because it generates relatively low emissions and uses natural processes, though the infrastructure for air compression and storage, including the use of natural gas in some systems, raises the environmental footprint (Lund & Salgi, 2009; Budt et al., 2016). The TRL is 8, reflecting maturity in regions with suitable underground formations like salt caverns. Its GreenScore of 7 is solid, based on its low-carbon footprint, though reliance on fossil fuels in some implementations slightly reduces its score. A Geopolitical Score of 6 reflects the need for specific geological conditions, which limit deployment to certain regions (Rogalev et al., 2022). Depreciation is rated at 7 because these systems tend to last long but require periodic maintenance tied to geological stability. It scores a 5 for $/Energy due to reasonable costs for storing energy once the system is in place. The $/Unit score of 6 indicates moderate capital costs, which become competitive in the long run (Sabihuddin et al., 2014). (Figure 4 – blue area and outline).

2. Liquid Air Energy Storage (LAES)

LAES receives an LCA score of 7 because it operates cleanly, using air as a working fluid, and avoids harmful chemicals. However, the process of compressing and liquefying air is energy-intensive and reduces its overall environmental advantage (Budt et al., 2016). With a TRL of 6, LAES is in the early stages of commercial use, with a few pilot plants built and ongoing development to improve efficiency. Its GreenScore of 7 reflects its sustainability potential, especially when powered by renewables, though the energy-intensive nature of the liquefaction and cooling processes remains a challenge. It scores a 7 for Geopolitical impact, as the technology is geographically flexible and not tied to specific resources, though the need for advanced cooling infrastructure can be a constraint (Rogalev et al., 2022). Depreciation is rated at 7, since the systems are expected to have long service lives, though maintenance and thermal losses could impact performance over time. Its $/Energy score is 5, indicating moderate storage costs that remain under optimization, while the $/Unit score of 6 reflects high initial capital costs that are expected to decrease with greater deployment (Rostami et al., 2022). (**Figure 4** – orange area and outline).

Figure 4.

Radar plot comparing the selected energy storage technologies based on exploiting kinetic energy effects. Made using Jupyter Notebook.



3. Flywheel Energy Storage (FES)

FES earns an LCA score of 7, largely due to its efficient and clean operation that avoids chemical degradation or emissions (Olabi et al., 2021). However, the use of advanced materials such as carbon composites and magnets does contribute to its environmental footprint. Its TRL is 8, as flywheels are commercially available and widely used in short-duration energy storage applications. The GreenScore of 7 reflects strong sustainability, especially because of low emissions and high recyclability, though the sourcing of specialized materials poses some concerns (Li & Palazzolo, 2022). A Geopolitical Score of 8 shows that the technology can be deployed nearly anywhere and does not rely on geography or rare resources. Depreciation is rated 6 because while flywheels are durable, mechanical wear from continuous high-speed rotation leads to eventual performance decline. The $/Energy score of 6 reflects good cost-effectiveness, particularly for applications that require frequent charge-discharge cycles. The $/Unit score of 7 suggests manageable capital investment, especially for high-throughput systems where performance benefits outweigh costs (Amiryar & Pullen, 2017). (Figure 4 – green area and outline).

4. Superconducting Magnetic Energy Storage (SMES)

SMES scores an LCA of 8 due to its clean energy handling and very high efficiency, but does not earn a perfect score because of the energy demands and environmental impact associated with cryogenic cooling systems (Adetokun et al., 2022). Its TRL is 6, as it remains under development with a few advanced prototypes but limited commercial use. The GreenScore of 8 reflects its impressive energy efficiency and lack of harmful emissions, although the need for specialized superconducting materials and cooling infrastructure creates additional environmental and resource concerns (Vulusala & Madichetty, 2018). A Geopolitical Score of 7 acknowledges that while SMES is flexible in deployment, it still relies on niche materials that could face supply or geopolitical risks. Depreciation is rated 6 because while the technology can have a long life, it involves complex maintenance, and performance can be sensitive to cooling system reliability. The $/Energy score of 5 indicates high current storage costs, though performance benefits may offset this in some cases. Similarly, the $/Unit score of 6 reflects high capital costs, largely due to the need for precision equipment and cryogenic systems (Sabihuddin et al., 2014). (**Figure 4** – red area and outline).

Analysis of Chemical Energy Storage Technologies

1. Power-to-Gas (Hydrogen)

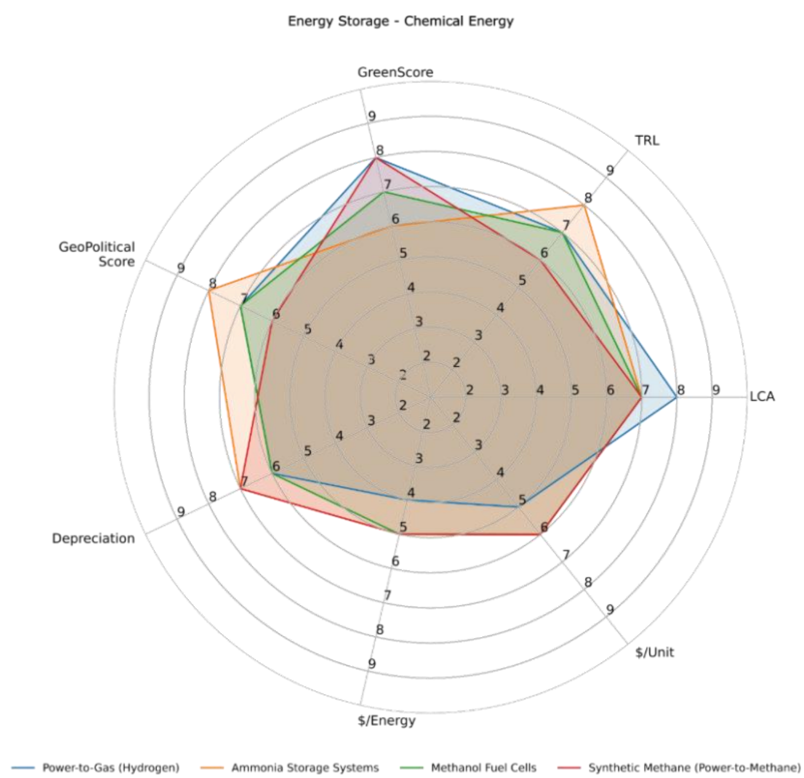
Hydrogen storage systems score an LCA of 8 when powered by renewables, thanks to low emissions and the clean-burning nature of hydrogen (Ozturk & Dincer, 2021). However, the electrolysis process is energy-intensive, which limits the environmental benefit if fossil-fuel-powered electricity is used (Revankar, 2019). Its TRL is 7, reflecting significant advancement and increasing deployment in sectors like transportation and long-duration storage. The GreenScore of 8 is based on the potential for fully green hydrogen when renewable energy is used, though the process still requires a great deal of infrastructure. Geopolitically, it scores a 7 because hydrogen can be produced in many locations, though the infrastructure and logistics for safe storage and transport are complex and unevenly developed (Khan et al., 2023). Depreciation is rated at 6 due to the gradual wear of tanks and pipelines, along with storage and compression losses. It earns a 4 for $/Energy, reflecting that hydrogen is still expensive to produce and store at scale (Gorre et al., 2019). The $/Unit score of 5 further reflects the high capital costs of current systems, although these are expected to decline as adoption increases (Rogalev et al., 2022). (Figure 5 – blue area and outline).

2. Ammonia Storage Systems

Ammonia energy storage receives an LCA score of 7, as it enables efficient long-term storage and transportation, but traditional ammonia production is carbon-intensive, especially if not paired with renewable energy (Tawalbeh et al., 2022). With a TRL of 8, the technology is considered mature, supported by existing industrial infrastructure and rising interest in clean ammonia applications (Wang et al., 2017). Its GreenScore of 6 reflects significant environmental drawbacks in current production methods, which rely heavily on natural gas, though green ammonia is an emerging solution. A Geopolitical Score of 8 highlights its versatility, as ammonia can be produced almost anywhere and transported with existing systems. Depreciation is scored at 7, as storage systems tend to last and degrade slowly. Its $/Energy score is 5, indicating a middle ground between efficiency and cost. The $/Unit score of 6 shows that while initial investments are high, particularly for clean ammonia production, costs are likely to fall as the technology scales (Revankar, 2019). (**Figure 5** – orange area and outline).

Figure 5.

Radar plot comparing the selected energy storage technologies based on devices exploiting chemical energy effects. Made using Jupyter Notebook.



3. Methanol Fuel Cells

Methanol fuel cells score a 7 in LCA, as they emit relatively low levels of pollution during operation, especially when methanol is derived from biomass or renewables (Joghee et al., 2015). However, traditional methanol production still involves fossil fuels, which raises its environmental footprint (Munjewar et al., 2017). With a TRL of 7, the technology is well-developed and is seeing increased use, particularly in transportation and off-grid backup systems.

ISSN 3069-8200

The GreenScore of 7 reflects this dual nature, as it has sustainable potential but is currently limited by reliance on conventional production methods. A Geopolitical Score of 7 shows that methanol is widely available and can be produced in many regions, although infrastructure and resource access vary. Depreciation is rated 6, acknowledging that fuel cells degrade over time with repeated use. $/Energy is scored a 5 and $/Unit is scored a 6, suggesting moderate cost levels now, with potential for improvements as technology adoption increases and production methods shift toward renewables (Rogalev et al., 2022). (Figure 5 – green area and outline).

4. Synthetic Methane (Power-to-Methane)

Synthetic methane receives a 7 in LCA, since it can be produced cleanly from CO_2 and renewable hydrogen, but the process is still energy-intensive and currently involves some emissions (Ghaib & Ben-Fares, 2018). Its TRL of 6 reflects that while prototypes and pilot projects exist, full-scale commercial use is still in the works (Gorre et al., 2019). The GreenScore of 8 acknowledges the high sustainability potential, especially when paired with carbon capture and renewable inputs. A Geopolitical Score of 6 shows its reliance on infrastructure and access to CO_2 and hydrogen sources, which may not be evenly available. Depreciation is rated 7, as the systems involved tend to be robust and long-lasting. The $/Energy score is 5, reflecting that production remains costly, particularly due to energy conversion losses. The $/Unit score of 6 shows that infrastructure costs are relatively high but are expected to drop as production processes become more standardized and efficient (Rogalev et al., 2022). (**Figure 5** – red area and outline).

The Princeton Journal of Interdisciplinary Research
ISSN 3069-8200

Analysis of Chemical Energy Storage Technologies

1. Lithium-Ion (Li-ion) Batteries

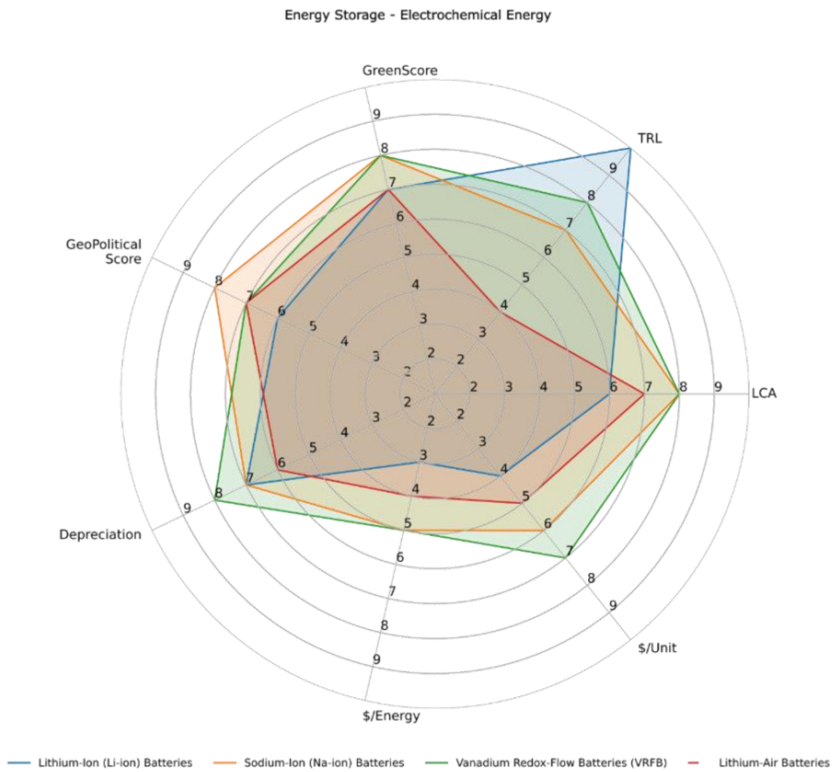
Li-ion batteries score a 6 in LCA, reflecting their high environmental cost during mining and manufacturing, especially from resource extraction such as lithium and cobalt (Kim et al., 2019; Humanity needs to diversify its lithium sources, 2025). Despite this, their clean operation earns them some environmental credit. With a TRL of 10, this is one of the most mature and commercially adopted energy storage technologies worldwide (Global EV Outlook, 2024). The GreenScore of 7 recognizes their usefulness in reducing emissions but accounts for the significant environmental burden during production and disposal. A Geopolitical Score of 6 reveals the dependency on a few countries for critical minerals, which introduces supply chain and ethical concerns (Mineral Commodity Summaries, 2024; Benchmark Mineral Intelligence, 2025). Depreciation is rated 7, acknowledging moderate degradation over time, especially with deep cycling. Its $/Energy score of 3 shows that Li-ion is among the most cost-effective energy storage options today. (Charted: Battery Capacity by Country, 2025) The $/Unit score of 4 supports this, with low upfront costs for small-scale systems making them accessible and competitive (The $400 Billion Lithium Battery Value Chain, 2023). (**Figure 6** – blue area and outline).

2. Sodium-Ion (Na-ion) Batteries

Na-ion batteries receive an LCA score of 8, as they use more abundant and environmentally friendly materials than lithium-based systems, resulting in a lower overall footprint (Vaalma et al., 2018). With a TRL of 7, the technology is gaining traction and is being explored for large-scale applications, though it's not yet as widespread as lithium-ion. The GreenScore of 8 reflects its sustainability advantages, especially the reduced mining impact. Geopolitically, it scores an 8 due to sodium's global abundance, reducing reliance on constrained or politically sensitive supply chains. Depreciation is rated 7, as performance and lifespan are similar to lithium-ion, though long-term field data is still limited. The $/Energy score of 5 shows that costs are becoming competitive, though still being refined. The $/Unit score of 6 reflects higher early-stage costs, which are likely to fall as production scales and manufacturing becomes more efficient (Rostami et al., 2022). (**Figure 6** – orange area and outline).

Figure 6.

Radar plot comparing the selected energy storage technologies based on devices exploiting electrochemical energy effects. Made using Jupyter Notebook.



3. Vanadium Redox-Flow Batteries (VRFB)

VRFBs score an 8 in LCA because they use recyclable electrolytes and have a minimal environmental impact over their very long operational life (Parasuraman et al., 2013). Their TRL is 8, indicating that the technology is mature and already in use, especially for grid-level applications. The GreenScore of 8 aligns with their recyclability, durability, and lack of toxic degradation products. A Geopolitical Score of 7 reflects some dependency on vanadium, which is more concentrated in a few regions but not critically scarce (Mineral Commodity Summaries, 2024).. Depreciation is rated 8, thanks to their extremely long life and resistance to capacity degradation, even with frequent cycling. The $/Energy score of 5 reflects the suitability of

VRFBs for storing large amounts of energy efficiently, even if initial investments are higher. The $/Unit score of 7 indicates that while the systems are costly upfront, they offer long-term value, particularly for large-scale or stationary applications (Rostami et al., 2022). (Figure 6 – green area and outline).

4. Lithium-Air Batteries

Lithium-air batteries earn an LCA of 7, based on their theoretical promise for low environmental impact, but real-world production remains inefficient and resource-intensive (Rolison & Nazar, 2011). With a TRL of just 4, this technology is still in its early research and prototype stages, facing major hurdles before practical use (Kim et al., 2019). The GreenScore of 7 recognizes its potential, especially if commercialized using renewable inputs, though it's not yet realized. A Geopolitical Score of 6 shows the reliance on lithium and advanced materials, which could create supply constraints similar to Li-ion systems (Humanity needs to diversify its lithium sources, 2025). Depreciation is scored at 6, with projected good performance, but limited real-world data to confirm. Its $/Energy score of 4 reflects high storage costs today, largely due to inefficiencies and low yields. The $/Unit score of 5 points reflects the current high capital costs, which could drop significantly if the technology overcomes its major scientific and engineering barriers (Rogalev et al., 2022).. (**Figure 6** – red area and outline).

Normalized Scores Weighed

To evaluate the commercial potential of various energy storage technologies, this study uses a weighted criteria framework. The framework considers both short-term feasibility and long-term sustainability by assigning relative weights to seven key factors. These factors were chosen based on their relevance to technological maturity, environmental performance, and financial viability. Each weight reflects the role the factor plays in real-world deployment and the ability to scale commercially.

The most heavily weighted factor is Technology Readiness Level (TRL), with a weight of 0.8. TRL measures how developed a technology is on a scale from early-stage research to full commercial use. Since a technology must be mature and proven before it can be widely adopted (TRL Assessment, 2025; UK Energy Storage Roadmap, 2025). TRL is prioritized because, regardless of innovation or environmental benefit, technologies that aren't close to commercial readiness cannot be deployed at scale in the near term.

Next is Life Cycle Assessment (LCA) with a weight of 0.7 evaluates the total environmental impact of a technology across its full life span, from raw materials and manufacturing to use and disposal (Ortiz et al., 2009; Rostami et al., 2022). As sustainability becomes more central to energy policy and regulation, LCA plays a critical role in identifying technologies that are not just viable now but also environmentally responsible in the long term. However, it comes after TRL, since market readiness must come first.

GreenScore with a weight: 0.6 provides a broader assessment of environmental sustainability over time This includes metrics such as long-term emissions, toxicity, and recyclability (Leahy et al., 2017; Sharpe, 2017). While it overlaps with LCA, the GreenScore emphasizes how "green" a technology is in practice over time. It's important for long-term

ISSN 3069-8200

integration into sustainable infrastructure, though slightly less so than LCA and TRL when it comes to immediate deployment.

Geopolitical Score with a weight of 0.5 evaluates risks tied to the sourcing and availability of materials. Technologies that depend on rare or politically sensitive resources may face supply chain disruptions, affecting their long-term scalability (Khan et al., 2023; Mineral Commodity Summaries, 2024). While this is an important factor, it's considered less urgent than readiness and environmental impact and is treated more as a long-term constraint.

Depreciation with a weight of 0.4 refers to how quickly a technology loses value or performance over time (Kumtepeli et al., 2024). This has implications for investment and operating costs, particularly over the lifespan of an energy storage system. While important for long-term planning, it plays a smaller role in the early adoption phase.

Two cost-related factors are included in the analysis. The first, cost per unit of energy stored ($/Energy), has a weight of 0.7 This metric is central to economic viability, especially for large-scale commercial use. Technologies with low $/Energy are more likely to be competitive as the market grows. The second, cost per unit ($/Unit), refers to upfront capital costs and has a weight of 0.4 (Rostami et al., 2022; Rogalev et al., 2022). While initial costs do matter, they are less critical than long-term efficiency and readiness as commercial adoption processes become more standardized and efficient (Rogalev et al., 2022).

ISSN 3069-8200

Table 3.

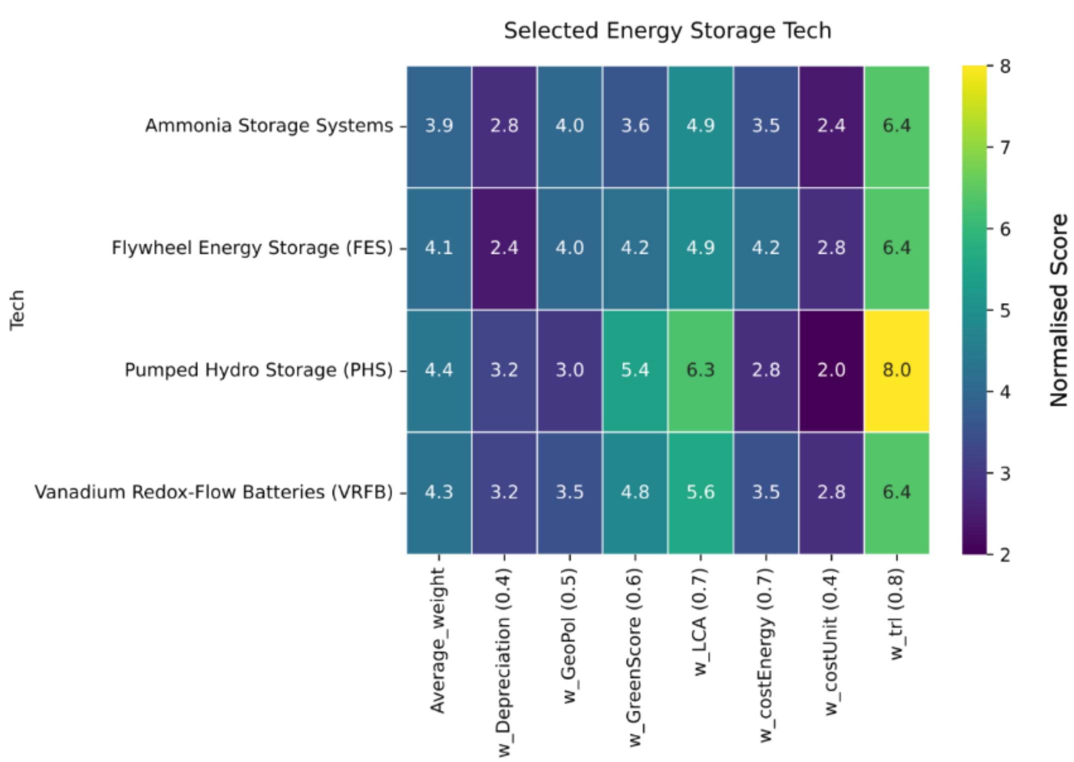
List of technologies with their criteria weighed.

Tech	Classification
Pumped Hydro Storage (PHS)	**4.39**
Solid Mass Gravity Storage (Energy Vault)	3.73
Gravitricity	3.51
Rail-Based Gravity Storage (ARES)	3.79
Compressed Air Energy Storage (CAES)	3.73
Liquid Air Energy Storage (LAES)	3.73
Flywheel Energy Storage (FES)	**4.13**
Superconducting Magnetic Energy Storage (SMES)	3.86
Power-to-Gas (Hydrogen)	3.81
Ammonia Storage Systems	**3.94**
Methanol Fuel Cells	3.79
Synthetic Methane (Power-to-Methane)	3.74
Lithium-Ion (Li-ion) Batteries	3.70
Sodium-Ion (Na-ion) Batteries	4.10
Vanadium Redox-Flow Batteries (VRFB)	**4.26**
Lithium-Air Batteries	3.29

Based on the ratings adjusted with the weights, the tech with the highest weight from each type of system was bolded and selected to be weighed across the different energy storage classifications. For Gravity-Based Systems, Pumped Hydro Storage (PHS) reached the highest average weight. For Kinetic Energy Systems, Flywheel Energy Storage (FES) reached the highest average weight. For Chemical Systems. Ammonia Storage Systems reached the highest average weight. Finally, for Electrochemical Systems, Vanadium Redox-Flow Batteries (VRFB) reached the highest average weight.

Figure 7.

Heatmap showing the normalized performance scores of selected energy storage technologies across seven weighted evaluation criteria. Made using Jupyter Notebook.



The heatmap presents the normalized performance of four energy storage technologies across seven evaluation criteria. Pumped Hydro Storage achieved the highest normalized score of 8.0 and also held the highest average weight score of 4.39, demonstrating strong and consistent performance across all categories. Flywheel Energy Storage, Vanadium Redox-Flow Batteries, and Ammonia Storage Systems each received a total normalized score of 6.4. Their average weight scores were 4.13, 4.26, and 3.94 respectively, showing that while their final scores were the same, their underlying strengths varied. Pumped Hydro Storage performed strongly in both raw and weighted evaluations, while the other technologies showed more uneven results depending on the specific criteria.

Discussion

The evaluation framework developed in this study reveals the strengths and limitations of the selected energy storage technologies. Each technology was first scored across seven unweighted criteria: life-cycle assessment (LCA), technological readiness level (TRL), GreenScore, geopolitical score, depreciation, cost per energy, and cost per unit. These scores captured baseline performance in environmental, technical, and economic dimensions. To reflect real-world relevance more accurately, weights were then applied to each criterion, with higher importance given to those more directly tied to commercial viability. For example, TRL and cost factors were given greater weight due to their influence on scalability and market readiness, while depreciation and geopolitical risk captured long-term operational feasibility (Khan et al., 2023; Kumtepeli et al., 2024).

After applying the weights, the analysis showed clear distinctions among storage categories. While past research often focuses on single-metric rankings such as cost or storage duration, this study incorporates additional dimensions such as geopolitical dependency and depreciation. This broadened evaluation adds context based on performance but also scalability and risk, which past works treat qualitatively rather than numerically (Rogalev et al., 2022). The two storage scoring-then-weighting process therefore highlights conditions that influence competitiveness rather than assuming ideal operating environments.

Pumped Hydro Storage consistently emerged as the strongest performer, achieving the highest normalized score and weighted ranking, which aligns with studies identifying it as technically mature, low impact, and infrastructure-stable (Rehman et al., 2015; Blakers et al., 2021). However, unlike previous comparisons that focus mainly on cost and efficiency, this study highlights geographic restrictions as a key barrier, indicating that its feasibility depends heavily on regional terrain and hydrological constraints.

Prior studies highlight Vanadium Redox-Flow Batteries for durability and long life cycle (Parasuraman et al., 2013). The present tanking shows that although this advantage holds, it does not outweigh cost barriers when compared directly to lithium-ion systems. Higher installation costs and slower deployment reduce their commercial impact, a contrast not previously emphasized (Rostami et al., 2022). This helps explain why these batteries will continue to see adoption in centralized grid storage rather than distributed applications.

Flywheel energy storage systems were previously reported as reliable, low impact, and well-suited for frequent cycling (Olabi et al., 2021; Li & Palazzolo, 2022). This study confirms those strengths but also shows that their rankings decline once cost-per-energy and depreciation metrics are weighted, which earlier evaluations did not incorporate. The findings indicate that while technically strong flywheels remain commercially constrained by energy density rather than performance.

Existing assessments place Ammonia Storage Systems as attractive for long duration and transport-based applications (Wang et al., 2017; Tawalbeh et al., 2022). However, when cost and degradation are considered, their rankings fall as energy-intensive synthesis and conversion losses reduce competitiveness. Unlike earlier analyses that assume optimized renewable production, these results show that the feasibility relies on advances in production efficiency and performance.

Several limitations are also acknowledged for this study. First, the values used in this evaluation were sourced from existing literature and technical reports rather than controlled experimental testing. As a result, performance ranges reflect averaged published data. Additionally, criteria such as geopolitical risk and depreciation evolve over time and may change with market conditions, material discoveries, or improved recycling processes. Finally, the weighting strategy prioritizes commercial readiness, and technologies already proven at scale show biased outcomes due to more literature and reports covered on them.

Future work could expand the framework by differentiating storage roles more explicitly such as short-duration regulation, daily shifting, and seasonal storage rather than treating all applications with equal weight. Incorporating embodied carbon, end-of-life recyclability scoring, and material scarcity indicators could further strengthen environmental differentiation. Finally, applying this framework within region-specific techno-economic simulations would support more accurate decision-making and reveal how technology ranking chances under local markets, policy, or resource conditions.

Overall, the results highlight that no single storage solution excels in every area. Pumped Hydro remains the most well-rounded and proven option, but other technologies offer targeted strengths depending on context. The scoring framework and visual tools developed here help clarify these trade-offs and support more informed decision-making when selecting energy storage systems for specific use cases.

Understanding these distinctions is crucial to shaping energy systems that are not only clean but also reliable and economically feasible. While some technologies show clear leadership today, others may become more competitive as innovation progresses, and deployment expands (Kim et al., 2019; Ghaib & Ben-Fares, 2018). This work helped clarify which systems are best positioned to support that transition and reinforced the need for careful, data-informed planning in the path toward a more sustainable energy future.

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