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List of abbreviations and technical terms (Alphabetical)

APS	Announced Pledges Scenario of IEA The Announced Pledges Scenario (APS), introduced in 2021, illustrates the extent to which announced ambitions and targets can deliver the emissions reductions needed to achieve net zero emissions by 2050. It includes all recent major national announcements as of the end of August 2023, both 2030 targets and longer-term net zero or carbon neutrality pledges, regardless of whether these announcements have been anchored in legislation or in updated Nationally Determined Contributions.
Ancillary Services	Ancillary services are a range of essential support functions that help maintain the reliability and stability of the electrical grid. Ancillary services maintain the proper flow and direction of electricity, address imbalances between supply and demand, and help the system recover after a power system event.
CAES	Compressed-air energy storage
CAGR	Compound Annual Growth Rate The compound annual growth rate is the annualized average rate of revenue growth between two given years, assuming growth takes place at an exponentially compounded rate.
CAPEX	Capital expenditures are funds used to acquire, upgrade, and maintain physical assets such as an energy storage system.
Capacity Mechanism	Capacity mechanisms are temporary support measures that EU countries can introduce to remunerate power plants for medium and long-term security of electricity supply.
IEA	International Energy Agency
LCA	Life Cycle Assessment - systematic analysis of environmental impact over the course of the entire life cycle of a product, material, process, or other measurable activity. LCA models the environmental implications of the many interacting systems that make up industrial production
LCOE	Levelized Costs of Energy is a measure of the average present cost of electricity generation for a generating plant over its lifetime
LCOS	Levelised Cost of Storage is a metric used to compare the economic viability of different energy storage technologies. It essentially represents the average cost per unit of usable energy stored over the lifetime of a storage system
LDES	Large-scale long-duration energy storage
MTBF	Mean time between failure is a measure of the reliability of a system or component. It's an element of maintenance management, representing the average time that a system or component will operate before it fails.
NZE	Net Zero Emissions by 2050 Scenario of IEA The Net Zero Emissions by 2050 Scenario (NZE Scenario) is a normative scenario that shows a pathway for the global energy sector to achieve net zero CO₂ emissions by 2050, with advanced economies reaching net zero emissions in advance of others.

OPEX	Costs incurred in running a company's day-to-day operations. Examples include wages, utilities, maintenance, repairs, and rent. These expenses are typically short-term and recurring.
PHES / PSH	Pumped HydroElectric Storage / Pumped-storage hydroelectricity
RTE	Round-trip Efficiency The round trip efficiency (RTE), also known as AC/AC efficiency, refers to the ratio between the energy supplied to the storage system (measured in MWh) and the energy retrieved from it (also measured in MWh). This efficiency is expressed as a percentage (%).
STEPS	Stated Policies Scenario of IEA The Stated Policies Scenario (STEPS) is designed to provide a sense of the prevailing direction of energy system progression, based on a detailed review of the current policy landscape. It provides a more granular, sector-by-sector evaluation of the policies that have been put in place to reach stated goals and other energy-related objectives, taking account not only of existing policies and measures but also those that are under development. The STEPS provides a more conservative benchmark for the future than the Announced Pledges Scenario (APS), by not taking for granted that governments will reach all announced goals.
TRL	Technology Readiness Levels are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest.

1 INTRODUCTION

This Energy Storage Outlook is a core component of the Interreg Danube Region Programme DRP0200271 StoreMore project. The primary goals of this document are:

- To highlight promising energy storage solutions with a focus on emerging technologies.
- To provide foundational input for the StoreMore project's in-depth 'Analysis and Cataloguing of Energy Storage Solutions', which emphasizes environmental impacts and sustainable practices.
- To serve as a publicly accessible resource under the project, potentially inspiring future initiatives and collaborations in the field of energy storage.

According to the IEA World Energy Outlook 2023¹: „We are on track to see all fossil fuels peak before 2030. A legacy of the global energy crisis may be to usher in the beginning of the end of the fossil fuel era: the momentum behind clean energy transitions is now sufficient for global demand for coal, oil and natural gas to all reach a high point before 2030 in the STEPS. The share of coal, oil and natural gas in global energy supply – stuck for decades around 80% – starts to edge downwards and reaches 73% in the STEPS by 2030.”

The 2023 World Energy Outlook report by the International Energy Agency (IEA) underscores the current turbulent times in the energy sector, influenced by geopolitical tensions and market volatility, yet reveals positive strides toward a cleaner energy future. Key findings from the report highlight that despite easing from the immediate crisis experienced in 2022, the energy sector remains fraught with challenges such as high fossil fuel prices, ongoing conflicts impacting energy supplies, and prevailing economic uncertainties marked by inflation and elevated debt levels. However, there is a silver lining as the report notes significant advancements in clean energy technologies and investments, which have increased by 40% since 2020. These developments are propelled not just by emission reduction goals, but also by the strong economic rationale for renewable energy sources, which are becoming integral to enhancing energy security and creating job opportunities in the sector.

The report outlines a transformation in the global energy landscape with increasing deployment of solar photovoltaics (PV) and electric vehicles (EVs), which are pivotal in driving down emissions. In 2023, record-breaking additions of over 500 gigawatts (GW) of renewable capacity are expected, highlighting a rapid pace of change compared to previous years. Moreover, a daily investment exceeding USD 1 billion on solar deployment signifies a robust move towards a sustainable energy system. This transition is further supported by expanding manufacturing capacities for key components like solar PV modules and EV batteries. Despite these positive

trends, challenges persist, and the report stresses the need for comprehensive solutions that address not only the diversification of energy sources but also the systemic changes necessary for a sustainable and secure energy future.

Energy Storage

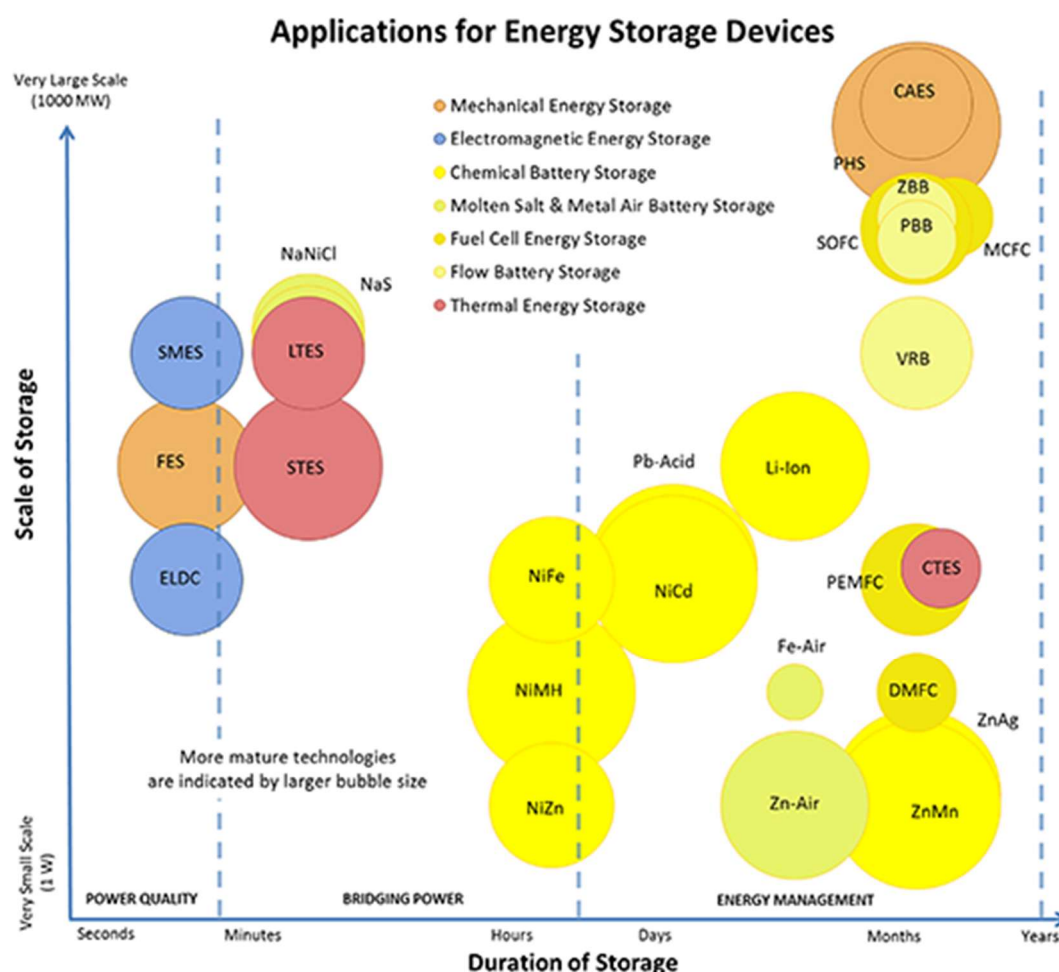
The 2023 World Energy Outlook report highlights significant developments in energy storage technologies, noting a robust expansion particularly in utility-scale and behind-the-meter battery storage. In 2022, the deployment of these battery storage systems surged by 90%, demonstrating a rapid scale-up to meet the growing demand for renewable energy integration and grid stabilization. This increased reliance on energy storage is pivotal for balancing intermittent renewable energy sources like solar and wind, ensuring a stable and reliable energy supply despite the variable nature of these resources.

Furthermore, the report discusses the strategic role of energy storage in facilitating the transition to a low-carbon economy. It emphasizes the substantial investments in battery technology and infrastructure are critical to achieving this transition. Energy storage systems enable more extensive use of renewable energy by mitigating issues of variability. Advancements in energy storage technology are also crucial for supporting the electrification of transportation and other sectors, ultimately contributing to significant reductions in carbon emissions and enhancing energy security globally.

„An important initial point is that rapid further deployment of solar PV in the NZE Solar Case would require measures to integrate the additional solar PV into electricity systems and maximise its impact. Scaling up battery storage would be crucial in most cases to improve the alignment of solar PV output with electricity demand patterns and system needs. In the NZE Solar Case, utility-scale battery deployment in 2030 is close to double the level in the STEPS.”

The rise of Lithium

Energy storage technologies are with us for a long time. Some of them since 2000 BC, others are results of recent technological development. The energy storage landscape is constantly evolving, a snapshot from 2014 shows a very different picture that we experience now. An ES comparison study from 2014 ² presents Lithium batteries as the solution with significant potential for growth and improvement, however did not recognize Li-Ion as the most mature battery technology:

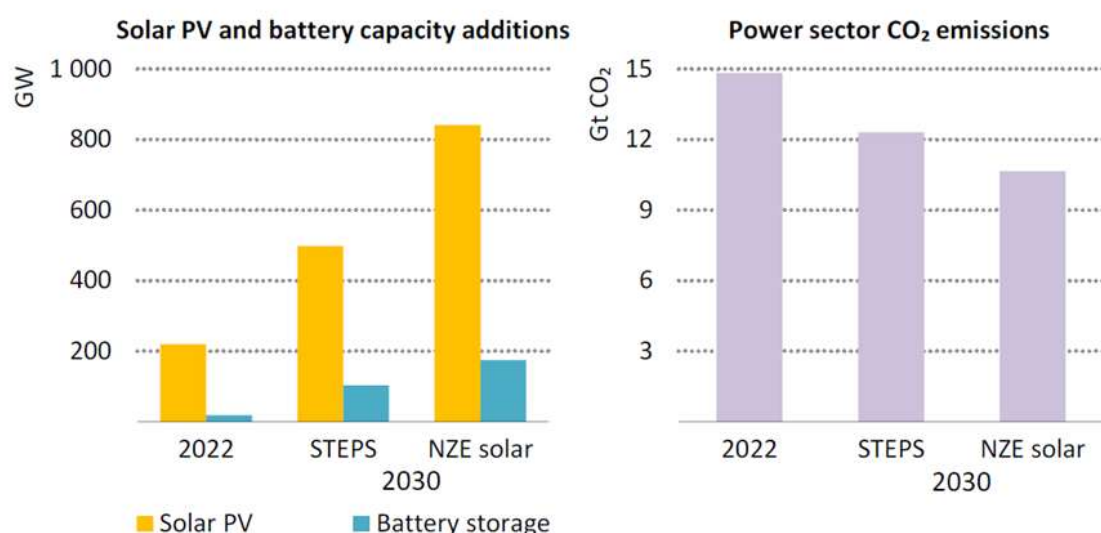
Figure 1.1 [Energy storage technologies in 2014](#)

In the years following 2014, however, lithium-ion technology rapidly matured. A combination of factors propelled its meteoric rise: a steep decline in production costs, significant improvements in energy density and cycle life, and the burgeoning electric vehicle market, which both incentivized innovation and benefited from the increased scale of battery manufacturing. Lithium-ion batteries quickly outpaced other electrochemical storage options, becoming the dominant technology in both grid-scale and behind-the-meter applications.

The Energy Landscape Shift

The rise of energy storage represents a fundamental shift in the global energy landscape. By addressing the limitations of renewable sources, storage technologies empower a future where clean energy sources can replace fossil fuels on a wider scale, promoting sustainability and combating climate change. Continued investment and innovation in this sector are crucial for realizing this vision. IEA World Energy Report 2023 projects a 10-fold increase in battery capacity additions between 2022 and 2030.

Global solar PV and battery storage capacity additions and power sector CO₂ emissions, 2022 and 2030

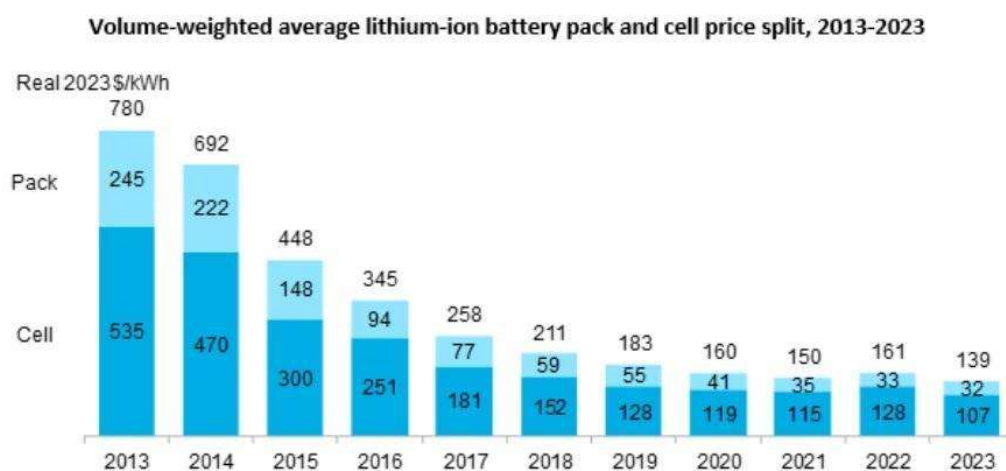


IEA. CC BY 4.0.

Figure 1.2 – International Energy Agency – World Energy Outlook 2023¹

It is important to acknowledge and recognize market trends which are at odds with StoreMore's original baseline assumptions: potential lithium shortages and increase of Li-ion battery prices in the mid term.

According to BloombergNEF's annual battery price survey³ finds a 14% drop from 2022 to 2023, the price of lithium-ion battery packs has dropped 14% to a record low of \$139/kWh, according to analysis by research provider BloombergNEF (BNEF). This was driven by raw material and component prices falling as production capacity increased across all parts of the battery value chain, while demand growth fell short of some industry expectations. Battery demand across electric vehicles and stationary energy storage is still on track to grow at a remarkable pace of 53% year-on-year, reaching 950 gigawatt-hours in 2023. Despite this growth, major battery manufacturers reported lower utilization rates for their plants, while demand and revenue fell short of many companies' expectations. As a result, many EV and battery makers revisited their production targets, which in turn impacted battery prices. Lithium prices reached a high point at the end of 2022, but fears that prices would remain high have largely subsided since then and prices are now falling again.

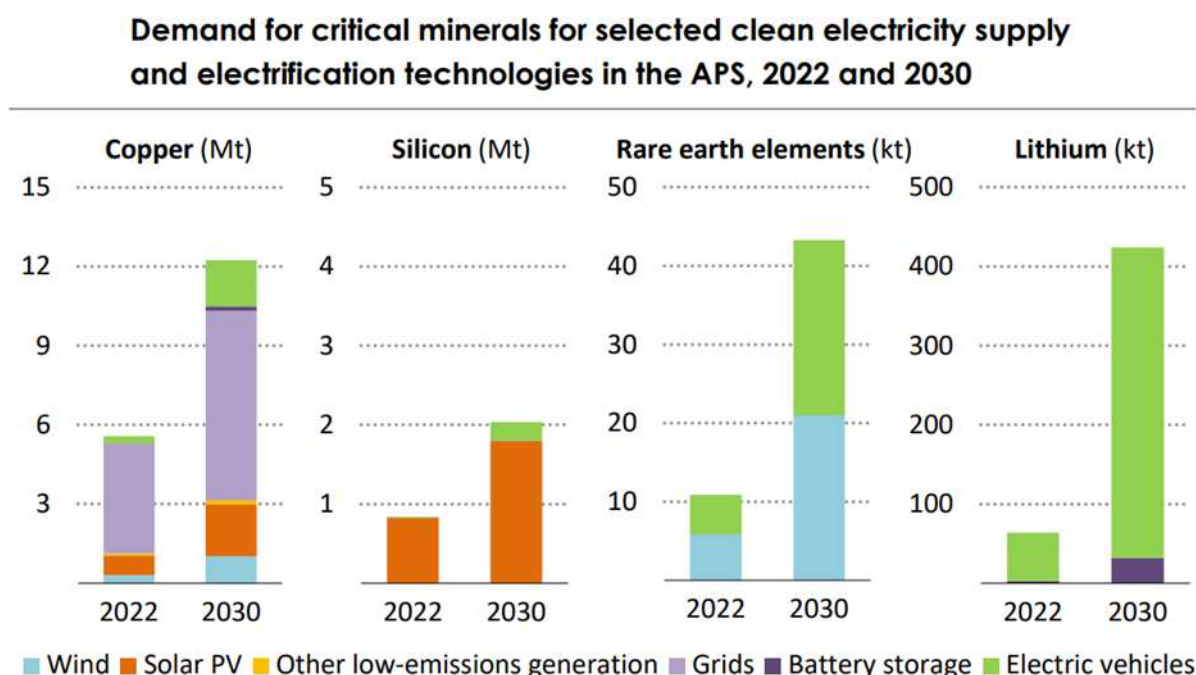


Source: BloombergNEF. Historical prices have been updated to reflect real 2023 dollars. Weighted average survey value includes 303 data points from passenger cars, buses, commercial vehicles, and stationary storage.

Figure 1.3 – BloombergNEF's annual battery price survey 2023

While the IEA World Energy Outlook 2023¹ forecasts significant growth in battery storage, and the BloombergNEF predicts further decrease of costs, it's essential to acknowledge the potential roadblock posed by lithium availability. Lithium is a crucial component of most current battery technologies, and the rapidly increasing demand for electric vehicles and grid-scale storage raises concerns about supply chains.

- **Surging Demand, Limited Resources:** Projections for electric vehicle adoption, alongside the demand for energy storage, suggest a dramatic increase in lithium requirements in the coming years. However, expanding lithium extraction and refining at the needed pace is likely to face challenges.
- **Extraction Challenges:** Lithium mining, especially from brine, requires significant water resources and raises environmental concerns. Expanding production needs to strike a balance between environmental sustainability and social impacts.
- **Rising Costs:** Increased demand coupled with potential supply constraints could lead to significant price hikes for lithium and other critical minerals, directly impacting battery costs. This conflicts with the projections of continued price decreases that are central to the widespread adoption of battery storage solutions. IEA forecast on demand for critical minerals supports this assumption.



IEA. CC BY 4.0.

Figure 1.4 – International Energy Agency – World Energy Outlook 2023¹

- **Geopolitical Factors:** Lithium resources are concentrated in a few regions worldwide, creating potential geopolitical vulnerabilities and supply chain disruptions. Diversifying lithium sources and increasing the recycling of lithium-containing components will be crucial for mitigating these risks. ([Source: Research into the geopolitical dimensions of lithium resource distribution])

Impact on Storage Deployment A sustained lithium shortage and the associated cost increases could have several implications for the deployment of battery-based energy storage systems:

- **Slowdown in Cost Reductions:** The anticipated rapid decline in battery storage costs may be hindered, slowing down the pace at which storage becomes economically competitive.
- **Focus on Alternative Storage Solutions:** This highlights the crucial need to explore and invest in alternative storage technologies with less reliance on critical materials facing supply constraints, such as the solutions explored in the StoreMore project.
- **Resource Efficiency:** Increased emphasis will need to be placed on recycling and repurposing end-of-life batteries to recover lithium and other valuable materials. ([Source: Lifecycle assessment studies of battery recycling])

It is imperative to consider these emerging supply chain challenges for lithium while evaluating the role of energy storage in the clean energy transition. By exploring diverse storage

technologies and emphasizing resource management, the StoreMore project has the potential to provide crucial solutions for a sustainable and reliable energy future.

Beyond Battery Storage

However the IEA report recognizes the importance of energy storage(„As the deployment of variable renewable technologies increases, the need for storage technologies to complement renewable electricity rises rapidly”) it does not mention any other technology than Battery storage (referring to Lithium-ion batteries), pumped hydro and hydrogen and ammonia (one mention as seasonal storage). Therefore, we believe it is even more important to deliver a comprehensive analysis of available alternative energy storage solutions during project StoreMore.

These technologies are gaining traction, demonstrating the potential to complement battery storage and address specific needs in the evolving energy grid.

Promising Technologies

The energy storage field is seeing a surge in innovation, with promising startups and novel (or reinvented) technologies emerging. Here's a look at several key technologies that the StoreMore project will examine:

- **Gravity Storage (GS):** Utilizes the potential energy of elevated weights (legacy mineshafts, surface-based structures, or underground pistons), offering long-duration storage.
- **Compressed Air Energy Storage (CAES):** Stores energy by compressing air into underground caverns or above-ground containers. Provides medium to long-duration storage, especially suitable for grid-scale applications.
- **Liquid Air Energy Storage (LAES):** Stores energy by cooling and liquefying air. Offers potential for high energy density and flexible deployment.
- **Flywheel Energy Storage (FES):** Stores energy in the rotational motion of a high-speed flywheel. Ideal for short-term power quality and grid stabilization applications.
- **Chemical Energy Storage – Hydrogen (H₂):** A versatile energy carrier, produced through renewable electricity and offering diverse storage potential for both short and seasonal durations.
- **Flow Cells (VRFB):** Stores energy in liquid electrolytes, providing scalable storage solutions for various applications.
- **Galvanic Cells – Battery Energy Storage (BES) - other than Lithium:** Exploring alternatives like sodium-ion and zinc-air batteries can address supply chain and sustainability concerns associated with lithium.

- **Superconducting Magnetic Energy Storage (SMES):** Stores energy within a magnetic field created by superconducting coils. Excels in ultra-fast response times for grid stabilization.
- **Ultracapacitors (UC):** Store energy electrostatically, offering extremely high power delivery and charge/discharge cycles, ideal for short-term energy needs.

The Importance of Scale, Function, and Duration

These diverse technologies offer distinct advantages in terms of scale, the specific function they serve, and the duration of energy storage they provide:

- **Scale:** Solutions range from small-scale, distributed storage (flywheels, ultracapacitors) to grid-level, large-scale installations (GS, CAES, hydrogen).
- **Function:** Technologies address different needs, such as fast-response frequency regulation (flywheels, SMES), peak shaving (batteries), or long-term, seasonal backup (hydrogen, LAES).
- **Duration:** Storage capabilities range from seconds/minutes (flywheels, ultracapacitors) to hours/days (batteries, CAES) and potentially months (hydrogen, pumped hydro).

The future of energy storage lies in a portfolio approach. By strategically combining technologies based on their strengths and specific applications, a resilient and sustainable energy grid can be achieved. The StoreMore project, with its comprehensive analysis of alternative energy storage solutions, plays a vital role in advancing this vision.

The Danube Region

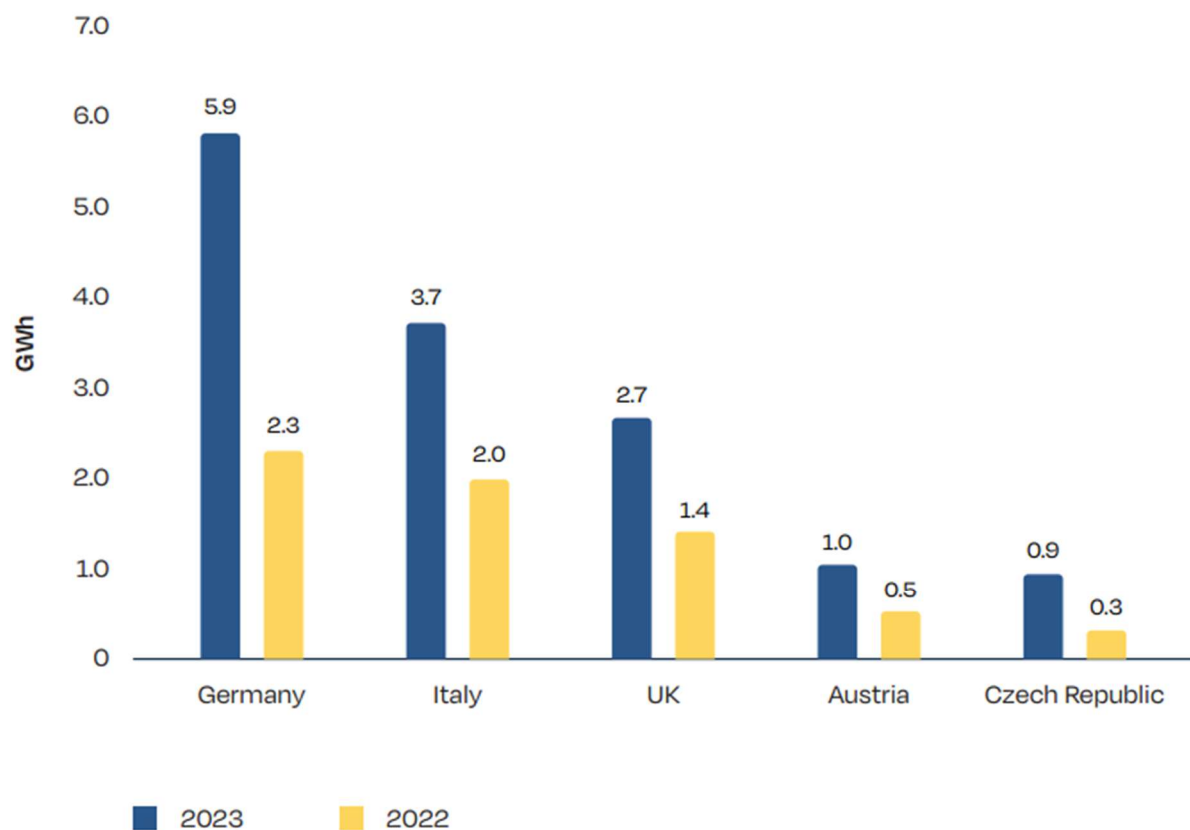
The Danube Region, in alignment with global trends, is rapidly shifting towards renewable energy sources to meet sustainability goals and combat climate change. However, the inherent variability of solar and wind power poses challenges to grid stability. Energy storage emerges as the critical linchpin, enabling the seamless integration of renewables, ensuring power reliability, and optimizing energy use. This Energy Storage Outlook study aims to illuminate this dynamic landscape, offering stakeholders a comprehensive guide to the technologies and trends shaping the future of energy storage.

The energy storage market is experiencing remarkable growth and innovation. We're witnessing breakthroughs in battery technologies, with increased energy density, longer lifespans, and declining costs. Beyond lithium-ion, exciting developments in flow batteries, hydrogen storage, gravity storage and lithium substitute materials offer diverse solutions tailored to specific applications. This rapid pace of innovation underscores the need for an up-to-date and forward-looking assessment of available options that can empower stakeholders within the Danube Region.

Projections indicate that Europe's grid-scale storage capacity will increase substantially by 2031. This growth is part of the broader European strategy to enhance energy security and reduce dependence on fossil fuels, particularly in the wake of geopolitical tensions affecting energy supply. The expansion is also fuelled by ambitious net-zero targets set by the EU, which necessitate significant increases in renewable energy capacity—solar and wind—which in turn require robust energy storage solutions to manage their intermittent nature.⁴

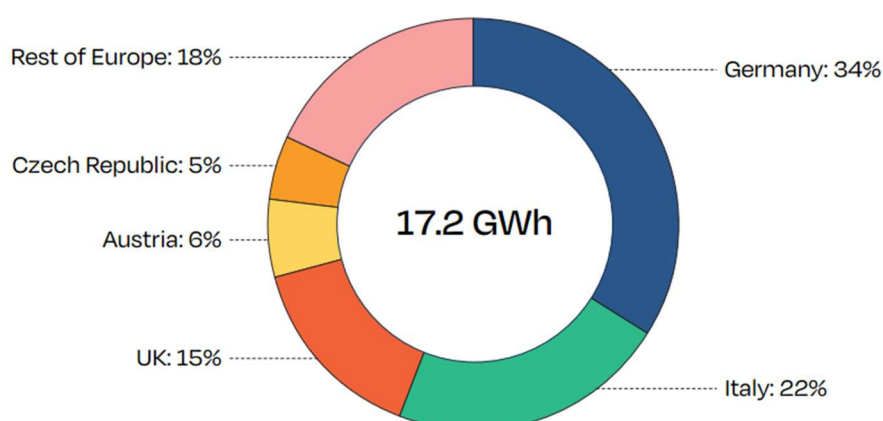
The market is also influenced by substantial investments in energy storage projects, reflecting growing investor confidence. These investments are not only enhancing the energy storage infrastructure but are also driving innovation in the sector, with new projects being implemented to provide balancing and ancillary services to the energy grid.⁵

According to the European Market Outlook for Battery Storage 2024-2028⁶ from [SolarPower Europe](#), out of the top 5 battery storage markets in Europe three are Danube Region countries.



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Figure 1.4 – Top 5 European annual battery storage markets 2023 – Source: [SolarPower Europe](#)



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Figure 1.5 – Top 5 European annual battery storage market shares 2023 – Source: [SolarPower Europe](#)

The European top 5 BESS markets accounted for 82% of new battery installations across the continent in 2023. As Europe transitions towards renewable energy sources, the demand for energy storage solutions has surged, with several Danube Region countries leading the way. In 2023, Germany, Austria and the Czech Republic were among the top five European countries in terms of new battery installations. This growth underscores the region's commitment to energy security and decarbonization, recognizing the crucial role of energy storage in balancing the intermittency of renewable sources. The focus on energy storage in these countries presents a unique opportunity to explore and implement innovative solutions beyond lithium-based batteries, addressing concerns about critical mineral shortages and promoting a more diverse and sustainable energy storage landscape.

Our Energy Storage Outlook builds upon existing regional assessments while delving deeper into the latest technological advancements. This document emphasizes smaller-scale, preferably but not exclusively behind the meter, cost-effective solutions, aiming to make energy storage accessible to a wider range of renewable energy operators. However, for this task, we must examine solutions that may ultimately prove economically unfeasible.

This practical focus is designed to inspire action and investment. The Outlook will provide a valuable roadmap, identifying promising technologies, facilitating informed decision-making, and ultimately accelerating the adoption of energy storage solutions across the Danube Region.

The solutions identified in this document as economically and technically feasible will be further examined, developed, and included in the Comprehensive Catalogue of Sustainable Energy Storage Solutions and the Modelling Tool for Energy Storage Solutions.

1.1 EUROPEAN POLICY

With the escalating effects of climate change, the 2015 Paris Agreement remains a critical framework for global action. This agreement, signed by 195 countries (responsible for 99.75% of global greenhouse gas emissions), aims to limit global average temperature rise to well below 2°C above pre-industrial levels, with efforts to maintain it under 1.5°C.⁷

To support this global effort, the European Union has established ambitious emissions-reduction targets:

- By 2030: A minimum 55% reduction in greenhouse gas emissions compared to 1990 levels.⁸
- By 2050: Achieving climate neutrality, aiming for net-zero greenhouse gas emissions.⁹

The energy sector plays a central role in mitigating climate change. In the EU, energy production, processing, and use contribute to around 79% of greenhouse gas emissions. To transition towards a low-carbon future, the EU has mandated increasing shares of renewable energy in its overall energy mix:

- By 2030: At least 42.5% of final energy consumption must come from renewable sources.¹⁰
- Increased renewable ambition in key sectors: heating and cooling (mandatory annual increase of 1.1% RES share)¹¹
- By 2040: This target is likely to be further increased to 90% of electricity coming from renewable sources (predominantly solar and wind).¹²

Energy storage is a crucial technology to provide the necessary flexibility, stability, and reliability for the energy system of the future. System flexibility is particularly needed in the EU's electricity system, where the share of renewable energy is estimated to reach around 69% by 2030 and 80% by 2050.¹³

Key facts

System flexibility is particularly needed in the EU's electricity system, where the share of renewable energy is estimated to reach around 69% by 2030 and 80% by 2050 (from 37% in 2021).

The need for flexibility in the electricity system will increase significantly in all EU countries, reaching 24% (288 TWh) of total EU electricity demand in 2030 and 30% (2 189 TWh) by 2050 across all timescales (from 11% in 2021).

The daily, weekly and monthly flexibility requirements should reach averages of 2.52 TWh/day, 14.6 TWh/week and 41.68 TWh/month by 2050.

On average across the EU, the overall flexibility requirements increase significantly when the share of renewable generation in the electricity system is above 74% of the total installed capacity.

Many European energy-storage markets are growing strongly, with 2.8 GW (3.3 GWh) of utility-scale energy storage newly deployed in 2022, giving an estimated total of more than 9 GWh.

Looking forward, the International Energy Agency (IEA) expects global installed storage capacity to expand by 56% in the next 5 years to reach over 270 GW by 2026.¹⁴

Different studies have analysed the likely future paths for the deployment of energy storage in the EU. These studies point to more than 200 GW and 600 GW of energy storage capacity by 2030 and 2050 respectively (from roughly 60 GW in 2022, mainly in the form of pumped hydro storage).

The EU recognizes the crucial role of energy storage to facilitate this transition. The revised Renewable Energy Directive and other key policy initiatives highlight the importance of energy storage in:

- Grid Balancing: Stabilizing the electricity grid to accommodate intermittent energy sources such as wind and solar, ensuring reliability and power quality.
- Prosumer Empowerment: Enabling active participation of prosumers (both energy producers and consumers) in the energy market, promoting decentralized energy generation.
- Expanding alternative fuel infrastructure: Particularly for electric vehicles.
- Increasing grid resilience: Enhancing the ability to integrate renewable energy sources into the grid.¹³

Recent Developments

"Fit for 55": This 2021 package includes several legislative proposals designed to align policies with the EU's updated climate goals.

REPowerEU: Initiated in 2022, this plan aims to rapidly decrease dependence on Russian fossil fuels while accelerating the clean energy transition. Energy storage is highlighted as a key solution.¹⁵

EU Hydrogen Strategy (2020): Recognizes hydrogen's potential as a large-scale, long-term energy storage solution.¹⁶

Staff working document on the energy storage - underpinning a decarbonised and secure EU energy system¹⁷

Circular economy: New law ([Regulation 2023/1542 concerning batteries and waste batteries](#)) on more sustainable, circular and safe batteries enters into force fully in steps until 2027.

On March 14, 2023, the European Commission took a significant step towards reforming the European electricity market, addressing the urgent need to reduce reliance on gas-fired generation by adopting non-fossil flexibility solutions like energy storage and demand response.

At Malta Inc., we are keenly analyzing the impact of the [Directive \(EU\) 2023/2413](#), issued by the European Parliament and the Council on October 18, 2023. This pivotal directive amends Directive (EU) 2018/2001 and Regulation (EU) 2018/1999, as well as Directive 98/70/EC, focusing on the promotion of energy from renewable sources. It also marks the repeal of Council Directive (EU) 2015/652, as noted in the Official Journal of the European Union on October 31.

The Directive, which came into force on November 20, 2023, sets an ambitious renewable energy target of at least 42.5% by 2030, with aspirations to reach 45%.

1.2 Overview of Energy Storage Techniques – preliminary analysis

The transformation of power grids globally depends on addressing the inherent challenge of balancing fluctuating renewable energy supply with demand. Energy storage provides the

solutions needed for power grid stability, reliability, and ultimately, the large-scale deployment of clean energy. This chapter provides an overview of key energy storage techniques, highlighting their potential and unique capabilities.

1. Pumped Hydroelectric Storage (PHS)

The Mature Giant: PHS is the elephant in the room we have to – however briefly - address. It is the most established and dominant form of energy storage globally, representing roughly 90% of current large-scale capacity. It utilizes excess electricity during low-demand periods to pump water uphill into elevated reservoirs. When energy demand peaks, water flows downhill through turbines to generate electricity.

Advantages: High energy capacity, long lifespan, and proven reliability. Ideal for long-duration grid-scale storage.

Limitations: Dependent on specific geographic conditions, potential environmental impacts, and lengthy project development timelines. Due to strict geographical limitations, disruptive impact on the environment and project StoreMore's focus on possibly behind the meter energy storage solutions, this study will not analyse further PHS, except specific use cases under Chapter 2, Gravity Storage.

2. Gravity-Based Energy Storage (GS)

Harnessing Potential Energy through Elevation: Gravity-Based Energy Storage (GS) systems store energy by using surplus electricity to lift heavy masses to higher elevations. When energy is needed, these masses are lowered, and the potential energy is converted back into electricity through generators. This method relies on the fundamental principles of gravity and mechanical movement to provide a sustainable and efficient energy storage solution.

Types of GS Systems:

- **Surface-Based GS:** Involves constructing modular structures or towers where heavy weights, such as massive concrete blocks, are lifted using electric motors. The weights are stored at elevation and lowered to generate electricity during peak demand periods.
- **Underground GS:** Utilizes existing underground spaces like abandoned mineshafts or purpose-built shafts. Heavy weights are raised and lowered within these shafts, or a large piston is used atop a high-pressure water chamber. Lowering the weight pressurizes the water, which can then drive turbines to produce electricity.

Advantages:

- **Long-Duration Storage:** GS systems can store energy for extended periods without significant losses, making them ideal for balancing intermittent renewable energy sources like wind and solar.

- **Scalability:** Energy capacity can be increased by adding more weight or height, allowing systems to be tailored to specific energy needs from small communities to large grid applications.
- **Minimal Environmental Impact:** Especially with underground systems, the environmental footprint is reduced by repurposing existing infrastructures like mines, thus minimizing land use and preserving natural landscapes.
- **Resource Efficiency:** Utilizes abundant and recyclable materials such as steel, concrete, and rock, avoiding reliance on scarce or hazardous substances.
- **Low Operational Costs:** After initial construction, GS systems have relatively low maintenance and operational expenses due to their mechanical nature and durability.

Challenges:

- **Technological Maturity:** While the concept is simple, large-scale commercial implementations are still in developmental stages, requiring further research and pilot projects to prove long-term viability and reliability.
- **High Initial Investment:** Significant upfront capital is needed for construction, including building robust lifting mechanisms, structural supports, and advanced control systems.
- **Site Specificity:** Effective deployment depends on suitable geographic locations with adequate elevation differences or existing underground spaces, limiting widespread applicability.
- **Mechanical Wear and Tear:** Moving heavy masses repeatedly can lead to mechanical stress and potential equipment degradation, necessitating regular maintenance and durable component design.
- **Regulatory Hurdles:** Projects may face challenges in obtaining permits and community acceptance, especially when involving large structures or modifications to existing landscapes.

Current Status:

Gravity-Based Energy Storage is gaining attention as a promising solution for sustainable and long-duration energy storage. Several companies and research institutions are developing prototypes and pilot projects worldwide. Innovations focus on improving efficiency, reducing costs, and integrating advanced materials to enhance system performance. Notable projects include the use of cranes and stacked blocks in modular designs and the adaptation of disused mines for underground systems. As the energy sector increasingly shifts toward renewable sources, GS offers a complementary technology to support grid stability and reliability. Continued investment and technological advancements are expected to accelerate the commercialization and adoption of GS systems in the near future.

3. Compressed Air Energy Storage (CAES)

Harnessing Air Pressure for Energy Storage: Compressed Air Energy Storage (CAES) systems utilize surplus electricity to compress air and store it in underground caverns or above-ground vessels. When electricity demand rises, the compressed air is released and expanded through turbines to generate electricity, converting the stored mechanical energy back into electrical energy.

Advantages:

- **Large-Scale Energy Storage:** CAES can handle substantial energy capacities, making it suitable for grid-scale applications and balancing intermittent renewable energy sources like wind and solar.
- **Long-Duration Storage:** Capable of storing energy over extended periods without significant losses, providing reliability during peak demand times.
- **Mature Technology:** Proven operational viability with existing plants, such as those in Germany and the United States, demonstrating long-term functionality.

Challenges:

- **Low Round-Trip Efficiency:** Traditional CAES systems have efficiencies around 40–55%, partly due to energy losses during compression and the need to reheat air before expansion.
- **Fossil Fuel Dependency:** Conventional CAES often requires natural gas combustion to heat the compressed air, leading to greenhouse gas emissions.
- **Geological Constraints:** Large-scale CAES depends on suitable underground formations like salt caverns or depleted gas fields, limiting site availability.
- **High Initial Costs:** Significant capital investment is needed for infrastructure, including compressors, turbines, and storage facilities.

Current Status:

CAES technology is commercially operational but not widespread. Recent advancements focus on adiabatic CAES, which aims to capture and reuse the heat generated during compression to improve efficiency and reduce fossil fuel reliance. Innovations also explore above-ground storage options and hybrid systems combining CAES with other energy storage technologies. As the integration of renewable energy accelerates, CAES presents a viable option for large-scale, long-duration energy storage, provided that efficiency and environmental impacts are addressed.

4. Liquid Air Energy Storage (LAES)

Cryogenic Energy Storage Solution: Liquid Air Energy Storage (LAES) systems store excess electricity by cooling and liquefying air at cryogenic temperatures (-196°C). The liquid air is stored in insulated, low-pressure tanks. When energy demand rises, the liquid air is pumped, evaporated, and expanded through a turbine to generate electricity, effectively converting the stored thermal energy back into electrical energy.

Advantages:

- **High Energy Density:** LAES offers a higher energy density compared to some other storage technologies, enabling more compact and efficient storage solutions.
- **Scalability:** The technology is highly scalable, suitable for both small-scale applications and large grid-level energy storage, with capacities ranging from tens to hundreds of megawatts.
- **Utilization of Established Components:** Relies on proven technology from the industrial gas sector and power generation industry, enhancing reliability and reducing technological risks.
- **Long Lifespan and Low Self-Discharge:** Capable of storing energy over extended periods without significant losses, making it ideal for long-duration storage requirements.
- **Environmental Compatibility:** Uses air as the working fluid, which is abundant, non-toxic, and poses minimal environmental risks.

Challenges:

- **Round-Trip Efficiency:** LAES systems typically achieve efficiencies of around 50–70%, lower than some other storage technologies, due to energy losses during liquefaction and regasification processes.
- **Capital Costs:** High initial investment is required for cryogenic equipment, insulation, and advanced materials to handle extremely low temperatures.
- **Energy Losses During Liquefaction:** The process of liquefying air is energy-intensive, which can impact overall system efficiency and operational costs.
- **Operational Complexity:** Requires sophisticated thermal management systems to handle the extreme temperatures and maintain operational stability.

Integration Opportunities:

- **Waste Heat and Cold Utilization:** LAES systems can integrate with industrial facilities to utilize waste heat or cold, improving overall efficiency and reducing operational costs.
- **Hybrid Systems:** Can be combined with other energy storage technologies or renewable energy sources to enhance performance, flexibility, and grid integration capabilities.

Current Status:

LAES technology is progressing from pilot projects to commercial-scale implementations. Companies like Highview Power have developed demonstration plants to validate the technology's performance and economic viability. Ongoing research focuses on improving efficiency through advanced materials, optimized thermodynamic cycles, and better integration with waste heat sources. As the energy sector increasingly demands large-scale, long-duration storage solutions to support renewable energy integration and grid stability, LAES presents a promising and environmentally friendly option. Widespread adoption will depend on addressing efficiency challenges, reducing costs, and demonstrating economic viability through additional large-scale deployments. Continued advancements and supportive policies are expected to accelerate its adoption in the coming years.

5. Flywheel Energy Storage (FES)

Storing Energy in Rotational Motion: Flywheel Energy Storage (FES) systems store energy by accelerating a rotor (flywheel) to high speeds and maintaining the energy as rotational kinetic energy. When electricity is needed, the flywheel's rotational energy is converted back into electrical energy by slowing down the rotor through a generator. FES is renowned for its rapid response times and ability to provide high power over short durations.

Advantages:

- **Fast Response Time:** Capable of delivering and absorbing power almost instantaneously, making them ideal for frequency regulation and grid stability.
- **High Power Density:** Provides significant power output in short bursts, suitable for applications requiring quick energy delivery.
- **Long Cycle Life:** Can endure hundreds of thousands to millions of charge-discharge cycles with minimal degradation, resulting in low maintenance costs over time.
- **High Efficiency:** Offers round-trip efficiencies typically between 85% and 95%, due to low energy losses in mechanical systems.
- **Environmental Friendliness:** Utilizes mostly recyclable materials and avoids hazardous chemicals, reducing environmental impact compared to some battery technologies.
- **Wide Operating Temperature Range:** Performs reliably across various temperatures, enhancing applicability in different environments.

Challenges:

- **Limited Energy Capacity:** Stores less energy compared to other technologies like batteries or pumped hydro storage, restricting use to short-duration applications (typically seconds to minutes).
- **Self-Discharge:** Energy loss over time due to bearing friction and air resistance, even with advanced magnetic bearings and vacuum enclosures.

- **High Capital Costs:** Advanced materials (e.g., carbon fiber rotors) and precision engineering increase upfront investment requirements.
- **Mechanical Stress and Safety:** High rotational speeds subject components to significant mechanical stress, necessitating robust containment systems to prevent accidents in case of rotor failure.
- **Complex Maintenance:** Requires specialized maintenance for components like magnetic bearings and vacuum systems to ensure optimal performance.

Technological Variations:

- **Low-Speed Flywheels:** Typically use steel rotors and conventional bearings, operating at lower rotational speeds (up to a few thousand RPM). They are heavier and have lower energy densities but are generally less expensive.
- **High-Speed Flywheels:** Employ advanced composite materials and magnetic bearings, allowing rotational speeds up to tens of thousands of RPM. These offer higher energy densities and efficiency but come at a higher cost.

Current Status:

Flywheel energy storage systems are commercially available and deployed in various sectors, including:

- **Grid Services:** Used for frequency regulation, voltage support, and smoothing out renewable energy fluctuations.
- **Transportation:** Integrated into regenerative braking systems for trains and buses to recapture kinetic energy.
- **Uninterruptible Power Supplies (UPS):** Provide backup power for critical facilities like data centers and hospitals during brief outages or transitions to backup generators.

Research and development efforts are focused on increasing energy capacity, reducing costs, and enhancing safety features. Innovations include the use of superconducting bearings, improved rotor materials, and hybrid systems combining flywheels with other energy storage technologies. As the energy landscape evolves with a greater emphasis on renewable integration and grid stability, FES offers a reliable and efficient solution for short-term energy storage needs.

6. Chemical Energy Storage – Hydrogen (H₂ES)

Hydrogen as an Energy Carrier: Hydrogen energy storage leverages excess electricity—often from renewable sources like wind or solar—to split water molecules into hydrogen and oxygen through a process called electrolysis. The produced hydrogen gas is then stored and can be converted back into electricity using fuel cells or burned in turbines when energy demand rises.

Advantages:

- **High Energy Density:** Hydrogen has a high gravimetric energy density, making it suitable for long-duration and large-scale energy storage.
- **Versatility:** Beyond electricity generation, stored hydrogen can be used in transportation, heating, and industrial processes, enabling cross-sector energy integration.
- **Renewable Integration:** Facilitates the absorption of surplus renewable energy, reducing curtailment and enhancing grid flexibility.

Challenges:

- **Efficiency Losses:** The round-trip efficiency—from electricity to hydrogen and back—is relatively low due to energy losses during electrolysis and reconversion.
- **Infrastructure Needs:** Requires substantial investment in production facilities, storage tanks, pipelines, and refueling stations.
- **Safety Concerns:** Hydrogen is highly flammable and requires careful handling and advanced materials to prevent leaks and ensure safe storage and transport.

Current Status: Hydrogen energy storage is emerging as a pivotal component in the transition to a low-carbon economy. Governments and industries worldwide are investing in "green hydrogen" projects, aiming to scale up production and reduce costs. Technological advancements and policy support are critical for overcoming current limitations and achieving widespread adoption.

7. Battery Energy Storage (BES) – Alternatives to Lithium

Electrochemical Powerhouse: Batteries store and release energy through electrochemical reactions. While lithium-ion batteries dominate the current market, several alternative chemistries are gaining attention due to their unique advantages and potential to address some limitations of lithium-based systems.

Emerging Alternative Chemistries:

- **Sodium-ion Batteries:** Utilize abundant sodium resources, potentially lowering costs and reducing dependence on critical minerals. They offer similar operating principles to lithium-ion but with inherently safer chemistry.
- **Zinc-air Batteries:** Leverage zinc and oxygen from the air to produce electricity, boasting high energy density and the potential for easy recyclability. Ideal for applications requiring long-duration energy storage.
- **Sodium-Sulfur (NaS) Batteries:** High-temperature batteries suitable for large-scale energy storage with high energy density and long cycle life. Commonly used in grid storage and industrial applications.
- **Flow Batteries:** Beyond vanadium redox flow batteries (VRFBs), other types include:

- **Zinc-Bromine Flow Batteries:** Offer scalability and are well-suited for medium to large-scale storage with the advantage of using more readily available materials.
 - **Iron-Chromium Flow Batteries:** Provide cost-effective solutions with long cycle life, ideal for stationary energy storage.
- **Lead-Acid Batteries:** A mature and widely used technology for backup power and off-grid energy systems. Known for low upfront costs and reliability but with lower energy density and shorter cycle life compared to newer technologies.
- **Nickel-Based Batteries:**
 - **Nickel-Cadmium (NiCd):** Durable with a long lifecycle and able to operate in extreme temperatures. Environmental concerns due to cadmium toxicity limit their use.
 - **Nickel-Metal Hydride (NiMH):** Improved over NiCd with higher energy density and less environmental impact, commonly used in hybrid vehicles.
- **Solid-State Batteries:** Employ solid electrolytes instead of liquid ones, enhancing safety and potentially increasing energy density. Still under development with commercial applications anticipated in the future.
- **Magnesium-Ion Batteries:** Offer higher theoretical energy density and improved safety due to magnesium's non-dendritic nature during charging, reducing the risk of short circuits.
- **Aluminum-Air Batteries:** Utilize aluminum as the anode and oxygen from the air as the cathode, providing high energy density suitable for certain applications like electric vehicles. Typically, not rechargeable, but research is ongoing.
- **Organic Batteries:** Use organic materials for electrodes and electrolytes, aiming for sustainable and environmentally friendly energy storage solutions.

Advantages:

- **Material Abundance:** Many alternatives use more abundant and less critical materials than lithium, potentially lowering costs and supply risks.
- **Safety Improvements:** Some chemistries offer enhanced safety features, such as reduced flammability and thermal stability.
- **Application Specificity:** Diverse options allow for tailored solutions to specific energy storage needs, from portable electronics to grid-scale applications.
- **Environmental Benefits:** Potential for easier recyclability and reduced environmental impact during production and disposal.

Challenges:

- **Technological Maturity:** Many alternatives are in developmental stages or early commercialization, requiring further research and scaling to compete with established technologies.

- **Performance Limitations:** Some have lower energy densities, shorter lifespans, or efficiency issues compared to lithium-ion batteries.
- **Infrastructure and Supply Chain:** Developing new supply chains and manufacturing processes is necessary, which can be capital-intensive and time-consuming.
- **Cost Structures:** Initial costs may be higher due to lack of economies of scale and ongoing R&D expenses.

By exploring and investing in these alternative battery technologies, the energy storage industry can diversify options, enhance sustainability, and better meet the varied demands of modern energy systems.

8. Flow cells (VRFB)

Energy Storage in Liquid Electrolytes: Vanadium Redox Flow Batteries (VRFBs) are a type of flow battery that stores energy in liquid electrolytes containing vanadium ions in different oxidation states. These electrolytes are stored in external tanks and circulated through a cell stack where electrochemical reactions occur, converting chemical energy to electrical energy and vice versa.

Advantages:

- **Scalability:** The power and energy capacities are decoupled; increasing tank size boosts energy capacity, while adding more cell stacks enhances power output. This makes VRFBs highly adaptable for various applications.
- **Long Cycle Life:** Capable of tens of thousands of charge-discharge cycles with minimal degradation, offering a lifespan of 20 years or more.
- **Safety:** Operates at room temperature using aqueous solutions, reducing fire risks associated with some battery types. However, the entire system must be protected against freezing in frost-prone areas.
- **Deep Discharge Capability:** Can be discharged to 100% without damaging the battery, allowing full utilization of the stored energy.
- **Rapid Response:** Provides quick ramp-up and ramp-down times, beneficial for grid stabilization and renewable energy smoothing.
- **Natural resources:** The chemical elements used are found in relatively larger quantities on Earth. Recyclable, VRFB has a low environmental impact.

Challenges:

- **Low Energy Density:** Compared to solid-state batteries, VRFBs have lower energy density, leading to larger system sizes for the same capacity.
- **High Initial Costs:** The use of vanadium, a relatively expensive material, and the complexity of the system contribute to higher upfront expenses.

- **System Complexity:** Requires auxiliary components like pumps, sensors, and control systems, increasing maintenance requirements and potential points of failure.
- **Electrolyte Management:** Cross-contamination of electrolytes can occur, necessitating careful system management to maintain efficiency.

Current Status: VRFB technology is commercially available and has been implemented in various large-scale energy storage projects globally. Ongoing research focuses on reducing costs through alternative vanadium sourcing, improving electrolyte formulations, and enhancing membrane technologies. VRFBs are particularly well-suited for applications requiring long-duration energy storage, such as integrating renewable energy sources into the grid, peak shaving, and load levelling. As the demand for sustainable and durable energy storage solutions grows, VRFBs are poised to play a significant role in future energy infrastructure.

9. Superconducting Magnetic Energy Storage (SMES)

Energy Stored in Magnetic Fields: SMES systems store energy by circulating direct current through a superconducting coil maintained at cryogenic temperatures. The energy is stored in the magnetic field generated by the current, allowing for rapid discharge and recharge cycles.

Advantages:

- **Instantaneous Response:** SMES can deliver and absorb power almost instantly, making them ideal for stabilizing grid frequency and voltage.
- **High Efficiency:** Offers round-trip efficiencies exceeding 95% due to negligible resistive losses in the superconducting state.
- **Power Quality Improvement:** Excellent for mitigating power disturbances in sensitive industrial processes and data centers.

Challenges:

- **High Costs:** Expensive superconducting materials and cooling systems increase capital expenditure.
- **Cryogenic Requirements:** Necessitates complex refrigeration to maintain low temperatures, leading to operational challenges.
- **Limited Energy Capacity:** Best suited for short-duration applications as energy storage capacity is relatively low compared to other technologies.

Current Status: SMES is commercially used in specialized applications requiring rapid power delivery and high efficiency. Research focuses on developing high-temperature superconductors to reduce cooling needs and costs, potentially broadening SMES applications in the energy sector.

10. Ultracapacitors (UC)

High-Power Energy Storage: Ultracapacitors, also known as supercapacitors or electric double-layer capacitors (EDLCs), store energy electrostatically in an electric field rather than chemically like batteries. They consist of two electrodes separated by an electrolyte and can rapidly charge and discharge large amounts of power.

Advantages:

- **Fast Charging and Discharging:** Capable of charging and discharging in seconds, making them ideal for applications requiring quick bursts of energy.
- **High Power Density:** Deliver high power output, beneficial for stabilizing voltage and frequency in power grids.
- **Long Lifespan:** Can endure millions of charge-discharge cycles without significant degradation, resulting in low maintenance costs.
- **Wide Operating Temperature Range:** Function effectively across a broad range of temperatures, enhancing reliability in various environments.
- **Environmental Friendliness:** Typically composed of non-toxic materials and are easier to recycle compared to some battery technologies.

Challenges:

- **Low Energy Density:** Store less energy per unit weight or volume compared to batteries, limiting their use in long-duration energy storage applications.
- **Self-Discharge:** Higher self-discharge rates than batteries, leading to energy loss over time if not managed properly.
- **Cost:** Higher cost per watt-hour of energy stored compared to traditional batteries, although costs are decreasing with technological advancements.

Current Status:

Ultracapacitors are commercially available and widely used in applications requiring rapid energy delivery and absorption, such as regenerative braking in vehicles, uninterruptible power supplies, and grid stabilization. Ongoing research aims to improve their energy density and reduce costs through advanced materials like graphene and novel electrode designs. As part of hybrid energy storage systems, ultracapacitors complement batteries by handling high-power demands, thereby extending the overall system performance and lifespan.

11. Heat storage (low-medium-high temperature) and cold storage (TES)

Harnessing Thermal Energy: Thermal Energy Storage (TES) systems store excess energy in the form of heat or cold, which can later be used directly or converted back into electricity. TES operates across various temperature ranges:

- **Low-Temperature Storage:** Utilizes materials like water or ice for heating and cooling in buildings.
- **Medium-Temperature Storage:** Employs materials such as molten salts for industrial processes and district heating.
- **High-Temperature Storage:** Involves advanced materials like molten metals or ceramics for large-scale energy storage.

Converting Heat Back to Electricity with Organic Rankine Cycle (ORC):

To reconvert stored thermal energy into electricity, TES systems can be integrated with an Organic Rankine Cycle (ORC). The ORC uses organic fluids with low boiling points, allowing efficient electricity generation from low to medium-temperature heat sources. This makes it suitable for recovering energy from TES systems operating at various temperatures.

Advantages:

- **Versatility:** TES can store energy from multiple sources, including surplus renewable electricity, waste heat, and off-peak grid power.
- **Enhanced Grid Stability:** By converting stored heat back to electricity via ORC, TES can supply power during peak demand, aiding grid balancing.
- **High Efficiency:** Especially when combined with ORC, TES can achieve efficient energy recovery, improving the overall efficiency of the energy system.
- **Long-Duration Storage:** Capable of storing energy over extended periods, making it ideal for compensating for the intermittency of renewable energy sources.
- **Scalability:** Systems can be scaled to meet various energy demands, from small-scale residential to large industrial applications.

Challenges:

- **Conversion Efficiency:** The efficiency of converting heat back to electricity is limited by thermodynamic cycles, particularly at lower temperatures.
- **Capital Costs:** High-temperature TES systems and ORC units require significant upfront investment in specialized materials and equipment.
- **Thermal Losses:** Heat loss over time can reduce the efficiency of TES systems, necessitating advanced insulation techniques.
- **Material Durability:** Repeated thermal cycling can lead to material fatigue, affecting the longevity and maintenance costs of the system.
- **Space Requirements:** TES systems, especially those storing large amounts of heat or cold, may require substantial physical space.

Current Status:

TES technologies are commercially deployed in various sectors. Low-temperature systems are common in residential and commercial heating and cooling. Medium and high-temperature TES, combined with ORC, are used in industrial processes and concentrated solar power (CSP) plants to generate electricity after sunset. Research is ongoing to develop advanced materials like phase-change materials (PCMs) and thermochemical storage to enhance storage capacity and efficiency. Innovations in ORC technology aim to improve performance and reduce costs, making the combined TES-ORC systems more economically viable. As the energy landscape shifts toward sustainability, TES offers a promising solution for integrating renewable energy sources, improving grid reliability, and enhancing energy security.

The Future is Diverse

As the world accelerates towards a sustainable energy future, it becomes increasingly evident that no single energy storage solution can fulfill all the diverse needs of renewable energy system operators. Each technology explored—ranging from gravity-based systems and hydrogen storage to advanced batteries and thermal energy storage—brings its unique set of strengths and limitations. The intermittent nature of renewable energy sources like wind and solar power presents complex challenges that require a multifaceted approach. By leveraging the distinct advantages of various storage technologies, we can build a more resilient and adaptable grid capable of meeting fluctuating energy demands.

Strategic combinations of different energy storage solutions will be crucial for enhancing grid resilience and optimizing the integration of renewable energy. Short-duration storage technologies such as flywheels and ultracapacitors excel in rapid energy discharge and absorption, making them ideal for frequency regulation and power quality improvement. On the other hand, long-duration storage options like flow batteries, thermal energy storage, and compressed air systems are better suited for load leveling and providing sustained power during periods of low renewable generation. By synergistically integrating these technologies, operators can address specific challenges such as peak shaving, backup power supply, and efficient energy utilization.

Continued innovation and technological advancements promise to unlock even greater potential for energy storage, solidifying its pivotal role in building the sustainable power systems of the future. Advancements in materials science, engineering, and digital technologies are driving improvements in efficiency, cost-effectiveness, and scalability across all storage modalities. As we refine these technologies, it becomes essential to evaluate them based on key performance indicators. This leads us to the next critical aspect of our exploration: a comprehensive comparison of the 11 energy storage technologies using standardized metrics. By systematically assessing factors such as efficiency, capacity, lifespan, and environmental impact, we can make informed decisions to guide investments and policy developments in the energy sector.

1.3 Metrics for comparison

A set of common metrics is essential for comparing the various energy storage solutions under assessment. To ensure valid comparisons, this study will utilize industry-accepted metrics. The following parameters will be used for evaluating the **technical aspects** of storage solutions:

- **Energy Density per Unit of Volume [Wh/L]:** The amount of energy that can be stored within a given volume. Higher energy density is generally desirable, allowing smaller installations for a required amount of storage.
- **Power Output [MW]:** The minimum and maximum power output of the storage system. This indicates the scale and suitability of the system for different grid service applications.
- **Energy Retention Period [hour]:** The maximum duration the energy can be stored with minimal losses. This differentiates between solutions suitable for short-term versus long-duration storage
- **Life time [years/cycles]:** The duration over which the energy storage system can reliably store and release energy before experiencing significant performance degradation or requiring major replacement of components.
- **Discharge Time [hour]:** The time span over which the stored energy can be released when needed. This ranges from seconds/minutes (e.g., flywheels) to hours or potentially days.
- **RTE (Round-Trip Efficiency) [%]:** The percentage of energy that can be retrieved from the storage system after a full charge/discharge cycle. Losses occur during conversion processes, and higher RTE is preferred.
- **RTE degradation:** The expected decline in round-trip efficiency over time and with repeated cycling. This factor influences long-term system performance.
- **Technology Maturity / Technological Readiness Level (TRL):** A measure of the technology's development stage. TRL ranges from early research to commercial deployment, providing an indication of risks and potential timelines for wider adoption.

The following parameters will be used for evaluating the **System cost** in term of CAPEX and O&M of storage solutions:

- **System Size** Typically measured in two ways:
 - **Energy Capacity (kWh):** The total amount of energy the system can store.
 - **Power Rating (kW or MW):** The maximum rate of energy the system can deliver at once.

Defining system size is crucial to reflect the economy of scale inherent in certain technologies, especially gravity storage, where efficiency often improves with increasing scale.

- **Capital Expenditure (CAPEX) to Power [EUR/kW] / Energy [EUR/kWh]:** The upfront investment cost associated with the power / energy storage capacity of the system. The

former reflects the expense of components that determine the system's power output (generators, power electronics, etc.), the latter the cost of components that determine how much energy the system can hold.

- **Operation & Maintenance & Decommission Costs (OPEX) [EUR/kWh, EUR/kW/year]:** Ongoing costs associated with running, maintaining and decommissioning the storage system. Can be expressed in two ways:
 - **EUR/kWh/year:** Cost per unit of energy cycled through the system, factoring in replacements and labour.
 - **EUR/kW/year:** Annual cost per unit of power capacity, often reflecting fixed maintenance contracts.

1.4 Will it change everything (WICE) score

Introducing the "Will it Change Everything Score"

The "Will It Change Everything Score" is a custom-designed index created to assess the disruptive potential of emerging energy storage solutions relative to conventional lithium-ion batteries. This score aims to go beyond solely technical performance and cost metrics. It incorporates factors crucial for widespread adoption and the potential to reshape the energy storage market. The index evaluates technologies based on a weighted combination of elements such as scalability, environmental impact, material sourcing sustainability, and policy compatibility.

Why Utilize this Score?

The clean energy transition presents an urgent need to identify energy storage technologies that not only offer technical promise but also possess the qualities to achieve large-scale deployment. The "Will it Change Everything Score" offers a vital perspective for stakeholders (like RES operators, investors and policymakers). By highlighting solutions that may potentially displace lithium-ion dominance, this score helps focus attention on those technologies most likely to accelerate the transformation of the global energy storage landscape. This proactive approach drives an assessment that supports informed decision-making about future energy storage investments and priorities.

Calculation Method

To develop a comprehensive metric for assessing the potential of various energy storage technologies to "change everything" in comparison to lithium-ion batteries, we need to create a scoring system that quantifies each parameter listed. This scoring system allows to measure how well each technology performs relative to the benchmarks set by lithium-ion batteries.

The approach to structure the evaluation:

1. Parameter Weighting

Each parameter will be weighted according to its importance in determining the overall impact and viability of the technology. The weights reflect the priorities and values of stakeholders, such as environmental sustainability, economic feasibility, and technological advancement.

Weighting

- Energy Density: 10%
- Energy Retention Period: 10%
- Lifetime and Life Cycles: 10%
- Round-Trip Efficiency (RTE): 15%
- Technological Maturity (TRL): 20%
- Capital Expenditure (CAPEX): 10%
- Operational Expenditure (OPEX): 10%
- Environmental Impact: 10%
- Scalability: 5%

2. Normalization of Data

Normalizing each parameter to a scale that allows comparison across different technologies. We score each parameter on a scale from 0 to 100, where 0 represents the least desirable outcome (worst performance observed or theoretically possible) and 100 represents the best. Where the parameter is similar to the Li-ion baseline, we give a 50 score in case there is a significant difference, we calculate accordingly but keeping the value in the 0-100 range. The exception is Li-ion, which achieves a TRL of 9, the highest possible value, resulting in a score of 100. Any technology with a lower TRL will receive a proportionately lower score. For instance, a 70,000 cycle lifetime of a Flywheel will get a 100 score but not above.

3. Lithium battery baseline

Parameter	Value/Range
Specific energy / Energy density	100 - 265 Wh/kg / 250 - 693 Wh/l
Energy Retention Period	6-12 hours
Lifetime and Life Cycles	10-15 years / 3000-5000 cycles
Round-Trip Efficiency (RTE)	85-95%
Technological Maturity (TRL)	9
Capital Expenditure (CAPEX)	133 €/kWh
Operational Expenditure (OPEX)	\$5-10 per kWh/year
Environmental Impact	Moderate to High (depending on production and recycling processes)
Scalability	High (widely scalable from small to large applications)

Material Sustainability	Sourcing	and	Moderate (depends on mining and recycling practices)

WICE baseline score for Li-ion: $50 \times 10\% + 50 \times 10\% + 50 \times 10\% + 50 \times 15\% + 100 \times 20\% + 50 \times 10\% + 50 \times 10\% + 50 \times 10\% + 50 \times 5\% = 60$

2. Gravity Storage

Summary of Metrics

Parameter	Technology		
	Gravity Storage		
	On surface (elevated weight)	Legacy mines	Underground piston
Energy density per unit of volume [Wh/kg]	0,41 with 150m hegiht difference	UGES system with sand: At 200m height diff.: 0.55 Wh/kg At 500m height diff.: 1.36 Wh/kg At 1000m height diff.: 2.73 Wh/kg At 1500m height diff.: 4.09 Wh/kg ¹⁸	Data not available
Power range [MW]	0.1 to 25MW	Data not available	
Time of Permanent Energy Storage [hour]	Unlimited		
Life time [years/cycles]	30-50 years		
Discharge Time [minutes]	from miniuts up to hours		
RTE (Round-Trip Efficiency) [%]	85-90	80-90	78-84
RTE degradation	No degradation		
Technology Maturity / Technological Readiness Level (TRL):	7-8	6-7	3-4
System size Energy Capacity (kWh)	up to GWhs		Data not available
CAPEX per kWh of Energy [EUR/kWh]	580-720	1-8(40M tons of sand weight with 1000m shaft depth)	180 for multi GWh projects
OPEX per kWh of Energy [EUR/kWh/year]	Data not available from real world scenarios		

Sources: ^{18, 19, 20}, [BloombergNEF](#)

<https://about.bnef.com/blog/lithium-ion-batteries-are-set-to-face-competition-from-novel-tech-for-long-duration-storage-bloombergnef-research/>

2.1 Gravity Storage introduction

Gravitational energy is energy stored in an object's mass and height above or under the ground. The higher and heavier the object, the more gravitational energy is stored. When a person rides a bicycle down a steep hill and picks up speed, the gravitational energy is converting to motion energy. Hydropower is another example of gravitational energy, where gravity forces water down through a hydroelectric turbine to produce electricity.

Gravity batteries offer a unique approach to storing energy. They utilize the concept of gravitational potential energy, the energy an object possesses due to its height. By raising a heavy object using excess energy, typically from sustainable sources, these systems store potential energy. When needed, the object's descent converts that stored energy back into electricity through a generator.

Physics

Formula of potential energy:

Gravitational potential energy (in joules) can be calculated using the following formula:

$$E = m * g * h$$

where:

- E represents the gravitational potential energy of the object (in joules)
- m is the mass of the object (in kilograms)
- g is the gravitational acceleration of Earth (approximately 9.81 m/s²)
- h is the height the object is lifted (in meters)

For comparison, a 1kg mass would need to be lifted to 110,092 meters (above the Kármán line, the conventional boundary between Earth's atmosphere and outer space) to achieve the same energy density as a lithium-ion battery (300 Wh/kg).

History of GS

The most established form of a gravity battery is pumped-storage hydroelectricity. This technology, dating back to 1907 in Switzerland, involves pumping water to higher elevations during periods of excess energy production. When electricity demand rises, the stored water is released through turbines to generate power. Today, pumped-storage hydro remains the dominant player in grid-scale energy storage.

Modern Innovations in Gravity Storage

Recent years have witnessed exciting advancements in gravity storage solutions. In 2012, the GravityLight, a small-scale gravity battery, emerged, offering a sustainable lighting option in specific regions. Additionally, companies like Energy Vault are developing large-scale systems that utilize cranes to raise and lower massive concrete blocks for energy storage. Similarly, Gravitricity has constructed a prototype gravity battery using a different design. Green Gravity, an Australian company recently concluded partnership aimed at delivering energy storage at seventeen sites in Romania in abandoned mineshafts.²¹

These developments showcase the growing potential of gravity-based energy storage solutions, offering a promising addition to the renewable energy landscape.

2.1.1 Main branches of GS technology

2.1.1.1 Surface GS

Structures hosting weights are built on the ground, upwards. Large, usually concrete, weights are lifted by electrical cranes during peak renewable energy source (RES) production hours. This grants potential energy to the concrete blocks proportional to their mass and height. When releasing the stored energy, the weights descend along high-strength steel wires that operate a generator, converting the potential energy back into electricity.



Figure 2.1 From left to right, Energy Vault's tower fully "charged," at partial levels of charge, and with its capacity fully expended. Source: Energy Vault²²

System Components and Functions

1. **Structural Framework:** Earlier designs (Energy Vault 2018) of primary structures consisted of tall, modular towers. These towers are equipped with a system of winches and cables that lift massive weights. Multiple cranes at the top of the towers raise and

lower the blocks. However, the only actual implementations of the technology is a rectangular block shape structure which is connected to the grid in early 2024 in Rudong, China's Jiangsu province. The Rudong EVx project will be the world's first commercial, utility-scale, non-pumped hydro gravity energy storage system once final provincial and state approvals are obtained for the start of commercial operations.²³

The structure needs to be robust enough to withstand the considerable forces involved during the weight lifting and lowering processes. While rigid strength is crucial, some degree of flexibility in the structure may be beneficial for mitigating wind loads or seismic stresses.

2. **Weights:** The core of the system's energy storage capability lies in the weights that are lifted and stored at height. While concrete and composite materials are common due to their density and cost-effectiveness, exploring alternative weight materials with even higher densities or utilizing recycled materials can positively impact the system's efficiency and environmental footprint.
3. **Lifting Mechanism:** This includes winches, cables, and sometimes rails or guideways. Electric motors are typically used to lift the weights, storing potential energy as the weights ascend. Additionally, alternative lifting mechanisms such as hydraulic systems may be suitable in certain applications. When energy is needed, the process reverses, and the descending weights drive generators to produce electricity.
4. **Control Systems:** Advanced control systems manage the operation, optimizing the lifting and lowering of weights based on energy demand and supply conditions. These systems are crucial for ensuring the reliability and efficiency of the GS system.
5. **Energy Conversion Units:** These are typically electric generators that convert the mechanical energy of the falling weights into electrical energy. The design of these units often needs to accommodate varying speeds and loads to maximize energy conversion efficiency. It's important to note that some energy loss is inherent in the conversion process, affecting the system's round-trip efficiency.

2.1.1.2 Legacy Mineshaft GS / UGES (Underground Gravity Energy Storage)

Existing abandoned mineshafts are repurposed. Heavy weights are attached to steel cables and lowered or raised within the shafts. This vertical movement converts gravitational potential energy into electricity and vice versa. Similar to the surface GS system, a generator is engaged when the weights descend, capturing the released energy.

As example for the technology, Green Gravity's energy storage system moves heavy weights vertically in legacy mine shafts to capture and release the gravitational potential energy of the weights. By simply using proven mechanical parts and disused mine shafts, Green Gravity's energy storage technology is low-cost, long life and environmentally responsible.

Storing energy in this way uses no processed chemicals and has no performance degradation. Moving weights vertically allows for high Round Trip Efficiency and using legacy mine shafts allows reuse of existing structures and materials for weights, contributing to the circular economy and lowering costs.²⁴

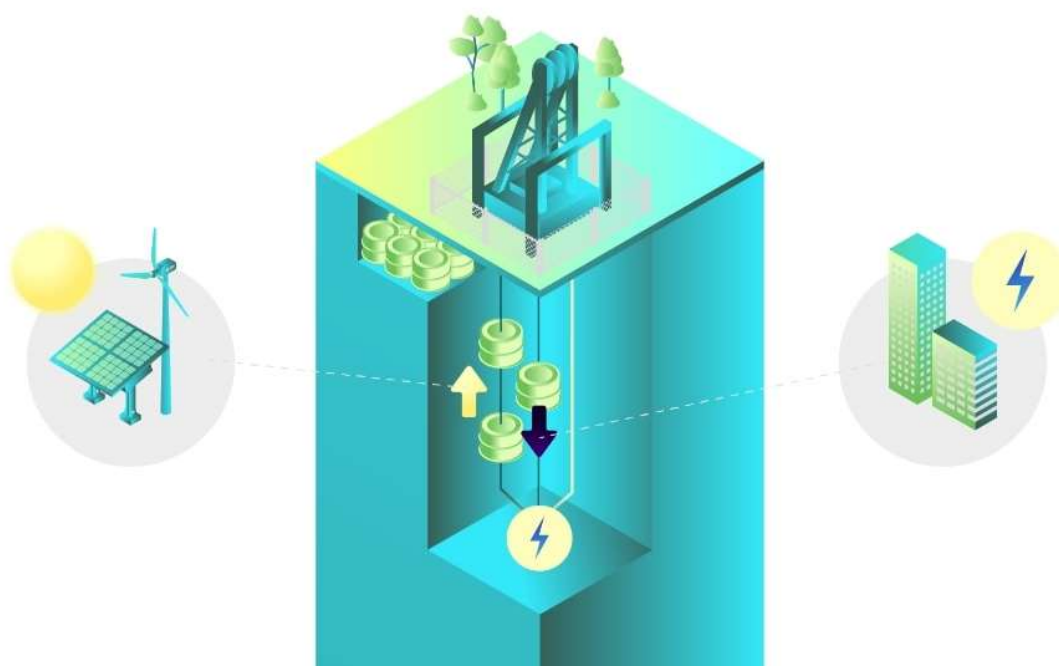


Figure 2.2 Concept of gravity storage in abandoned mineshafts – @Green Gravity 23²⁴

2.1.1.3 Underground Piston GS

Underground piston gravity storage is an innovative energy storage technology designed to harness the potential of hydraulic and gravitational forces in a subterranean setting. At the heart of the system is a massive, waterproof piston chamber that acts as a barrier between a water-filled chamber and the surrounding environment.

During periods of excess electricity production, such as from renewable energy sources, the surplus electricity is used to pump water into the chamber, thereby raising the piston and storing energy in the form of potential energy. Conversely, when there is a demand for electricity, the stored water is released under pressure. As the piston descends, the pressurized water is channeled to drive turbines, converting the potential energy back into electrical energy.

This technology offers a unique approach to large-scale energy storage, leveraging the natural geological features and advanced engineering to provide a solution that is both effective and environmentally considerate.

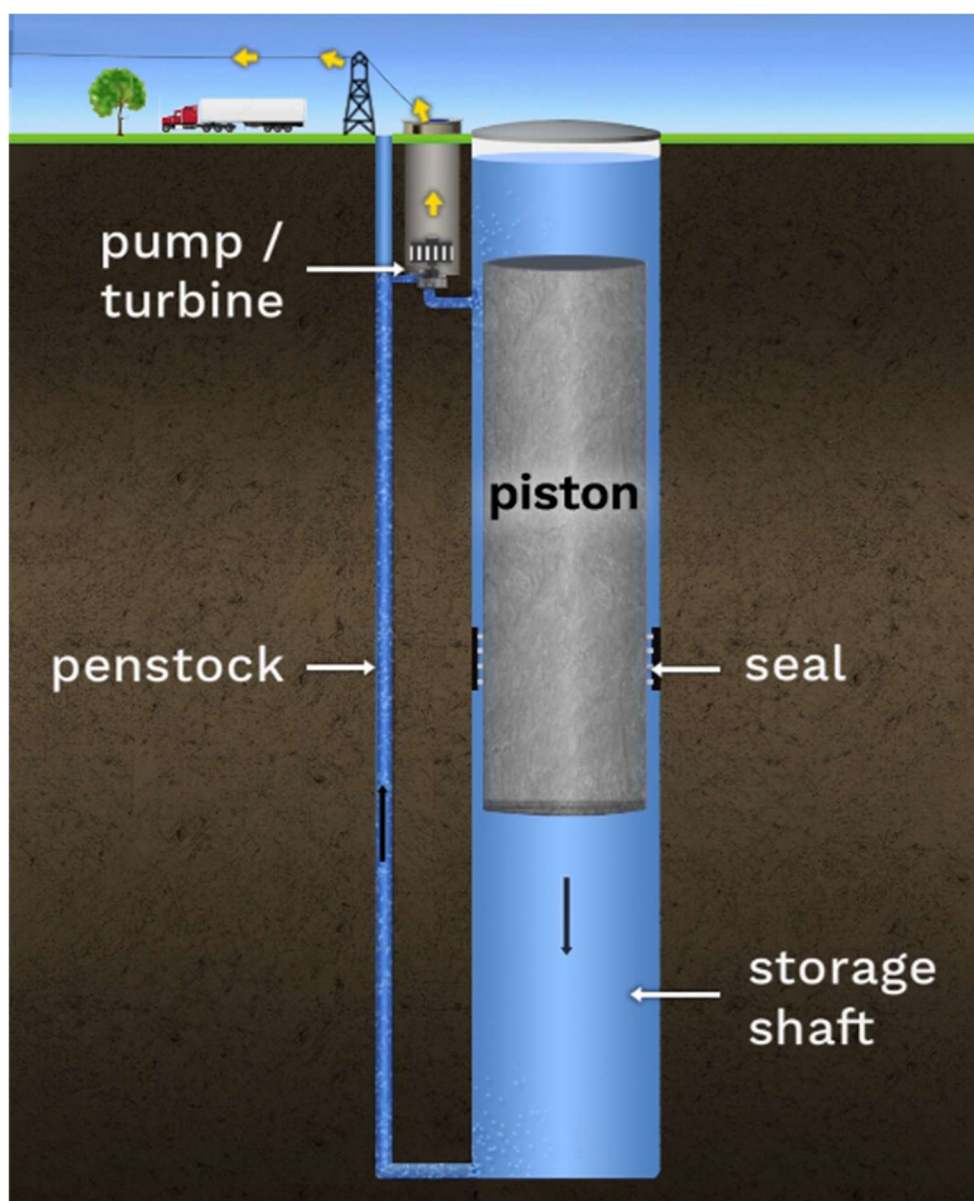


Figure 2.3 Concept of gravity storage in abandoned mineshafts – Gravity Power ²⁵

Innovative Use of Existing Technologies: This method cleverly combines principles of hydraulic mechanics and gravity storage. It uses a large piston and water pressure, similar to traditional pumped hydro storage but in a more contained and possibly more efficient system.

Energy Efficiency: The underground piston gravity storage system is designed to provide relatively high energy efficiency by directly converting gravitational potential energy into electrical energy with minimal intermediate conversions. This streamlined process results in fewer energy losses compared to other energy storage systems that involve multiple energy transformation steps. However, one notable disadvantage is the buoyant force exerted by the water on the piston. This buoyancy effect reduces the effective mass of the piston, thereby

significantly decreasing the system's energy storage efficiency per unit volume compared to surface gravity storage and mineshaft-based gravity storage solutions. This limitation needs to be carefully considered when evaluating the overall performance and feasibility of the system.

Environmental Impact: Since the system is underground, it could have a lower surface land use and visual impact compared to above-ground energy storage facilities. Using naturally occurring geological formations or depleted mines could further reduce the environmental footprint.

Technical Challenges: The feasibility of creating large, watertight underground caverns that can withstand the pressures involved without leaking or collapsing is a significant engineering challenge. The integrity of these structures over time, under the cyclical loading and unloading of hydraulic pressure, would be critical. These systems have not been commercially deployed or validated by a demonstration project. While the equipment used in these systems are commercially available, sealing of water within the shaft as the piston moves needs to be validated.²⁶

Cost and Scalability: The initial construction costs could be high, given the need for significant excavation and engineering to ensure safety and functionality. However, if these challenges can be overcome, the scalability of such a system could be advantageous, especially in areas with suitable geological conditions.

Regulatory and Safety Issues: Regulatory approval processes for such a system could be complex, involving thorough assessments of environmental impacts and long-term safety. Additionally, managing the risk of catastrophic failure, which could have severe implications due to the sudden release of high-pressure water, is crucial.

Overall, the underground piston GS concept is intriguing and could offer an interesting solution for large-scale energy storage if technical and economic challenges can be effectively addressed. However, its very low TRL and high cost makes it rather a curiosity than a viable solution.

2.1.2 Additional GS technologies

2.1.2.1 legacy mineshafts with PHS

Certain concepts examined by researchers or pioneered by startup companies are on the radar which can be combined with the GS storage concepts, especially with legacy mineshafts. One of these concepts is essentially a combination of PHS and abandoned mineshaft utilisation. The space and elevation difference is given in mines, and on the surface there is hardly any intrusion to the landscape, flora and fauna.²⁷ According to a study by Aachen University researchers the achievable altitude differences from the surface to the deepest brines in Germany of up to 1000 meters can otherwise only be realized in the high mountains of the Alps or in Norway, i.e. typically in remote areas and above ground.²⁸

The document titled "Exploratory Economic Analysis of Underground Pumped-Storage Hydro Power Plants in Abandoned Coal Mines" explores the feasibility of utilizing abandoned underground coal mines in Germany for PHS. This study, conducted by researchers at RWTH Aachen University, examines the technical and economic viability of transforming old mines into energy storage facilities that use water's potential energy to balance power supply with demand.

Key findings from the study include:

- **Technical Feasibility:** It is technically possible to convert abandoned coal mines into underground pumped storage facilities. This includes using existing mine shafts and possibly expanding new tunnels or cavities for water storage.
- **Economic Analysis:** The economic viability depends heavily on the geographical and structural conditions of the mines. The cost-effectiveness of such projects improves with larger differences in elevation, known as head, and the potential for larger storage volumes.
- **Environmental and Social Impact:** Such projects have a minimal surface impact, which might enhance public acceptability. They also provide a use for post-mining landscapes, potentially turning them into energy storage sites that contribute to grid stability.
- **Comparative Advantage:** Underground PHS in flat regions could be a competitive alternative to traditional mountain-based PHS, especially in densely populated or ecologically sensitive areas.

The report concludes that under favorable conditions, such as significant vertical elevation (head) and suitable geological conditions, underground pumped hydro storage plants can be both technically feasible and economically viable. These projects could play a crucial role in energy transition strategies, particularly in areas where traditional renewable energy installations face significant opposition or environmental constraints.

2.1.2.2 HD fluids in PHS scenarios

Another concept is replacing water with a high density fluid for PHS applications. This technology can be combined with abandoned mineshaft PHS storage increasing its efficiency and economic viability depending on additional costs of the HD fluid.

This gravity-based energy storage system operates by pumping a high-density fluid to elevated storage tanks during periods of low electricity demand and cost, often coinciding with surplus renewable energy generation. When energy is needed, the fluid is released, flowing downhill (or down the mineshaft) through turbines to regenerate electricity. The utilization of a fluid with 2.5 times the density of water enables deployment on modest hills rather than requiring mountainous terrain. Typical system sizes range from 10MW to 50MW, allowing for integration into existing grid infrastructure and potential co-location with renewable energy projects. The higher density fluid also results in a significantly smaller footprint for a given power capacity. As

civil engineering expenses represent a major portion of project costs, this size reduction offers substantial potential for cost savings compared to traditional pumped hydro storage.²⁹

Potential Risks and Questions

- **Material Considerations:** The properties of the high-density fluid are crucial. It needs to be non-corrosive, have minimal environmental risks, and maintain stable density over a wide range of temperatures.
- **Long-Term Durability:** The pumps, tanks, turbines, and piping need to withstand the specific fluid and its increased density compared to water.
- **Technology Maturity:** While the concept builds on established principles, the use of high-density fluid in this context likely requires technological innovations and thorough testing.
- **Cost vs. Savings:** While civil engineering costs may be reduced, other components could be more expensive. A full lifecycle cost analysis is needed for comparison with other storage solutions.

2.2 Main applications of GS

Gravity storage technologies serve as innovative solutions in the energy sector, harnessing the potential energy inherent in elevated masses to augment the flexibility and robustness of electrical grids. The choice of the most fitting gravity storage system hinges substantially on the application it is intended for. Systems located on the surface boast of their modular nature and swift reaction capabilities, whereas those in mineshafts make use of already existing infrastructures. Conceptual underground piston-based systems show potential for long-term energy storage needs. The following discussion offers a deeper understanding of how different gravity storage systems align with specific grid applications, guiding strategic implementation decisions:

Grid Stabilization and Peak Shaving

- **Purpose:** This involves swiftly countering short-term fluctuations in electricity supply and demand and managing peak demand situations.
- **Ideal Solution:** Surface-based gravity storage systems, which are lauded for their modular design, scalability, and quick activation times.

Integration of Renewable Energy Sources

- **Purpose:** Aims to mitigate the variability of renewable energy sources like wind and solar, allowing for the storage of excess power for later use.
- **Ideal Solution:**

- For smaller, site-specific setups: Surface-based systems are preferable due to their versatility in scaling and potential for co-location with renewable energy installations.
- For broader applications: Mineshaft-based systems, where suitable mines are available, provide larger storage capacities and are an effective solution.

Load Following and Frequency Regulation

- **Purpose:** Adjusts power output continually to meet the ebb and flow of electricity demand and maintain a stable grid frequency.
- **Ideal Solution:** Surface-based systems are recommended due to their ability to rapidly respond to changes and handle frequent charging and discharging cycles effectively.

Energy Arbitrage

- **Purpose:** Involves buying electricity when prices are low during off-peak times and selling it when prices spike during peak times to maximize economic gains.
- **Ideal Solution:**
 - For brief arbitrage opportunities: Surface-based systems excel with their rapid response and flexible design.
 - For longer durations: Mineshaft-based systems, where appropriate, offer higher capacity and potential for cost savings.

Emergency Backup and Grid Resilience

- **Purpose:** Provides critical power supply during outages to ensure that essential services are not interrupted.
- **Ideal Solution:** Surface-based systems are valued for their ability to be rapidly deployed in various locations, thus enhancing the resilience of the grid.

Extended Duration Storage

- **Purpose:** Stores energy for prolonged periods — from several days to entire seasons — to compensate for the extended lulls in renewable energy generation in areas heavily dependent on these resources.
- **Ideal Solution:** Underground piston-based systems, which are under conceptual development, are promising for their high energy density and minimal energy loss over time, making them suitable for shifting energy seasonally.

2.3 Technological barriers, regulatory framework and scalability

While gravity storage offers attractive features, certain technological challenges must be addressed for wider adoption and successful scalability. This chapter examines limitations and potential solutions affecting the three main GS branches.

2.3.1 Surface Gravity Storage

Technology challenges

Material Strength and Wear: Essential components such as cables, winches, and lifting mechanisms are subject to immense stresses due to the substantial weight of the masses and their repetitive cycling. To address this, there is a necessity for the development and employment of materials that are not only high in strength but also resistant to wear, such as advanced composites or specialized steel alloys. Additionally, regular inspections and maintenance are imperative to ensure longevity and operational reliability.

Structural Stability: Constructing tall towers or structures to facilitate weight lifting introduces significant engineering challenges. Designs must account for wind loads, potential seismic activities, and the overall stability of these structures, which becomes progressively complex with increased height. Modular construction techniques offer enhanced flexibility and structural integrity compared to traditional, monolithic structures.

Energy Losses: The conversion process between potential and electrical energy inherently suffers from inefficiencies. RTE is negatively effected by mechanical friction within lifting mechanisms and electrical losses in generators diminish the overall round-trip efficiency of these systems. Thus, optimizing both mechanical components and power electronics is critical to minimize these energy losses.

Regulatory Challenges

Regulatory frameworks significantly influence the feasibility and deployment of gravity storage systems. Specific concerns arise from the placement of elevated weight systems, which may face strict regulations related to their proximity to urban areas, airports, or military radars.

Zoning and Land Use: The installation of gravity storage projects often requires careful navigation through complex zoning laws and land use regulations, which can vary widely by region and may impose restrictions on the size or height of structures.

Environmental and Safety Regulations: Compliance with environmental impact assessments and safety standards is crucial. These regulations aim to protect local ecosystems and communities but can limit the scope and operational practices of projects.

Permitting Processes: The process of obtaining necessary permits for construction and operation can be lengthy and hindered by bureaucratic delays or public opposition, which may stem from concerns over the visual or environmental impacts of large-scale installations.

Scalability

Surface gravity storage systems offer unique scalability advantages over underground or piston-based alternatives. This stems from their inherent flexibility in site selection and design customization. Unlike underground solutions, these systems do not rely on specific geological formations, and they do not require existing infrastructures like abandoned mines. This flexibility opens a wider range of potential locations, including areas near energy demand centers where minimizing transmission losses is vital, offering economy of scale for LCOE and LCOS.

The modular design of these systems further enhances their scalability. Individual units can be adjusted to meet specific energy storage needs by modifying the number or size of the weights and the height of the lifting structures. This allows for precise tailoring of the system and the ability to phase investments based on demand growth.

The development of surface gravity storage aligns with the evolving needs of the grid and technological advancements. As renewable energy adoption continues to rise, the demand for flexible and responsive energy storage solutions increases. Surface systems can be readily expanded by adding more weights or constructing additional towers, providing a scalable solution that adapts to the intermittent nature of renewable sources. This scalability offers both technical and financial benefits, enabling staged investment that reduces upfront costs and spreads financial risk. Each added unit contributes directly to increased capacity, making it easier to meet rising energy storage demands while incorporating technological improvements.

An indicator that these challenges are being addressed is the patent applications filed for gravitational potential energy storage systems. We observe a steady growth in the number of yearly applications since 2016:

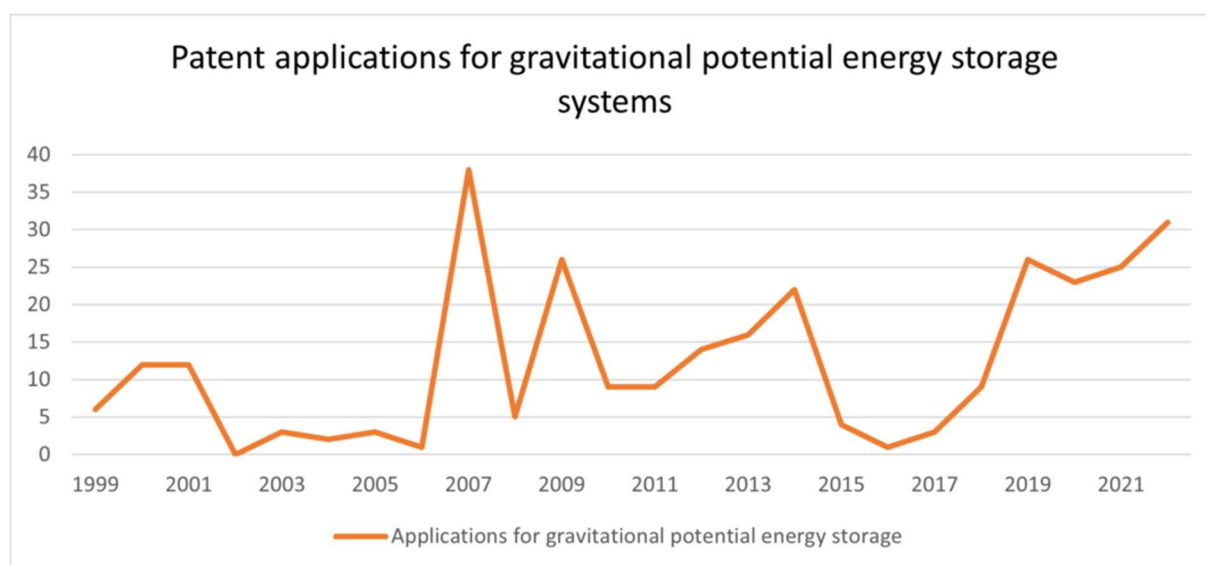


Figure 2.4 Chart: Ben Lincoln / Potter Clarkson

China leads the way in the filing of patent applications in this area. The lead filer is Xi'an Thermal Power Research Institute with patent filings involving steel balls and micro-solid particles. Huaneng Group Tech Innovation Center Co Ltd also have many patent filings. Outside China, US-based Energy Vault Inc and UK-based Gravitricity Ltd are active in the patent application databases.³⁰

2.3.2 Legacy Mineshaft Gravity Storage

Technology challenges

Shaft Depth and Geometry: The energy storage capacity of mineshaft GS is directly tied to the available shaft depth and geometry. Deeper shafts offer greater potential energy storage, but existing mines have limited depth, constraining the achievable capacity. Shaft geometry (e.g., width, inclination) can also pose limitations to the size and weight of the masses used.

Cable Wear and Fatigue: The constant movement of heavy weights within the shaft places significant strain on the lifting cables. Over time, cables can experience wear, fatigue, and corrosion, posing safety risks and requiring regular inspections and potential replacements. The development of durable, high-strength cables and advanced monitoring systems is crucial.

Underground Environmental Conditions: Mineshaft environments are often harsh, with high humidity, potential for water infiltration, and exposure to corrosive substances. These factors can accelerate the degradation of the system components, including the weights and lifting mechanisms negatively affecting the OPEX of the system. Corrosion-resistant materials and protective coatings are essential for long-term reliability.

Regulatory challenges

Mine Safety and Liability: Utilizing abandoned mineshafts requires careful consideration of existing safety regulations and potential liabilities associated with accidents or environmental impacts. Regulatory frameworks for repurposing mines for energy storage might still be evolving.

Environmental Impact Assessments: Thorough assessments are needed to ensure that repurposing the mine for energy storage does not negatively impact groundwater, surrounding ecosystems, or nearby communities. This can involve complex permitting processes and stakeholder engagement.

Scalability

Site-Specific Constraints: While mineshaft GS offers the advantage of utilizing existing infrastructure, its scalability is limited by the availability and suitability of abandoned mines. The geographical distribution of mines may not always align with areas of high renewable energy generation or demand.

Retrofit Complexity: Adapting existing mineshafts for energy storage can involve complex engineering and construction challenges. The need for structural modifications, cable installation, and integration of safety systems can be costly and time-consuming inflating CAPEX.

Limited Capacity Expansion: Unlike surface-based systems, where additional towers can be built, expanding the capacity of a mineshaft system is restricted by the existing mine's dimensions. This limits the potential to incrementally increase storage capacity as demand grows.

While legacy mineshaft gravity storage offers a promising avenue for sustainable energy storage, it faces unique technological and regulatory barriers to large-scale deployment. Addressing these challenges through innovation and collaboration between industry and policymakers is crucial to unlocking the full potential of this technology.

2.3.3 Underground Piston Gravity Storage

Technology Challenges

- **High-Pressure Seal Design:** The immense water pressures within underground piston GS systems necessitate incredibly robust and durable seals. These seals must maintain their integrity over millions of cycles, resisting wear, fatigue, and chemical degradation from the surrounding environment. Advanced materials engineering, including the development of specialized elastomers or composites, is essential to achieving reliable long-term performance.
- **Cavern Integrity:** The stability and integrity of the excavated underground cavern are paramount. The rock formations or salt deposits must be carefully selected to withstand

the cyclic pressure fluctuations and prevent leakage or catastrophic failure. Geological surveys and advanced modeling techniques are crucial in identifying suitable sites and optimizing cavern design for long-term durability.

- **Piston Construction:** The piston itself poses significant engineering challenges. It must be both massive enough to provide sufficient energy storage capacity and strong enough to withstand the forces exerted by the water pressure. Materials selection, structural design, and manufacturing techniques are critical to ensure the piston's integrity and longevity.

Regulatory Challenges

- **Geologic Site Permits:** Securing permits for large-scale underground excavation projects can be complex and time-consuming. Detailed environmental impact assessments, geotechnical studies, and consultations with local communities are often required.
- **Safety and Risk Assessment:** The potential risks associated with high-pressure systems, underground caverns, and large-scale water management necessitate stringent safety protocols and comprehensive risk assessments throughout the project's lifecycle.

Scalability

- **Massive CAPEX:** Underground piston GS systems have inherently high CAPEX due to the extensive excavation and construction required. This can pose a significant barrier to entry and necessitate large-scale investments.
- **Economy of Scale:** The technology exhibits strong economies of scale, with larger systems potentially achieving lower costs per unit of energy stored. This suggests that scaling up is essential for improving cost-competitiveness with other storage solutions.
- **OPEX:** The primary OPEX for piston systems involves pumping water to lift the piston, which is an energy-intensive process. However, ongoing maintenance requirements are expected to be relatively low due to the simple mechanical design and minimal moving parts. The system's longevity and durability can offset the initial CAPEX over time.

Technological Readiness: While interesting, underground piston GS is a nascent technology with no existing full-scale projects in operation. Further research and development are needed to address technical challenges, optimize system design, and demonstrate the long-term viability of the technology for grid-scale deployment.

Underground piston GS could have the potential to become a significant player in long-duration energy storage. However, addressing technological hurdles, mitigating regulatory barriers, and demonstrating the economic viability of large-scale projects are crucial for widespread adoption. Its high investment requirements and risk make a breakthrough less likely in today's competitive environment for novel energy storage technologies.

2.4 Raw material restrictions

The increasing demand for energy storage solutions, including gravity-based systems, highlights the importance of considering potential limitations in raw material availability:

Concrete

GS often relies heavily on concrete for tower structures and weights. Concrete production is a major source of greenhouse gas emissions due to cement manufacturing. The global cement industry is responsible for 27% of total direct CO₂ emissions, making it the second-largest CO₂ producer of the industrial sectors. (Source: Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context ³¹). Efforts to incorporate alternative materials or recycled concrete would increase sustainability.

Steel and aluminium

High-strength steel is crucial for cables, lifting mechanisms, structural components, - in case of underground piston systems - pumps, piping, and potentially generators will need to withstand high operating pressures. This might require specialized steel alloys or advanced composites. The World Economic Forum (WEF) shares some interesting facts about the supply and demand gap in metals and mining³². In essence, the report on the mining and metals industry, specifically focusing on the steel industry, presents a stable and abundant supply of steel as a key component in supporting global economic activities. However, the rise in labour and energy costs impacts the metal manufacturing industry.

While steel itself is abundant, the report discusses broader concerns about raw material restrictions that could impact the mining and metals industry. These restrictions are mainly due to geopolitical factors, environmental regulations, and the increasing demand for materials essential for the energy transition.

Metal production has a significant carbon footprint. Despite manufacturers making major efforts to improve recycling rates and reduce emissions, the production of aluminium and steel still contributes more than 10% of CO₂ emissions globally,³³ while aluminium alone accounts for [2% of all human-caused greenhouse gas emissions](#), [3% of the world's direct industrial CO₂ emissions](#) each year.

Geological Materials

Creating the underground caverns necessitates either suitable rock formations or salt deposits. Geological availability is a limiting factor in many locations.

Sealing Materials

Pistons require highly durable and flexible seals to withstand immense water pressure (in case of underground piston systems). The development and production of such specialized materials may encounter constraints. High-Performance Elastomers: Seals need to maintain flexibility,

elasticity, and leak-tightness under extremely high pressures and over a long lifespan. Specialized synthetic rubbers (like nitrile, fluoroelastomers, or custom compounds) may be required.

Water

While water itself isn't usually a scarce resource, water use within piston GS systems necessitates careful consideration of local water resources and any competing demands. Employing a closed-cycle system reduces the water demand of the investment, limiting consumption of this valuable resource to a one-time requirement.

Chemicals

Chemicals for water treatment are also relevant as over time, even small numbers of microorganisms could lead to the formation of biofilms, which are layers of microorganisms that adhere to surfaces, such as the piston walls. A combination of **silver or copper ions**, possibly with **stabilised hydrogen peroxide**, would be a strong, long-lasting solution. These chemicals can be applied during installation and potentially keep the water sterile for **decades** without needing additional maintenance or refilling. Properly sealing the system and using a compatible biocide will ensure that no biological growth occurs over time.

Rare Earth Elements

While not directly a major component of GS systems, certain motors, generators, and control systems might utilize rare earth elements. Any global supply disruptions in these critical materials could indirectly impact GS development (Source: The role and challenges of Rare Earths in the Energy Transition - Lisa DEPRAITER* and St´ephane GOUTTE)³⁴.

Summary

Raw material restrictions present a challenge for the scaling of GS technologies. Proactive material selection, prioritizing recycled or sustainable resources, and designing systems for long-term use and recyclability are crucial for a responsible transition toward large-scale GS deployment.

2.5 Energy storage costs in GS

The economic viability of gravity storage (GS) hinges on understanding its capital expenditure (CAPEX) and operational expenditure (OPEX). While specific figures vary significantly depending on the technology, project size, and location, some general trends and estimates can be gleaned from available information.

According to the source we obtained ([Energy Storage Grand Challenge Cost and Performance Assessment](#)), cost information for various gravity-based storage systems was obtained directly from developers.

CAPEX

Surface GS:

„Heavy Brick Systems” (Surface GS): Initial estimates for systems such as those developed by Energy Vault suggest a power equipment cost of approximately €430/kW at 100 MW and €418/kW at 1,000 MW.

Cost per kWh: The total installed cost for heavy brick systems decreases with longer durations, from €1,000/kWh for a 2-hour duration to €178/kWh for a 100-hour duration at 100 MW. For a 1,000 MW system, the corresponding costs are €595/kWh and €117/kWh, respectively

Potential for Cost Reduction: By 2030, a 15% reduction in costs is expected due to improvements in materials and technology, resulting in a total installed cost of €604/kWh for a 4-hour, 100 MW system

More recent analyses ([BloombergNEF Research](#)) indicate that gravity-based systems like Energy Vault's can have a higher average CAPEX compared to other long-duration energy storage technologies, ranging from €577/kWh to €718/kWh.

The modular nature of surface GS allows for phased investment, reducing upfront costs and spreading financial risk.

Legacy Mineshaft GS/UGES:

Gravitricity, a company specializing in this technology, estimates a CAPEX of around €190/kWh.

The reuse of existing infrastructure (abandoned mineshafts) can significantly reduce the CAPEX compared to surface systems. The ***Underground Gravity Energy Storage: A Solution for Long-Term Energy Storage***¹⁸ study states, that, the use of sand as storage media alleviates any risk for contaminating underground water resources as opposed to an underground pumped hydro storage alternative. UGES offers weekly to pluriannual energy storage cycles with energy storage investment costs as low as about 0.9 to 9 EUR/kWh.

Retrofit complexity and site-specific constraints can influence costs.

Underground Piston GS:

- CAPEX for this technology is expected to be high due to extensive excavation and construction.
- Estimates are scarce, but some suggest that it could be competitive with pumped hydro storage on a large scale, potentially reaching €180/kWh or lower for multi-GWh projects. ([ESGC Cost Performance Assessment 2022](#))
- Economies of scale play a crucial role in reducing the CAPEX of underground piston GS.

OPEX

- Surface GS:
 - OPEX is generally low due to the simple mechanical design with minimal moving parts.
 - Maintenance costs for cranes, cables, and other components need to be considered.
 - Energy consumption for lifting the weights contributes to OPEX but is offset by the value of the stored energy.
- Legacy Mineshaft GS:
 - Similar to surface GS, OPEX is expected to be low due to the simplicity of the system.
 - Maintenance of cables and lifting mechanisms is necessary, as is monitoring for potential wear and corrosion in the underground environment.
- Underground Piston GS:
 - The primary OPEX component is the energy cost for pumping water to lift the piston.
 - Maintenance requirements are expected to be minimal due to the limited number of moving parts.
 - The long lifespan and durability of the system can help offset the initial CAPEX over time.

Overall

While gravity storage technologies offer promising solutions for grid-scale energy storage, their economic viability is still under evaluation as projects are being deployed and data is collected on their performance and costs. The available estimates suggest that:

- Surface GS might have a higher upfront cost but offers scalability and flexibility.
- Legacy mineshaft GS can leverage existing infrastructure for cost reduction but faces site limitations.
- Underground piston GS is a nascent technology with potentially high CAPEX but promising long-term cost benefits due to low maintenance and longevity.

Further research, development, and real-world project implementation will provide more accurate cost data and help determine the competitiveness of gravity storage technologies in the energy market.

2.6 GS environmental impact

Gravity storage (GS) solutions offer the potential for long-duration energy storage, crucial for stabilizing grids powered by fluctuating renewable energy sources. While still in its relative

infancy, GS is gaining attention due to its inherent advantages and the flexibility afforded by its various configurations.

2.6.1 Surface Gravity Storage

Surface-based GS systems feature structures, often modular towers, where massive weights are lifted vertically. Their relative simplicity is appealing, but they come with potential challenges.

- **Land Use:** Surface GS requires a sizable footprint, potentially competing with other land uses such as agriculture or housing. Careful site selection is crucial.
- **Visual Impact:** Large tower structures can alter landscapes, necessitating community engagement for acceptance.
- **Material Considerations:** Building the structures themselves necessitates the use of concrete, steel, and other materials whose production has environmental consequences ([Source: a study on the embodied carbon in construction]).

2.6.2 Legacy Mineshaft Gravity Storage

Repurposing abandoned mineshafts for GS offers unique benefits:

- **Minimal Surface Impact:** The bulk of the system resides underground, reducing land use conflicts and visual disruption.
- **Reusing Existing Infrastructure:** Mineshaft utilization lessens the need for new construction, reducing the overall environmental footprint.
- **Safety Considerations:** Careful assessment is needed to address safety protocols in these potentially hazardous environments.

2.6.3 Underground Piston Gravity Storage

Underground piston-based GS involves creating large subterranean caverns for water storage. Key considerations include:

- **Geological Suitability:** Finding suitable rock formations or salt deposits is vital for maintaining high pressure and preventing leakage.
- **Excavation Impact:** Creating the underground chambers presents potential environmental concerns related to ground disturbance.
- **Water Management:** Source water and potential changes to water tables require assessment. With proper sealing of the underground chamber, the system can operate in a closed cycle without any interaction with local water tables. Advanced materials and engineering techniques must ensure that the chamber is impermeable and can withstand the pressures involved without leakage. Regular inspections and maintenance of the seals are necessary to ensure long-term integrity. The closed-cycle system inherently reduces

the risk of water loss or contamination, provided the initial fill and seals are managed correctly.

Environmental Impact Across GS Systems

Despite the differences in specific implementations, some broad environmental impacts apply to most GS systems:

- **Low Operational Emissions:** Once constructed, GS systems have negligible greenhouse gas emissions during their energy storage and release cycles. This makes them an environmentally friendly option for long-term energy storage.
- **Wildlife Habitat:** Depending on the scale and location, GS installations could potentially disrupt wildlife habitats. Mitigation strategies are often needed to minimize these impacts. This can include careful site selection, construction planning to avoid critical habitats, and implementing restoration projects post-construction.
- **Material Recyclability and Usage:** Materials used in GS systems, such as steel and concrete, have varying levels of recyclability. End-of-life planning is essential to ensure these materials can be reused or recycled, minimizing environmental impact. Additionally, using local construction waste materials or a solution including a sand and water mixture can be appropriate due to its low cost to construct the weights can significantly contribute to recycling efforts. This approach has several benefits: (See 2.4 Raw material restrictions):
 - Lower Costs: Utilizing local construction waste reduces the costs associated with sourcing and transporting new materials.
 - Reduced CO₂ Emissions: By repurposing waste materials, the CO₂ emissions associated with producing and transporting new materials are substantially lowered.
 - Resource Efficiency: This practice supports a circular economy by diverting waste from landfills and reusing it in a productive manner.

However, there are some trade-offs:

- Reduced Storage Capacity: Construction waste materials may have lower density compared to traditional materials like concrete and steel, resulting in less weight per volume. This could slightly reduce the energy storage capacity of the system.
- Material Variability: Construction waste can vary in composition and quality, which may affect the consistency and reliability of the weights. Careful sorting and processing of the waste materials are necessary to ensure their suitability for use in GS systems.

Overall, the innovative use of construction waste materials in GS systems highlights a significant opportunity to enhance sustainability and reduce environmental impact while maintaining the

functional benefits of gravity-based energy storage. By considering these factors, GS systems can be designed to be both effective and environmentally responsible.

Further Research

Thorough life-cycle assessments of different GS implementations will shed more light on their complete environmental profiles as compared to other energy storage technologies. This LCA however is the subject of the Comprehensive Catalogue of Sustainable Energy Storage Solutions (CSESS) of project StoreMore.

2.7. Conclusions: advantages, disadvantages, and recommendations for GS

2.7.1 Pros and cons

Pros:

1. **Low Operational Emissions:** Once constructed, gravity storage systems have negligible greenhouse gas emissions during their operation, making them an environmentally friendly energy storage solution.
2. **Long Lifespan and Durability:** Gravity storage systems typically have a long operational life with minimal degradation over time, unlike chemical batteries which degrade and require replacement.
3. **Scalability:** Gravity storage systems can be scaled to different sizes, from small installations using construction waste for weights to large-scale systems utilizing existing mineshafts or custom-built towers.
4. **(relative) Flexibility in Location:** These systems can be implemented in various settings, including urban areas with surface-based systems, rural areas using repurposed mineshafts, and specialized underground piston systems in suitable geological formations. Legacy mines, however, lack flexibility due to their fixed geographical location.
5. **Utilization of Local Materials:** Using local construction waste for weights reduces costs and environmental impact, supporting circular economy practices.

Cons:

1. **High Initial Capital Expenditure (CAPEX):** The construction of gravity storage systems, especially those involving large-scale infrastructure like towers or deep underground chambers, requires significant upfront investment.
2. **Land Use and Visual Impact:** Surface-based systems require substantial land and can impact local landscapes, potentially facing opposition from communities.

3. **Geological and Structural Constraints:** Underground systems depend on suitable geological conditions, and both surface and underground systems require robust engineering to ensure safety and efficiency.
4. **Energy Density Limitations:** Compared to chemical batteries, gravity storage systems have much lower energy densities, which limits their effectiveness for certain applications

2.7.2 Existing systems

Up to the date of this study we know only one operational surface GS system, Energy Vault's 25MW/100MWh system in **Rudong**, China. The 25 MW/100 MWh EVx™ Gravity Energy Storage System (GESS) is a 4-hour duration project being built outside of Shanghai in Rudong, Jiangsu Province. The company anticipates a 80% RTE and 35-year lifetime.³⁵



Figure 2.6 Rudong GS system³⁵

Energy Vault and partners China Tianying and Atlas Renewable on three additional projects, which commenced in 2023, including:

- 17MW/68MWh EVx GESS deployment in Zhangye City, Gansu Province, being built adjacent to a renewable energy generation site and a national grid interconnection site;
- 50MW/200MWh EVx located in Ziuquan City, Jinta County, Gansu Province;
- 25 MW/100 MWh EVx located in Huailai Cunrui Town, Zhangjiakou County, Hebei Province

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The **Leith Concept Demonstrator** system constructed in 2021 in Edinburgh. The company had been operating a 250kW, grid-connected gravity energy storage demonstration project using a 15-metre-high rig as a demonstration for 3 months.³⁷ Previous engineering simulations showed

that the system would operate within acceptable parameters. The test rig was there to validate those results which purpose it successfully served.

The company from the UK will soon begin work to convert Europe's deepest mine into the first-ever gravity-based battery. The 1,444 meters deep mine is located in Pyhäjärvi, ~450 km north of the Finnish capital of Helsinki. The company will utilise a 530 m auxiliary shaft to build a 2MW prototype to demonstrate its technology, the first of its kind in Europe.³⁸

Zooming in the Danube Region, Gravitricity's GraviStore system is planned to be implemented in Germany (Grube Teutschenthal mine near Halle),³⁹ the Czech Republic (Darkov mine⁴⁰ is in the Moravian-Silesian region) and Slovenia.⁴¹

Green Gravity has built a 10m R&D facility at Bluescope's Port Kembla Steelworks to aid the development of the technology. In December 2023, the Wollongong-based startup established a collaborative agreement with the local mining company. This agreement focuses on the feasibility of deploying gravitational energy storage technology within eight decommissioned mine shafts.⁴²

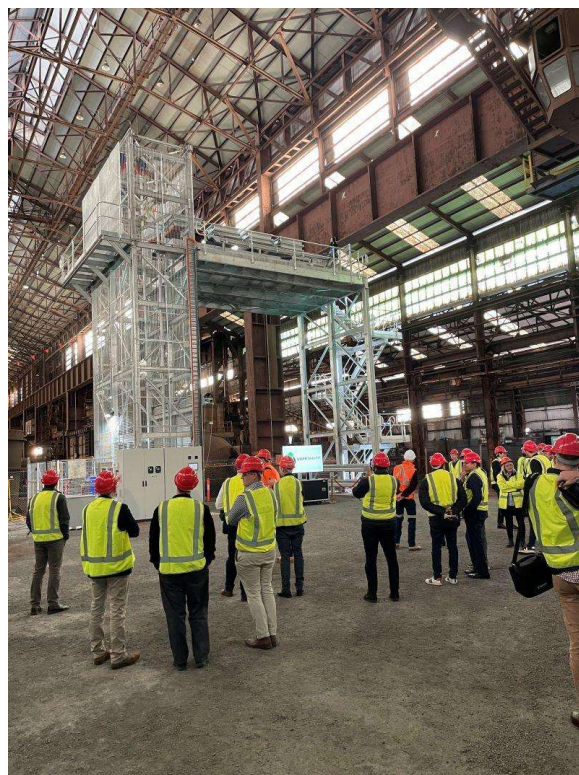
In November 2023, the Australian company entered into a framework cooperation agreement with Complexul Energetic Valea Jiului SA (CEVJ), a Romanian government-backed energy company. This agreement aims to explore potential deployment opportunities for the company's energy storage technology in 17 disused coal mine shafts located within Romania's Jiului Valley.²¹

To date, there is no fully operational underground piston gravity storage system, highlighting the technology's infancy and its low Technology Readiness Level (TRL) of 2-3. This reflects that

the concept is still in the early research and experimental stages, with significant development and validation required before it can be considered for broader implementation.

2.7.3 Will it change everything (WICE) index

Gravity storage systems represent a promising alternative to traditional lithium-ion batteries, offering a distinct set of advantages and challenges. To assess their potential to revolutionize the energy storage landscape, we will calculate their "Will it Change Everything Score" based on a weighted combination of key factors. This score will provide a comprehensive evaluation of gravity storage systems' disruptive potential, considering not only their technical capabilities but also their environmental impact, scalability, and market viability compared to the current dominant technology, lithium-ion batteries.



Scoring Gravity Storage Systems

1. **Energy Density** Gravity storage systems generally have lower energy density compared to lithium-ion batteries due to the large volumes required for substantial energy storage. Their energy density is very much dependent on the height difference. With minimal difference, the storage volume must be significantly higher.

Score: 20

2. **Energy Retention Period** Gravity storage systems can store energy for long periods without significant losses, making them suitable for long-term energy storage. Their storage duration is almost unlimited, therefore a maximum score is well justified

Score: 100

3. **Lifetime and Life Cycles** Gravity storage systems can offer an exceptionally high number of cycles with minimal degradation, especially when using robust materials like steel and concrete.

Score: 100

4. **Round-Trip Efficiency (RTE)** Gravity storage systems typically have a round-trip efficiency of around 70-85%, which is lower than lithium-ion batteries.

Score: 40

5. **Technological Maturity (TRL)** Gravity storage systems have different TRL levels with very few actual implementation usecases. Both underground piston and mineshaft systems have very low TRL level (3-6) while on surface systems are commercial available and operational (TRL 8-9). In conclusion, GS is much less established than lithium-ion batteries and have fewer market actors.

Score: 50

6. **Capital Expenditure (CAPEX)** Gravity storage systems often have high initial costs due to the need for substantial infrastructure and materials.

Score: 30

7. **Operational Expenditure (OPEX)** Gravity storage systems have relatively low operational costs, primarily due to minimal maintenance requirements.

Score: 70

8. **Environmental Impact** Gravity storage systems are environmentally friendly due to the use of common materials and minimal reliance on toxic substances. They also have a lower risk of accidents, reducing the chance of environmental contamination.

Score: 90

9. **Scalability** Gravity storage systems are scalable, especially in modular formats like surface gravity storage, but they can face limitations in specific applications such as legacy mineshaft storage.

Score: 50

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	20	2
Energy Retention Period	0.1	100	10
Lifetime and Life Cycles	0.1	100	10
Round-Trip Efficiency (RTE)	0.15	40	6

Technological Maturity (TRL)	0.2	50	10
Capital Expenditure (CAPEX)	0.1	30	3
Operational Expenditure (OPEX)	0.1	70	7
Environmental Impact	0.1	90	9
Scalability	0.05	50	2.5
Total	1		59.5

Conclusion

The "Will it Change Everything Score" for gravity storage systems is **59.5**, indicating a potential to impact the energy storage landscape significantly compared to the baseline score of Li-ion (60). While they may not match the energy density and efficiency of lithium-ion batteries, their advantages in terms of long-term storage, environmental impact, and low operational costs make them a viable and sustainable alternative, especially in applications requiring large-scale, long-duration energy storage. Further development and optimization could enhance their competitiveness and broader adoption.

Impact potential of technology

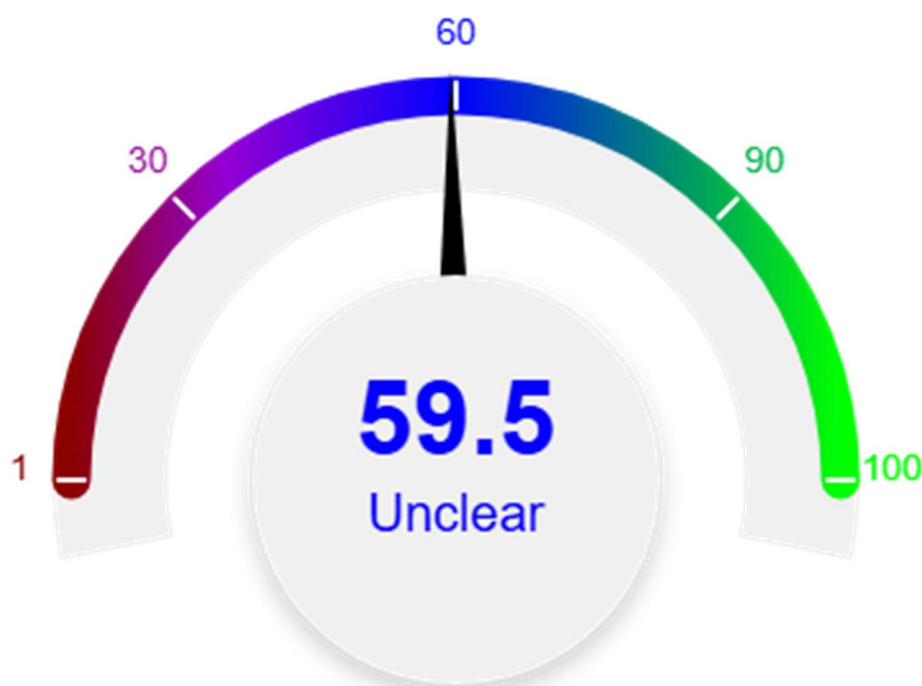


Figure 2.7 Gravity Storage WICE index

3 Compressed air energy storage (CAES)

Summary of Metrics

Parameter	Technology		
	CAES types		
	D-CAES	A-CAES	ICAES
Energy density per unit of volume [kWh/m ³]*	3-24		
Power range [MW]	1 – 320		
Time of Permanent Energy Storage [hour]	hours to weeks		
Life time [years/cycles]	20 – 40 years		
Discharge Time [minutes]	2 – 26 hours		
RTE (Round-Trip Efficiency) [%]	42-53%	52-60%	up to 83%
RTE degradation	No degradation		
Technology Maturity / Technological Readiness Level (TRL):	9	7-8	5-6
System size Energy Capacity (kWh)	up to GWhs		
CAPEX per kW of Power Capacity [EUR/kW]	360 – 900		
CAPEX per kWh of Energy [EUR/kWh]	2 - 225		
OPEX per kWh of Energy [EUR/kW/year]	8 **		

* based on operation data of Huntorf and McIntosh Alabama CAES plants

** based on [Energy Storage Cost and Performance Database](#) Pacific Northwest Laboratory for 1000MW 24h duration system.

3.1 Introduction

Compressed Air Energy Storage (CAES) represents a pivotal advancement in the realm of large-scale energy storage technologies. Designed to balance power supply and demand effectively, CAES involves the compression and storage of air in underground caverns or above-ground

containers, which is then used to generate electricity during peak demand periods. This innovative method addresses the intermittency of renewable energy sources like wind and solar, ensuring a more stable and reliable energy supply. The technology's development has been marked by significant milestones, such as the establishment of the Huntorf plant in Germany and the McIntosh facility in the USA, which have demonstrated the practical and economic viability of CAES. Recent advancements, including adiabatic CAES, have further enhanced efficiency and environmental performance, solidifying CAES as a crucial component in the future of sustainable energy systems.

3.1.1 What is CAES?

Compressed Air Energy Storage (CAES) is a technology designed to store energy in the form of compressed air, which can be housed in underground caverns, aquifers, or above-ground containers. This method of energy storage is particularly suited for large-scale applications and offers a viable solution for balancing supply and demand in power systems. During periods of low energy demand, excess electricity is used to compress air and store it. When energy demand peaks, the stored compressed air is released to drive turbines that generate electricity.

CAES systems generally operate by using electric compressors to store energy in the form of high-pressure air. This air is then stored in geological formations such as salt caverns or man-made pressure vessels. When electricity is needed, the compressed air is heated and expanded in a turbine, generating power. This process allows CAES to serve as a flexible and efficient energy storage solution, particularly valuable in integrating renewable energy sources like wind and solar into the grid (Haisheng et al., 2013).⁴³

3.1.2 Basic Principles of CAES

The fundamental principle behind CAES involves the compression of air to store energy. This process typically occurs in two main phases: the compression phase and the expansion phase.

Compression Phase:

During periods of low electricity demand, surplus electricity powers compressors that pressurize air, which is then stored in underground caverns or large above-ground containers. This phase converts electrical energy into potential energy by increasing the air's pressure and temperature.

Storage:

The compressed air is kept in storage until there is a demand for electricity. The storage medium must be capable of maintaining high pressure without significant loss over time. Suitable geological formations such as salt caverns are often used due to their ability to hold large volumes of air at high pressure without leakage (Budt et al., 2016).⁴⁴

Expansion Phase:

When electricity demand peaks, the stored compressed air is released and expanded through turbines to generate electricity. To increase efficiency, the air is often heated before expansion, which can be done using the waste heat from the compression process or external heat sources. This expansion process converts the stored potential energy back into electrical energy, which can then be fed into the power grid.

The efficiency of CAES systems can vary, but they generally offer high energy storage capacities and long discharge durations, making them particularly suitable for grid-scale energy storage applications. Innovations such as adiabatic CAES (A-CAES), which captures and reuses the heat generated during compression, are improving the overall efficiency and reducing the environmental impact of these systems (Garvey & Pimm, 2016).⁴⁵

Physics

1. Work Done During Compression

The work done to compress air from an initial state (P_1, V_1) to a final state (P_2, V_2) can be calculated using the adiabatic process formula (assuming no heat exchange with the environment):

$$W_{compression} = \frac{P_1 V_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

where:

- P_1, V_1 are the initial pressure and volume,
- P_2, V_2 are the final pressure and volume,
- γ is the heat capacity ratio C_p / C_v ,
- The term $\gamma/(\gamma-1)$ is a constant that depends on the type of gas. For diatomic gases like air, γ is typically around 1.4.

2. Energy Stored in Compressed Air

The energy stored in the compressed air, which is essentially the work done on the air during compression, can be approximated as:

$$E_{stored} = \frac{P_1 V_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

This formula assumes an ideal adiabatic process for simplicity.

3. Work Done During Expansion

When the compressed air is expanded through a turbine to generate electricity, the work done by the air can be calculated using the adiabatic expansion formula:

$$W_{\text{expansion}} = \frac{P_2 V_2}{\gamma - 1} \left[1 - \left(\frac{P_1}{P_2} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

where:

- P_2, V_2 are the pressure and volume of the compressed air before expansion,
- P_1, V_1 are the pressure and volume after expansion.

4. Round-Trip Efficiency

The round-trip efficiency (η) of a compressed air energy storage (CAES) system is the ratio of the energy output during expansion to the energy input during compression:

$$\eta = \frac{W_{\text{expansion}}}{W_{\text{compression}}}$$

In a practical CAES system, this efficiency is affected by losses during both compression and expansion, as well as any additional energy required to heat the air before expansion.

5. Overall System Efficiency

Including practical considerations, the overall system efficiency can be expressed as:

$$\eta_{\text{overall}} = \eta_{\text{compression}} \times \eta_{\text{storage}} \times \eta_{\text{expansion}}$$

where:

- $\eta_{\text{compression}}$ is the efficiency of the compressor,
- η_{storage} accounts for any losses during storage (e.g., thermal losses),
- $\eta_{\text{expansion}}$ is the efficiency of the turbine or expander.

To compare the energy density of compressed air energy storage (CAES) to a 1 kg lithium battery with an energy density of 300 Wh/kg, we need to determine how much air needs to be compressed to store the same amount of energy. We'll assume average efficiencies for compression, storage, and expansion in a CAES system.

Assumptions

- Energy density of lithium-ion battery: 300 Wh/kg = 1080 kJ/kg
- Efficiencies:
 - Compression efficiency ($\eta_{\text{compression}}$): 85%
 - Storage efficiency (η_{storage}): 90%
 - Expansion efficiency ($\eta_{\text{expansion}}$): 85%
- Total round-trip efficiency: (η_{overall}) = $\eta_{\text{compression}} \times \eta_{\text{storage}} \times \eta_{\text{expansion}}$

Step-by-Step Calculation

1. Total Round-Trip Efficiency:

$$\eta_{\text{overall}} = 0.85 \times 0.90 \times 0.85 = 0.65025 \approx 65$$

2. Energy Required to Store:

Given the energy density of 300 Wh/kg (1080 kJ/kg) for lithium batteries, we need to account for the efficiency losses in CAES. The actual energy that needs to be stored (input energy) is:

$$E_{\text{input}} = \frac{E_{\text{stored}}}{\eta_{\text{overall}}} = \frac{1080 \text{ kJ}}{0.65} \approx 1661.54 \text{ kJ}$$

3. Energy Density of Compressed Air:

Using the formula for energy stored in compressed air:

$$E_{\text{stored}} = \frac{P_1 V_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]$$

Assuming initial conditions: $P_1 = 1 \text{ atm} = 101325 \text{ Pa}$ and final pressure $P_2 = 10 \text{ atm} = 1013250 \text{ Pa}$, and $\gamma = 1.4$ (for air).

Rearranging to find the volume of air needed, V_1 :

$$1661.54 \text{ kJ} = \frac{1.4 - 1}{101325 \times V_1} \left[\left(\frac{101325}{1013250} \right)^{\frac{1.4}{1.4 - 1}} - 1 \right]$$

$$1661.54 \times 1000 = 101325 \times V_1^{0.4} [10^{0.2857} - 1]$$

$$1661.54 \times 1000 = \frac{0.4}{101325 \times V_1} [10^{0.2857} - 1]$$

$$1661540 = 101325 \times V_1^{0.4} \times (1.885 - 1)$$

$$1661540 = 253312.5 \times V_1 \times 0.885$$

$$1661540 = 224131.3125 \times V_1$$

$$V_1 \approx \frac{1661540}{224131.3125} \approx 7.41 \text{ m}^3$$

4. Mass of Air Needed:

Assuming the density of air at standard conditions is $\rho = 1.225 \text{ kg/m}^3$

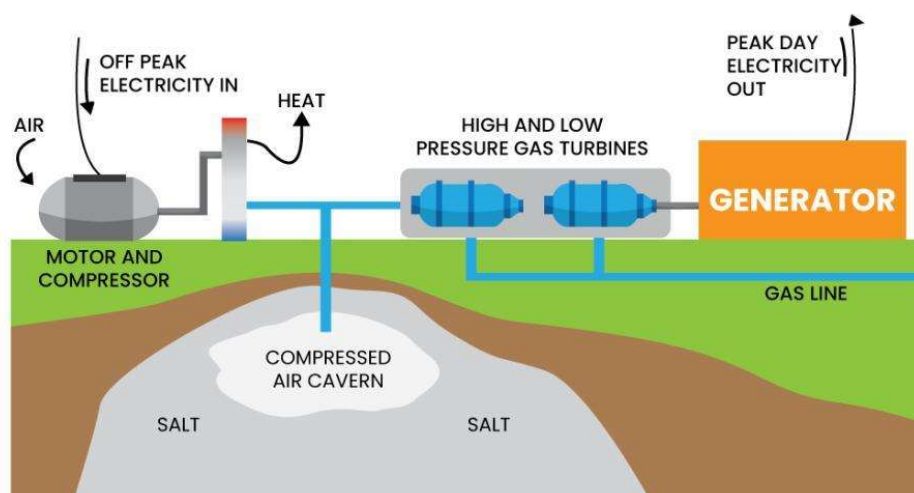
$$m_{\text{air}} = V_1 \times \rho \approx 7.41 \text{ m}^3 \times 1.225 \text{ kg/m}^3 \approx 9.07 \text{ kg} \quad (\text{about } 7.5^3 \text{ of air})$$

Conclusion

To achieve the same energy density of 300 Wh/kg (1080 kJ/kg) as a 1 kg lithium battery, we would need to compress approximately 9.07 kg of air at an efficiency of 65% round-trip. This highlights

the difference in energy density between CAES and lithium-ion batteries, with CAES requiring significantly more mass to store the same amount of energy, primarily due to the inherent inefficiencies in the compression and expansion processes.

Schematics of Isothermal CAES



Isothermal Compressed Air Energy Storage

Figure 3.1 Source: <https://sinovoltaics.com/learning-center/storage/isothermal-caes/>

Historical Development of CAES

Compressed Air Energy Storage (CAES) technology has its roots in the early 20th century when the concept of storing energy in the form of compressed air began to take shape. The initial development of CAES technology was driven by the need to balance electricity supply and demand, especially in regions with significant fluctuations in energy generation. The first practical implementations of CAES were experimental, focusing on small-scale systems that demonstrated the basic principles of the technology.

The major breakthrough for CAES came in the late 20th century with the construction of the first commercial CAES plants. In 1978, the Huntorf plant in Germany became the world's first operational CAES facility. Located in Lower Saxony, Germany, it had an initial capacity of 290 MW. The Huntorf plant demonstrated the viability of using salt caverns for large-scale energy storage. It operated by compressing air during periods of low electricity demand and storing it in caverns. During peak demand, the stored air was released, heated, and expanded in turbines to generate electricity. This plant provided critical insights into the operational and economic feasibility of CAES technology (Budt et al., 2016).⁴⁴

CAES power plant in Huntorf, Germany



Figure 3.2 Source: Compressed Air Energy Storage Installation for Renewable Energy Generation - Researchgate⁴⁶

Following the Huntorf plant, the McIntosh CAES facility in Alabama, USA, became the second major operational CAES plant. Commissioned in 1991, it had a capacity of 110 MW and introduced several technological advancements. The McIntosh plant integrated natural gas to reheat the compressed air before it was expanded, significantly improving efficiency. This hybrid approach combined the benefits of CAES with those of natural gas turbines, setting a precedent for future hybrid energy storage systems (Wang et al., 2017).⁴⁷

3.1.3 Key Milestones in CAES Technology

Huntorf Plant, Germany (1978): The Huntorf plant, located in Lower Saxony, Germany, marked the first large-scale application of CAES. It utilized salt caverns for air storage and operated at a capacity of 290 MW. The plant demonstrated the feasibility of using underground formations for energy storage and established a foundation for future developments in CAES technology (Budt et al., 2016).⁴⁴

McIntosh Plant, USA (1991): Following the success of the Huntorf plant, the McIntosh CAES facility was commissioned in Alabama, USA. This plant, with a capacity of 110 MW, introduced several advancements, including the integration of natural gas to reheat the compressed air before expansion. This hybrid approach improved the overall efficiency of the system and showcased the potential for combining CAES with other energy sources (Wang et al., 2017).⁴⁷

Adiabatic CAES Developments (2000s): The early 2000s saw significant research and development efforts focused on improving the efficiency of CAES systems. Adiabatic CAES (A-CAES) technology emerged as a promising solution by capturing and storing the heat generated during air compression, which could then be reused during the expansion phase. This innovation

aimed to reduce the reliance on external fuel sources and enhance the overall energy efficiency of CAES systems (Tola et al., 2017).⁴⁸

3.1.4 Present-day Implementations

Compressed Air Energy Storage (CAES) is an established and evolving technology that has been implemented in various projects worldwide. The Huntorf plant in Germany remains operational and continues to serve as a benchmark for CAES technology. Utilizing underground salt caverns for air storage, the Huntorf plant operates with a capacity of 290 MW and plays a critical role in balancing supply and demand on the grid (Budt et al., 2016).⁴⁴ Similarly, the McIntosh plant in Alabama, USA, also remains a key CAES facility. With a capacity of 110 MW, it integrates natural gas to reheat the compressed air, enhancing overall efficiency. This hybrid approach serves as a model for future CAES installations (Wang et al., 2017).⁴⁷

The Iowa Stored Energy Park was a significant project aiming to provide 270 MW of storage capacity, although it was ultimately canceled due to geological limitations. The lessons learned from this project have informed subsequent CAES developments, particularly in site selection and geological assessments (Holst et al., 2012).⁴⁹ Recent studies have identified potential sites in the UK and India for new CAES facilities. The UK, with its abundant salt beds, shows high potential for large-scale CAES projects, while India could benefit from aquifer storage-based CAES systems to support its renewable energy goals (King et al., 2021).⁵⁰

Recent Advancements

Technological advancements in CAES have focused on improving efficiency, reducing costs, and expanding the applicability of the technology. Adiabatic CAES (A-CAES) systems capture and store the heat generated during air compression, which is then used during the expansion phase to reheat the air, significantly improving overall efficiency. This reduces reliance on external fuel sources and enhances the environmental benefits of CAES (Tola et al., 2017).⁴⁸

Integrating Thermal Energy Storage (TES) with CAES systems has been a major focus, allowing for the storage of heat generated during compression. This heat can then be utilized during the expansion process, improving the round-trip efficiency of CAES systems. Innovations in TES materials and designs are crucial for this integration (Zhou et al., 2019).⁵¹ Isothermal compression, which minimizes temperature changes during the compression and expansion of air, is another significant advancement. This approach involves multi-stage compression with intercooling, providing substantial efficiency gains over traditional methods (Borri et al., 2022).⁵²

Developments in control systems for CAES facilities have improved their operational flexibility and efficiency. Advanced algorithms and real-time monitoring allow for better management of charging and discharging cycles, optimizing performance and reducing energy losses (Bai et al., 2020).⁵³

Current Research Trends

Ongoing research projects and studies are continuously focusing on improving CAES technology. One significant research trend is optimizing the thermodynamic cycles used in CAES systems. Recent studies have explored the combination of high-expansion ratio turbines with advanced gas turbine technology to increase the thermal efficiency of CAES systems. These innovations can lead to efficiency improvements of at least 5% over existing systems (Fu et al., 2015).⁵⁴

Research is also being directed towards small-scale CAES systems, which can offer more flexible power system applications. These systems are particularly suitable for standalone renewable energy power plants, such as photovoltaic power plants designed to meet the energy demand of specific facilities, like radio base stations for mobile telecommunications (Jannelli et al., 2014).⁵⁵

The integration of CAES with other technologies, such as biogas production, is being explored. This approach, known as BIO-CAES, involves using the heat generated during the air compression stage to support anaerobic digestion processes for biogas production. This integration can enhance the overall efficiency and sustainability of the energy storage system (Llamas et al., 2020).⁵⁶

Advanced control systems and optimization models are being developed to improve the market participation and economic viability of CAES systems. These models help in maximizing the utilization of CAES air storage and optimizing market participation decisions, thereby enhancing profitability and paving the way for broader investment and market integration of this technology (Khatami et al., 2019).⁵⁷

LDES technology BaroMar has enlisted consultancy Jacobs to develop the preliminary design for an underwater, large-scale pilot project with 4MWh of energy storage capacity using its technology off the coast of Cyprus.

The 4MWh project would store compressed air in large rigid tanks ballasted on the seabed, making it a form of compressed air energy storage (CAES), one of the more commercial mature LDES technologies.

BaroMar claims that the underwater nature of its solution gets around the main regulatory and geographical constraints of conventional CAES on land.⁵⁸

Crondall Energy and Durham University have worked in partnership to accelerate the development of Compressed Air Energy Storage (CAES) in the UK continental shelf.

This comes after the award of funding under a £6.7 million UK government Longer Duration Energy Storage competition to investigate feasibility of an offshore CAES system.

Upon completion of the feasibility study, it is hoped that the UK Government will progress the project to develop a full prototype of the technology.⁵⁹

The project would utilise existing offshore pipeline systems as the storage medium.

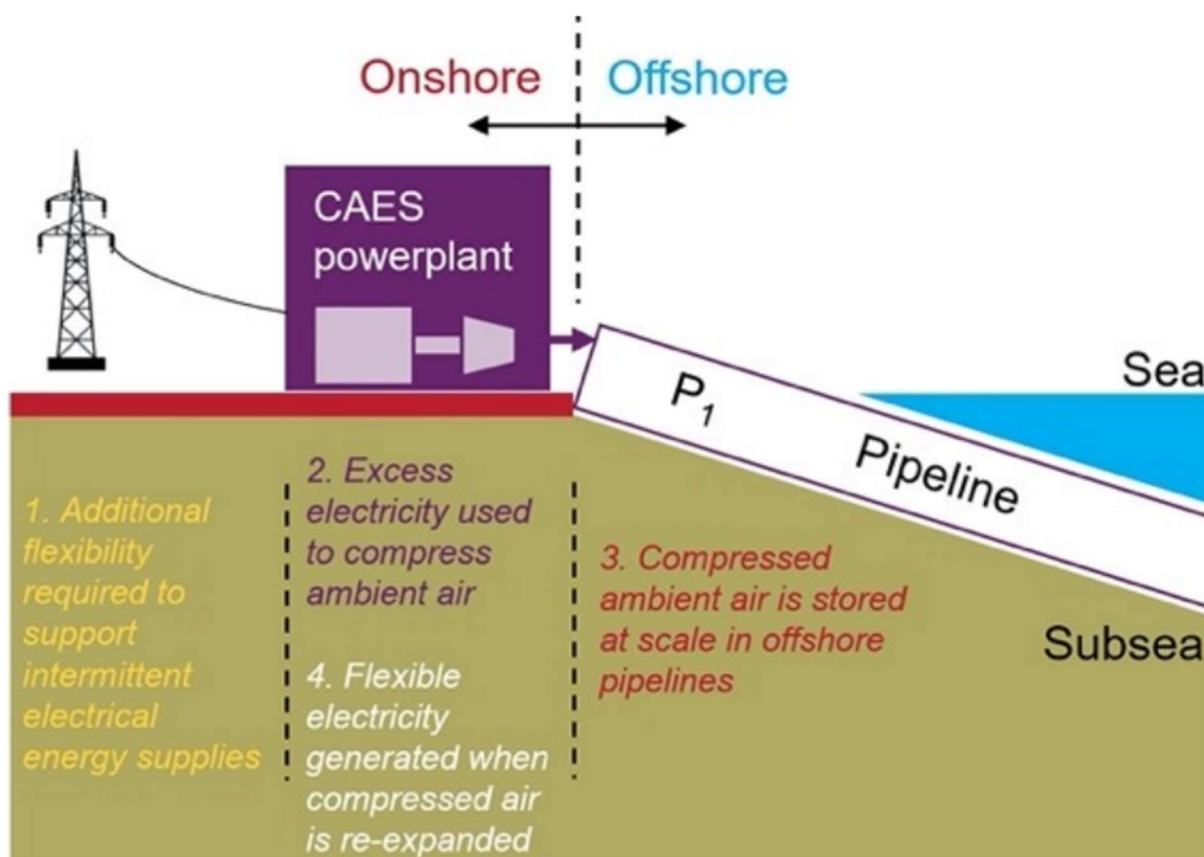


Figure 3.3 Crondal Energy Subsea and Durham University CAES prototype scheme⁶⁰

The system operates under high pressure (100-500 bar) and long lengths (hundreds of kilometres) which mean a high storage volume of compressed air. The resulting high potential storage capacity is 60.17GWh in the proposed 52 UK sights:

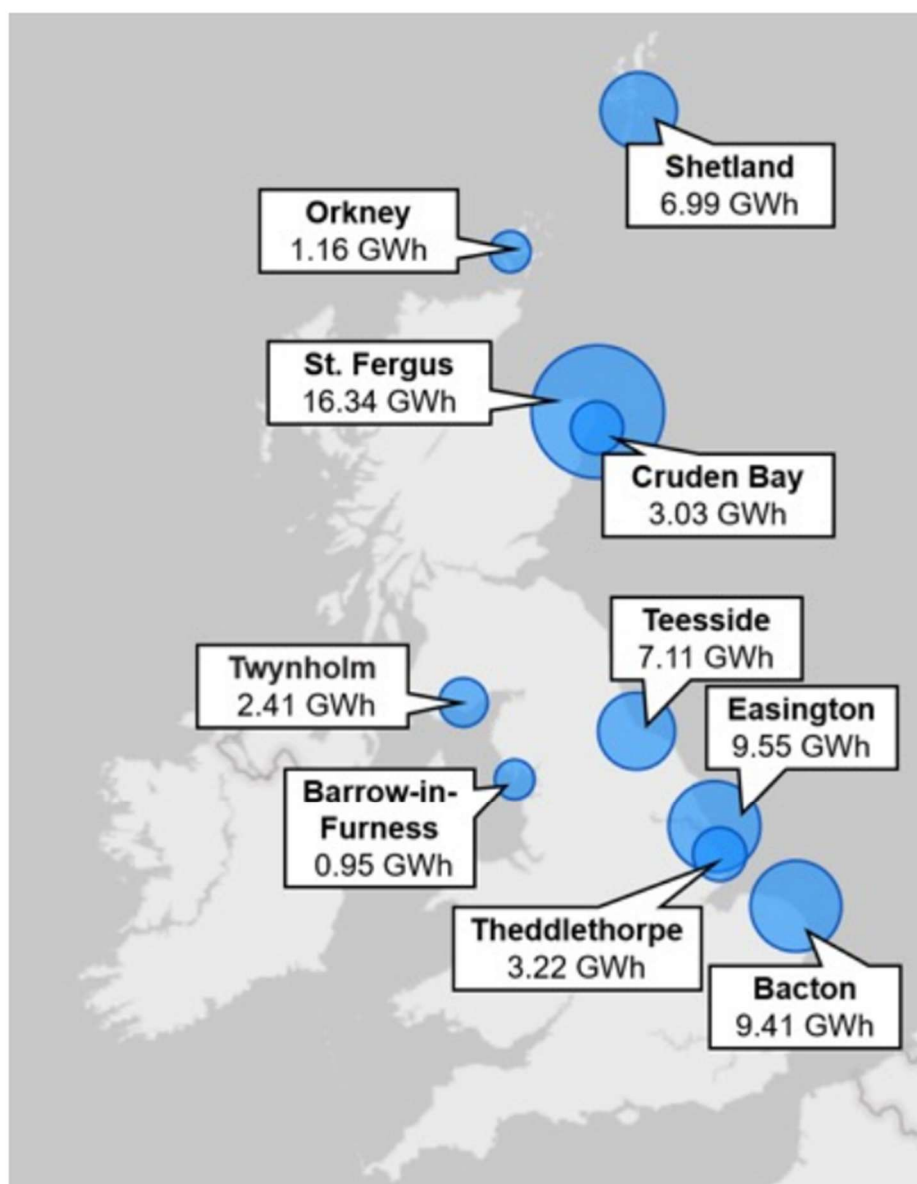


Figure 3.4 Crondal Energy Subsea and Durham University [proposed CAES system locations](#)

3.1.5 Main branches of CAES

Compressed Air Energy Storage (CAES) systems can be categorized into distinct groups based on several criteria, offering various technological approaches and catering to different applications.

One common categorization is based on the storage medium's location:

- **Subsurface CAES - underground:** These systems utilize underground geological formations, such as depleted natural gas reservoirs, salt caverns, or specially excavated rock caverns, to store compressed air. The natural containment provided by the

underground environment offers advantages in terms of scalability and lower environmental impact. However, suitable geological formations are not universally available, limiting potential project sites.

- **Underwater CAES / OCAES (ocean CAES):** The underwater setting provides natural insulation and the high ambient pressure of the deep ocean helps maintain the compressed state of the air without requiring extensive reinforcement of the storage vessels. When energy is needed, the compressed air is brought to the surface, heated, and expanded through turbines to generate electricity. This approach reduces the need for extensive above-ground infrastructure and mitigates visual and environmental impacts on land. A study financed by the Department for Business Energy & Industrial Strategy in the UK examined different concepts of subsea CAES⁶⁰.



Figure 3.5 Concept of a PowerBundle/FLASC B.V. demonstrator subsea CAES

These system utilise existing offshore pipelines promoting cost efficiency and circular economy.

- **Surface CAES:** To date, this concept is theoretical. These systems store compressed air in above-ground vessels, such as tanks or pipes. While this approach offers greater flexibility in terms of siting, the vessels require substantial construction and can occupy significant land areas. Surface CAES is generally more suitable for smaller-scale applications or where underground storage options are not feasible. There are a few conceptual or developmental-stage projects for surface-based CAES (Compressed Air Energy Storage), though they are not as common as subsurface CAES due to land use and storage volume constraints. Some unsuccessful projects:

LightSail Energy (US, now defunct): This company developed a prototype of a surface-based CAES system that used carbon fiber tanks to store compressed air. Their design aimed to be modular and scalable, but the company eventually ceased operations due to financial difficulties.⁶¹

General Compression (US, now defunct): This company proposed a large-scale surface-based CAES project in Texas, using massive tanks to store compressed air. The project was envisioned to integrate with wind energy, but it faced challenges in securing financing and ultimately did not proceed.

Another way to categorize CAES is by their thermodynamic process:

- **Diabatic CAES (D-CAES):** In these systems, the heat generated during compression is released to the environment, usually through cooling systems. While simpler in design, diabatic CAES is less efficient as it requires additional energy input (often from natural gas) to reheat the air before expansion.

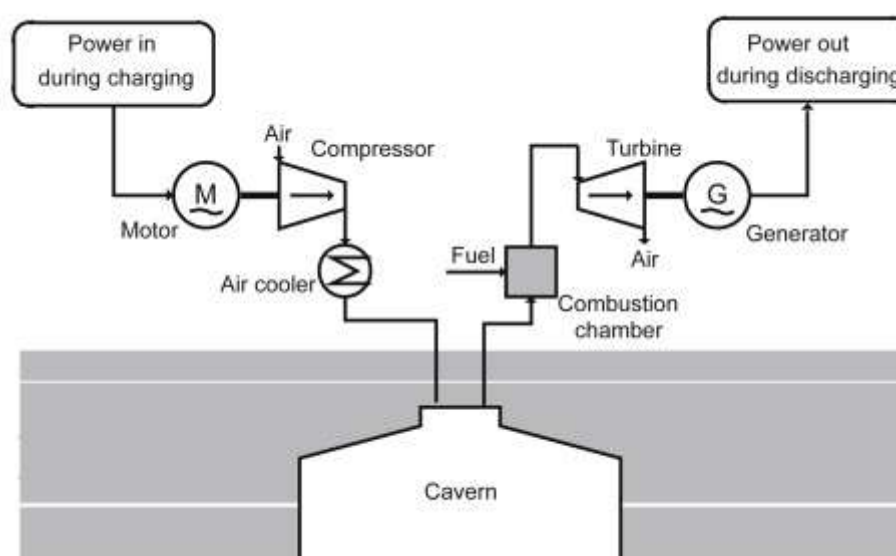


Figure 3.6 Source: Compressed Air Energy Storage System - Sciencedirect⁶²

- **Adiabatic CAES (A-CAES):** These systems store the heat generated during air compression, typically using a thermal energy storage (TES) medium like rocks or molten salts. This stored heat is then used to reheat the air before expansion, significantly improving the system's round-trip efficiency.

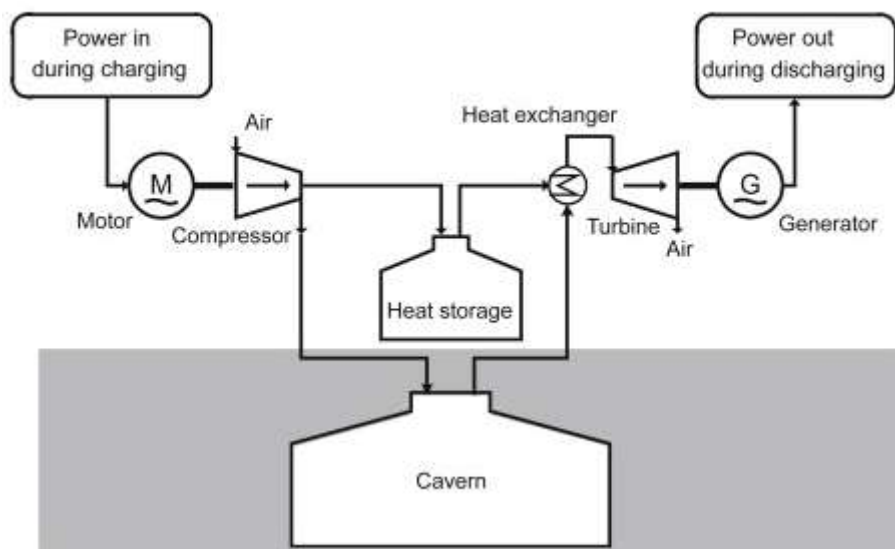


Figure 3.7 Source: Compressed Air Energy Storage System - Sciencedirect⁶²

- **Isothermal CAES (I-CAES):** This approach involves compressing air at a constant temperature, theoretically minimizing energy losses. During discharging, the compressed air drives the expander, and the extra heat is directly or indirectly transferred to the air from the liquid with a high heat capacity. The ideal ICAES system efficiency can be as high as 90%. However, achieving true isothermal compression is technically challenging and requires complex heat exchange mechanisms.

The choice of CAES technology depends on various factors, including project scale, geological constraints, cost considerations, and desired efficiency levels. By understanding the different types of CAES systems, stakeholders can make informed decisions about the most suitable approach for their specific needs and contribute to the ongoing energy transition towards renewable sources.

3.2 Main CAES Applications

3.2.1 Role in Stabilizing Grid Supply and Demand

Compressed Air Energy Storage (CAES) plays a crucial role in stabilizing the electrical grid by balancing supply and demand. The primary function of CAES in grid stabilization is to provide backup power during peak demand periods. During off-peak times, when electricity demand is low, excess electricity is used to compress air and store it in underground caverns or above-ground containers. This stored energy can then be released during peak demand periods, generating electricity and ensuring a stable supply to meet the fluctuating demands of the grid.

For example, the Huntorf CAES plant in Germany and the McIntosh CAES plant in the USA have demonstrated the ability of CAES to stabilize the grid by efficiently storing and dispatching energy as needed. These facilities help to flatten the demand curve, reducing the need for peaking power plants that are typically less efficient and more costly to operate (Budt et al., 2016).⁴⁴

3.2.2 Integration with Renewable Energy Sources

CAES systems can be coupled with distributed renewable energy installations to enhance their efficiency and economic viability. For instance, Distributed CAES (D-CAES) systems, which place compressors near heat loads to utilize waste heat, have shown to improve overall system efficiency and reduce costs.

A techno-economic study of CAES systems integrated with wind power found that CAES can significantly improve the efficiency and economic performance of wind energy systems. The study modeled both adiabatic (A-CAES) and conventional (C-CAES) configurations, demonstrating that A-CAES systems, despite higher initial costs, offer better efficiency and lower environmental impact compared to C-CAES systems (Huang et al., 2017).⁶³

3.2.3 Use in Industries Requiring Large Energy Storage

Compressed Air Energy Storage (CAES) systems are highly suitable for industrial applications that demand large-scale energy storage to maintain operational stability. Industries such as manufacturing plants, chemical processing facilities, and mining operations often experience significant fluctuations in energy demand. CAES can help these industries manage their energy needs more efficiently by storing excess energy during periods of low demand and releasing it during peak consumption times.

Manufacturing plants, for example, can benefit from CAES by stabilizing their energy supply, thereby avoiding costly interruptions and ensuring continuous production. The ability of CAES to provide a reliable energy supply is particularly valuable in processes that cannot afford downtime, such as continuous production lines in the automotive and electronics industries (Haisheng et al., 2013).⁴³

In chemical processing facilities, energy demand can be highly variable, with peak loads occurring during specific operations like heating or cooling cycles. CAES systems can store energy during off-peak times and supply it when the demand spikes, thereby smoothing out energy consumption and reducing the reliance on more expensive peak-time energy sources. This not only lowers operational costs but also enhances the facility's energy efficiency and environmental footprint (Guanwei et al., 2018).⁶⁴

3.2.4 Backup Power Solutions

Compressed Air Energy Storage (CAES) systems can provide reliable backup power during emergencies, ensuring the availability of energy during outages or disasters. CAES operates by storing energy in the form of compressed air during periods of low demand, which can then be released to generate electricity when needed. This capability is particularly useful during unexpected power failures or natural disasters when the grid might be compromised.

For instance, the integration of CAES units as emergency generators has been explored in various regions. A study in Korea highlighted the use of CAES for providing supplementary power generation and district heating supply systems during emergencies. These units, which store compressed air in underground caverns or modular-type pressurized vessels, can be rapidly deployed to stabilize the grid and provide essential services during power failures (Lee et al., 2007).⁶⁵

The use of CAES in isolated areas, such as remote communities or critical infrastructure sites, further exemplifies its role in emergency energy storage. For example, an integrated system combining CAES with diesel generators was developed to supply power to isolated end-users in the UK. This system demonstrated significant fuel savings and enhanced reliability compared to traditional diesel-only systems, proving the effectiveness of CAES in emergency backup applications (Li et al., 2016).⁶⁶

3.2.5 Role in Disaster Preparedness and Recovery

CAES systems are crucial in disaster preparedness and recovery plans due to their ability to provide reliable energy storage for critical infrastructure. During disasters, maintaining power supply to essential services such as hospitals, emergency response centers, and communication networks is vital. CAES offers a robust solution by ensuring a continuous power supply even when the main grid is down.

The importance of CAES in disaster preparedness is highlighted by its ability to store large amounts of energy that can be dispatched quickly. This makes it an ideal solution for areas prone to natural disasters like hurricanes, earthquakes, or floods. By having CAES systems in place, regions can enhance their resilience and ensure that critical infrastructure remains operational during and after a disaster.

A feasibility study conducted in Huai'an City, China, demonstrated the potential of CAES to ensure the safety, stability, and economic operation of the power network in one of the most developed regions. The study evaluated the geotechnical feasibility of constructing CAES power plants in bedded salt formations and concluded that CAES could be a reliable backup power source during emergencies, supporting the region's disaster preparedness efforts (Zhang et al., 2015).⁶⁷

3.3 Technological Barriers and Scalability

3.3.1 Efficiency and Energy Loss Issues

Compressed Air Energy Storage (CAES) systems face several inherent inefficiencies, primarily due to energy losses during the compression and expansion processes. One of the main challenges is the heat loss that occurs when air is compressed. During compression, air temperature increases significantly, and this heat is often dissipated into the environment if not properly managed. This results in a loss of potential energy that could be otherwise utilized (Budt et al., 2016).⁴⁴

To mitigate these losses, adiabatic CAES (A-CAES) systems have been developed. In A-CAES, the heat generated during compression is captured and stored using thermal energy storage (TES) systems, and later reused during the expansion process to reheat the air. This approach can significantly improve the round-trip efficiency of CAES systems. For example, integrating TES can help achieve round-trip efficiencies of up to 70-75% in A-CAES plants (Tola et al., 2017).⁴⁸

However, despite these advancements, the overall efficiency of CAES systems still lags behind other energy storage technologies such as pumped hydro storage or lithium-ion batteries. The primary reason for this is the large exergy destruction in the compressors and turbines, as well as inefficiencies in the thermal energy storage systems. A detailed study using dynamic simulation models has shown that the biggest exergy destruction occurs in the compressors (276.191 MWh/cycle) and turbines (190.394 MWh/cycle), indicating significant areas for improvement (Szablowski et al., 2017).⁶⁸

3.3.2 Technical limitations of current CAES systems

The current CAES systems are limited by several technical barriers, including the performance of compressors and turbines. Compressors and turbines used in CAES systems must operate under high-pressure conditions and handle large volumes of air efficiently. However, existing technologies often fall short in terms of efficiency and durability under continuous high-stress conditions (Wang et al., 2017).⁴⁷

One innovative approach to overcoming these limitations is the development of low-temperature adiabatic CAES (LTA-CAES). LTA-CAES systems use multistage radial compressors and expanders with intermediate cooling and reheating, which allow for better management of the air temperature and pressure throughout the storage cycle. This design can achieve round-trip efficiencies in the range of 52-60%, which is slightly lower than high-temperature A-CAES but offers benefits in terms of easier handling and faster start-up characteristics (Wolf & Budt, 2014).⁶⁹

The intermittent nature of renewable energy generation requires CAES systems to be highly flexible and responsive. Distributed CAES (D-CAES) systems, where compressors are placed near heat loads to utilize waste heat, show promise in improving system efficiency and economic feasibility. However, these systems also involve higher capital costs due to the need for extensive pipeline infrastructure to connect distributed compressors with the central storage site (Safaei et al., 2013).⁷⁰

3.3.3 Scaling up from Pilot Projects to Large-scale Implementations

Scaling up Compressed Air Energy Storage (CAES) technology from small pilot projects to full-scale commercial operations presents several challenges. These include technical, economic, and logistical factors that need to be addressed to ensure successful implementation.

Technical Challenges

One of the main technical challenges in scaling up CAES technology is maintaining efficiency at larger scales. Pilot projects often operate at lower pressures and volumes, which simplifies management of heat and mechanical stresses. However, at commercial scales, managing the heat generated during compression and the cold generated during expansion becomes significantly more complex. Large-scale systems require sophisticated thermal management solutions, such as the integration of thermal energy storage (TES) to capture and reuse heat (Sciacovelli et al., 2017).⁷¹

Another technical challenge is the design and operation of compressors and turbines that can handle the high pressures and volumes required for large-scale CAES. Advanced adiabatic CAES (A-CAES) systems, which use high-efficiency compressors and expanders along with TES, have shown promise in overcoming these barriers. These systems can achieve efficiencies of up to 70-75% by optimizing the thermodynamic cycles and reducing energy losses (Tola et al., 2017).⁴⁸

Economic and Logistical Challenges

Economic challenges include the high initial capital investment required for developing large-scale CAES facilities. The cost of constructing underground storage caverns or above-ground pressure vessels, along with the necessary compressors, turbines, and TES systems, can be substantial. Additionally, the integration of CAES with the existing power grid requires significant investment in infrastructure, including pipelines and grid connections (Wang et al., 2017).⁴⁷

Logistical challenges involve the selection of suitable sites for CAES facilities. Underground storage requires specific geological formations, such as salt caverns, aquifers, or depleted gas fields, which are not uniformly distributed. Identifying and securing these sites can be time-consuming and costly. Furthermore, the construction of necessary infrastructure, such as pipelines to transport compressed air, adds to the logistical complexity and cost of scaling up CAES systems (Aghahosseini & Breyer, 2018).⁷²

3.3.4 Economic and Logistical Challenges in Scaling

Infrastructure Investment

The infrastructure investment for large-scale CAES deployment includes not only the construction of storage caverns or pressure vessels but also the development of extensive pipeline networks for transporting compressed air. This is particularly critical for distributed CAES (D-CAES) systems, which place compressors near heat loads to utilize waste heat and require extensive pipelines to connect to central storage sites. The high capital costs associated with these infrastructure requirements can be a significant barrier to large-scale deployment (Safaei et al., 2013).⁷⁰

Grid Integration

Integrating CAES with the power grid involves overcoming technical and regulatory challenges. CAES systems must be highly flexible and responsive to fluctuations in supply and demand. Advanced control systems and optimization algorithms are essential to manage the charging and discharging cycles effectively, ensuring grid stability and reliability (Bai et al., 2020).⁵³

3.4 Resource Restrictions

3.4.1 Geographical Requirements

Compressed Air Energy Storage (CAES) systems rely on specific geological formations to store compressed air effectively. The most suitable formations for underground CAES include salt caverns, aquifers, and depleted gas fields. These formations are preferred due to their ability to withstand the high pressures required for energy storage and their natural containment properties.

Salt caverns are particularly ideal for CAES because they offer excellent sealing properties and structural integrity. The process of solution mining creates these caverns, which can then be used to store compressed air at high pressures. Salt formations are found in various parts of the world, including North America, Europe, and China (Li et al., 2018).⁷³

Aquifers, which are porous and permeable rock formations containing water, are another option for CAES. These formations can be found widely distributed across many regions, making them a versatile choice for energy storage. However, using aquifers requires careful management to avoid contamination and ensure efficient operation (Guo et al., 2021).⁷⁴

Depleted gas fields are also considered for CAES due to their proven containment capabilities. These fields, which have already been used for gas extraction, offer a ready-made infrastructure for storing compressed air. Their geological characteristics, such as porosity and permeability, are well understood, making them a reliable option for CAES (Cooper et al., 2011).⁷⁵

3.4.2 Raw Materials Needed for Construction and Maintenance

The construction and maintenance of CAES facilities require various raw materials to ensure structural integrity and operational efficiency. Key materials include:

Steel

Steel is essential for constructing pressure vessels, pipelines, and support structures. Its strength and durability are crucial for withstanding the high pressures involved in CAES operations. Steel is also used in the fabrication of compressors and turbines, which are critical components of the CAES system.

Concrete

Concrete is used to create the foundations and support structures of CAES facilities, especially for above-ground installations. It provides stability and durability, ensuring the long-term integrity of the storage system (Perazzelli & Anagnostou, 2016).⁷⁶

Compressors and Turbines

The compressors used in CAES systems require materials that can withstand high temperatures and pressures, such as specialized alloys and high-strength steel. Similarly, turbines used to convert compressed air back into electricity need materials that can endure the thermal and mechanical stresses of repeated cycles (Kantharaj et al., 2015).⁷⁷

Insulation Materials

Insulation is necessary to minimize thermal losses during the compression and storage processes. Materials such as polyurethane foam, fiberglass, and other advanced insulators are used to maintain the temperature and efficiency of the system (Kim et al., 2014).⁷⁸

Sealing and Lining Materials

To ensure the airtightness of underground storage caverns, materials like high-strength polymers, rubber gaskets, and specialized sealants are used. These materials prevent air leakage and maintain the integrity of the storage system (Zhang et al., 2015).⁶⁷

3.4.3 Global Distribution of Suitable Resources

Compressed Air Energy Storage (CAES) systems require specific geological formations for effective underground storage of compressed air. The global availability of suitable geological formations includes salt caverns, aquifers, and depleted gas fields. Salt caverns, in particular, are highly preferred due to their excellent sealing properties and structural integrity, making them ideal for long-term and large-scale energy storage.

In a comprehensive study assessing the geological resource potential for CAES globally, the world was divided into 145 regions and aggregated into 9 major regions. The study identified North America, Sub-Saharan Africa, and South America as regions with significant potential for

CAES. North America led with 0.26% of its total area deemed suitable, followed by Sub-Saharan Africa and South America with 0.20% and 0.19%, respectively. The analysis showed that salt formations are widely distributed in these regions, providing substantial opportunities for CAES development (Aghahosseini & Breyer, 2018).⁷²

Aquifers also present a viable option for CAES. For instance, aquifers in the North German Basin have been investigated for their potential to store compressed air. These formations offer widespread distribution and accessibility, which are crucial for developing large-scale energy storage systems. However, the geological characteristics such as porosity, permeability, and structural integrity need careful evaluation to ensure suitability (Guo et al., 2021).⁷⁴

Depleted gas fields are another promising geological formation for CAES. These fields, having already been used for gas extraction, possess known containment capabilities and infrastructure, making them suitable for repurposing as CAES sites. The use of these fields can leverage existing infrastructure and reduce the initial costs associated with site development (Cooper et al., 2011).⁷⁵

3.4.4 Legal and regulatory barriers

The development of CAES projects faces several legal and regulatory challenges related to resource extraction, land use, and environmental protection. These challenges vary by region and can significantly impact the feasibility and timeline of CAES projects.

Regulatory Issues Common to CAES Facilities

All CAES projects must navigate a complex regulatory landscape that includes obtaining permits for construction and operation, adhering to environmental regulations, and securing property rights. Federal, state, and local regulations often impose stringent requirements to ensure that CAES projects do not adversely affect the environment or public health. For example, environmental impact assessments (EIAs) are mandatory to evaluate potential impacts on air and water quality, wildlife habitats, and local communities (Hendrickson, 1981).⁷⁹

Geological Specific Regulations

Specific geological formations such as salt caverns, aquifers, and depleted gas fields each have unique regulatory requirements. For instance, using salt caverns for CAES necessitates compliance with regulations governing solution mining and subsurface storage. Similarly, aquifer storage must meet water quality standards to prevent contamination of potable water sources. Depleted gas fields require careful monitoring to ensure that residual hydrocarbons do not pose safety or environmental risks (Wang et al., 2017).⁴⁷

Liability and Property Rights

Liability issues related to CAES operations include potential subsurface trespass, environmental damage, and risks associated with high-pressure air storage. Ensuring adequate insurance

coverage and addressing liability through contractual agreements are essential steps in mitigating these risks. Additionally, securing property rights involves negotiating land leases or purchases, which can be a complex process, particularly in regions with fragmented land ownership (Hendrickson, 1981).⁷⁹

3.5 Energy Storage Costs in CAES

3.5.1 Cost Breakdown of Building a CAES Facility

Constructing a Compressed Air Energy Storage (CAES) facility involves significant initial investment costs, which can be divided into several key components. Firstly, site preparation is crucial and involves geological surveys and assessments to identify suitable underground storage sites, such as salt caverns, aquifers, or depleted gas fields. This phase also includes land acquisition and site development, which encompasses excavation and infrastructure setup for access and safety.

The next major cost component is the equipment. High-capacity, high-efficiency compressors and expanders are essential for the CAES system, and these components are typically custom-designed to handle the specific pressures and volumes required. Additionally, thermal energy storage (TES) systems are crucial for adiabatic CAES systems to capture and store heat generated during the compression phase, which is then reused during expansion to improve efficiency. The air storage infrastructure itself, whether it involves drilling and constructing underground caverns or installing large above-ground pressure vessels, also represents a significant expense.

Installation costs cover the pipeline infrastructure needed to transport compressed air from the compressors to the storage site and from the storage site to the turbines. This also includes the electrical systems required to integrate with the electrical grid, including transformers, switchgear, and control systems to manage energy input and output. Other costs encompass engineering design and project management, permitting and regulatory compliance, and construction labor and site logistics.

For example, a detailed cost analysis of a 270 MW CAES project in Iowa estimated the total cost at approximately €359 million, with significant expenses allocated to geological site development and infrastructure (Holst et al., 2012).⁴⁹

3.5.2 Long-term Maintenance and Operational Expenses

Operating and maintaining a Compressed Air Energy Storage (CAES) facility involves various ongoing costs, which are critical to its overall economic feasibility. These expenses include labor, energy input, and equipment replacement.

Energy Input

The energy input costs are significant in the operation of CAES facilities. During the compression phase, electricity is used to compress air and store it in underground caverns or above-ground pressure vessels. The cost of this electricity varies based on market conditions and the source of the power. Utilizing off-peak electricity can mitigate these costs. Moreover, distributed CAES (D-CAES) systems that use waste heat from industrial processes can improve overall energy efficiency and reduce operational costs (Safaei & Keith, 2014).⁸⁰

Equipment Replacement and Maintenance

Equipment replacement and maintenance are ongoing expenses that ensure the long-term reliability and efficiency of the CAES system. This includes regular maintenance of compressors, expanders, and thermal energy storage (TES) systems. High-pressure components are subject to wear and tear, necessitating periodic inspections and replacements. Advanced adiabatic CAES systems, which incorporate TES, require additional maintenance for thermal management components to ensure they function efficiently (Kantharaj et al., 2015).⁷⁷

3.5.3 Cost-efficiency Over the Lifespan of a CAES Facility

Evaluating the long-term cost-efficiency of CAES compared to other storage methods involves considering factors such as lifespan, efficiency, and reliability.

Lifespan

CAES systems generally have a long operational lifespan, often exceeding more than 40 years. (Bazdar, 2022).⁸¹ This is advantageous compared to battery energy storage systems (BESS), which typically have a lifespan of 8-12 years before significant degradation occurs. The long lifespan of CAES facilities contributes to their overall cost-efficiency, as the initial capital investment is amortized over a more extended period. (Ohrelius, 2023)⁸²

Efficiency

The efficiency of CAES systems varies depending on the specific technology used. Traditional CAES systems have round-trip efficiencies of around 40-50%, while advanced adiabatic CAES (A-CAES) systems can achieve efficiencies of up to 70-75% by capturing and reusing the heat generated during compression. While the efficiency of CAES systems is lower than that of lithium-ion batteries, which can reach efficiencies of 85-90%, CAES offers advantages in terms of scalability and suitability for long-duration storage (Lund & Salgi, 2009).⁸³

Reliability

CAES systems are known for their high reliability and low self-discharge rates. Unlike batteries, which can lose charge over time even when not in use, CAES systems can store compressed air for extended periods without significant energy loss. This makes them particularly suitable for applications requiring long-term energy storage and grid stabilization (Dooner & Wang, 2020).⁸⁴

3.5.4 Cost-benefit Analysis

Conducting a cost-benefit analysis of Compressed Air Energy Storage (CAES) projects involves evaluating both direct and indirect benefits to determine their economic viability. CAES systems are capital-intensive, but their ability to provide large-scale energy storage can offer significant economic advantages.

A comprehensive economic evaluation must consider various factors, including capital costs, operational expenses, potential revenue from energy arbitrage, and ancillary services. For instance, a study by Safaei and Keith (2013) demonstrated that Distributed CAES (D-CAES), which places compressors near heat loads to utilize waste heat, can significantly enhance the economic feasibility of CAES. The study found that the total cost of supplying heat and electric loads is less expensive with D-CAES given a 50km pipeline when fuel prices exceed \$7.6/GJ. The minimum effective fuel price required for economic superiority of the D-CAES system ranges from \$7.0/GJ at 25km to \$8.3/GJ at 100km (Safaei & Keith, 2013).⁷⁰

The U.S. Department of Energy (DOE) has conducted a Framework Study to identify promising research, development, and deployment (RD&D) pathways to reduce the LCOS of CAES technology in 2023.⁸⁵ The levelized cost of storage (LCOS) for CAES systems is influenced by several factors, including capital costs, operating expenses, and system efficiency. Recent techno-economic studies have estimated CAES-based stored electricity costs at \$0.15 to \$0.60/kWh. The study found that a 100-MW, 10-hour CAES system could achieve an LCOS of \$0.064/kWh by 2030, assuming no marginal increase in industry investment over currently planned levels. However, with increased investment in RD&D, the LCOS could be further reduced to between \$0.021 and \$0.030/kWh.

Several innovations have been identified that could contribute to significant cost reductions. These include advanced analytics for system modeling and design optimization, technologies for subsurface evaluation of porous rock for storage, alternative approaches to high-temperature thermal storage, and demonstration projects incorporating novel CAES strategies. While CAES systems are relatively easy to set up using commercially available components, they are most profitable in large capacities, which require significant capital investment. Therefore, reducing capital costs through mass production, standardization of components, and innovative manufacturing techniques is crucial for enhancing the economic viability of CAES technology.

Table 3.1 CAES cost and performance (2030 estimates)

Parameter	Value	Description
CAES System Calendar Life	60	Deployment life (years)
Cycle Life	20,805	Base total number of cycles
RTE	52%	Base RTE
Turbine, Compressor, Balance of Plant, and Engineering, Procurement, and Construction (EPC)	1,153	Base Capital Costs for Compressor, Balance of Plant, and EPC (\$/kW)
Cavern Storage	6.84	Base cavern storage cost (\$/kWh)
O&M Costs	16.12	Base fixed O&M (\$/kW-year)

[DOE/OE-0037 - Compressed-Air Energy Storage Technology Strategy Assessment](#)⁸⁵

3.5.5 Financial Incentives and Subsidies

The economic attractiveness of CAES projects can be significantly enhanced through financial incentives, subsidies, and regulatory support. Governments and regulatory bodies around the world have implemented various policies to promote the adoption of energy storage technologies, including CAES.

In the United States, for example, the Federal Energy Regulatory Commission (FERC) has introduced policies to support energy storage integration into the grid. These policies include allowing energy storage systems to participate in capacity, energy, and ancillary service markets, thereby providing multiple revenue streams for CAES projects. Additionally, state-level incentives such as California's Self-Generation Incentive Program (SGIP) provide financial support for energy storage projects, further improving the economic feasibility of CAES (Wang et al., 2017).⁴⁷

In Europe, the German Renewable Energy Sources Act (EEG) provides feed-in tariffs and other incentives for renewable energy and associated storage technologies, including CAES. This support is crucial for making CAES projects economically viable by ensuring stable revenue streams and reducing investment risks. Additionally, the European Union's Horizon 2020 program funds research and innovation projects related to energy storage, including CAES, promoting technological advancements and cost reductions (Madlener & Latz, 2013).⁸⁶

Case studies, such as the D-CAES project in Alberta, Canada, illustrate the impact of financial incentives and regulatory support. The project achieved superior economic and environmental performance with a negative abatement cost of -\$40/tCO₂e due to the efficient use of waste heat and favorable market conditions for energy storage (Safaei & Keith, 2014).⁸⁰

3.6 CAES Environmental Impact

3.6.1 Emissions and Environmental Footprint

A study assessing the life cycle environmental impacts of CAES used to balance offshore wind power found that while CAES increases certain environmental impacts such as acidification, particulate matter, and photochemical oxidant formation, it also decreases eutrophication,

toxicity, and mineral resource depletion impacts. The study highlighted that Adiabatic CAES (A-CAES) systems, which capture and reuse compression heat, generally have a moderate increase in environmental impacts across all assessed categories but remain lower in impact compared to the average European energy mix (Budt et al., 2016).⁴⁴

3.6.2 Benefits Over Other Energy Storage Methods

One of the primary environmental benefits of CAES over other energy storage methods is its ability to store large amounts of energy with minimal environmental impact. CAES systems can release stored energy over extended periods, which is particularly useful for providing backup power and ensuring grid stability. Moreover, CAES does not require toxic or flammable materials, unlike some battery technologies, making it safer and more environmentally friendly. CAES also has the advantage of using existing geological formations, such as salt caverns, which minimizes land use compared to above-ground storage solutions like batteries or pumped hydro storage (Kim et al., 2023).⁸⁷

Additionally, CAES systems can be designed to utilize waste heat from industrial processes or other sources, further enhancing their environmental performance by improving overall energy efficiency. This integration can lead to a reduction in the need for additional energy input and lower emissions associated with energy generation (Safaei & Keith, 2014).⁸⁰

3.6.3 Potential Future Advancements

The future of Compressed Air Energy Storage (CAES) technology promises several potential advancements that could significantly enhance its efficiency and feasibility. One area of innovation is the development of Advanced Adiabatic Compressed Air Energy Storage (A-CAES) systems. These systems capture and store the heat generated during the compression phase, which is then reused during the expansion phase to reheat the air. This process improves the overall efficiency of CAES systems by reducing the reliance on external fuel sources and enhancing the thermodynamic cycle (Tola et al., 2017).⁴⁸

Furthermore, the development of hybrid CAES systems, which combine CAES with other energy storage technologies like thermal energy storage (TES) and liquid air energy storage (LAES), shows great potential. These hybrid systems can enhance the flexibility and efficiency of energy storage solutions, providing more robust and adaptable systems capable of meeting diverse energy demands (Lund & Salgi, 2009).⁸³

3.7 Conclusions: Advantages, Disadvantages, and Recommendations for CAES

Compressed Air Energy Storage (CAES) stands out as a promising solution to the growing need for efficient and large-scale energy storage, especially in the integration of renewable energy

sources. Despite its substantial initial costs and dependence on specific geological formations, CAES offers notable advantages in terms of scalability, long discharge duration, and reduced environmental impact when advanced technologies are employed. The historical success of facilities like the Huntorf and McIntosh plants, along with ongoing innovations in adiabatic and hybrid CAES systems, highlight the potential of CAES to contribute significantly to grid stability and energy sustainability. Future research and policy support will be essential to overcoming current limitations and ensuring the widespread adoption of CAES, ultimately fostering a more resilient and sustainable energy infrastructure.

3.7.1 Pros and cons

3.7.1.1 Key Benefits of CAES Technology

Compressed Air Energy Storage (CAES) offers several significant advantages, making it a viable and attractive option for large-scale energy storage. One of the primary benefits is its large storage capacity. CAES systems can store vast amounts of energy by compressing air in underground caverns or above-ground tanks, making them suitable for applications requiring bulk energy storage. This large capacity is essential for balancing supply and demand on the electrical grid, particularly during periods of high demand or low renewable energy output (Rabi et al., 2023).⁸⁸

Another key advantage of CAES is its long discharge duration. CAES systems can release stored energy over extended periods, which is particularly useful for providing backup power and ensuring grid stability (Zhou et al., 2019).⁵¹

CCAES is also known for its suitability for grid-scale applications. The technology can be integrated into existing energy infrastructure, providing a reliable and scalable solution for energy storage. The ability of CAES to quickly respond to changes in energy demand makes it an effective tool for grid management and stability, helping to prevent blackouts and maintain a consistent energy supply (Wang et al., 2017).⁴⁷

3.7.1.2 Comparative Advantages Over Other Storage Methods

When compared to other energy storage technologies, CAES offers several unique strengths. One notable advantage is its high lifetime scalability. CAES systems typically have long operational lifespans, often exceeding 30-40 years, which is significantly longer than the lifespans of battery storage systems. This long lifespan reduces the need for frequent replacements and lowers the overall cost of ownership (Kim et al., 2012).⁸⁹

CAES also benefits from low self-discharge rates. Unlike batteries, which can lose charge over time even when not in use, CAES systems can store compressed air for extended periods without significant energy loss. This makes CAES a reliable option for long-term energy storage, ensuring that stored energy is available when needed (Rabi et al., 2023).⁸⁸

Furthermore, CAES systems have high durability and can handle frequent charge and discharge cycles without significant degradation. This robustness makes them suitable for applications requiring frequent and rapid cycling, such as grid stabilization and frequency regulation. The ability to handle high cycling rates without loss of performance is a critical advantage over other storage technologies that may degrade more quickly under similar conditions (Lemieux, 2016).⁹⁰

3.7.1.3 Main Drawbacks and Limitations

Compressed Air Energy Storage (CAES) technology, while advantageous in many respects, has several significant drawbacks and limitations that affect its feasibility and widespread adoption.

Geographical Constraints

One of the primary limitations of CAES is its dependency on suitable geological formations for storing compressed air. Traditional CAES systems often require underground caverns, such as salt domes, aquifers, or depleted gas fields, to store the compressed air. These geological formations are not uniformly distributed, which limits the locations where CAES plants can be economically and technically viable. In Europe, for instance, the limited availability of suitable salt caverns poses a significant challenge to the implementation of CAES on a large scale (Lutyński, 2017).⁹¹

Initial Costs

The initial capital investment required for CAES is substantial. The construction of underground storage caverns or above-ground pressure vessels, combined with the cost of high-efficiency compressors and expanders, leads to high upfront costs. While the operational costs of CAES can be lower over time, the significant initial expenditure can be a barrier to entry, especially for smaller energy markets or developing regions (Rabi et al., 2023).⁸⁸

Efficiency Issues

Another major drawback is the relatively low round-trip efficiency (RTE) of CAES systems. Traditional CAES systems have efficiencies ranging from 40% to 50%, which is lower than other energy storage technologies like lithium-ion batteries, which can achieve efficiencies of up to 72%. Although advanced adiabatic CAES (A-CAES) systems aim to improve efficiency by capturing and reusing heat generated during compression, these systems are still in developmental stages and not widely implemented (Rabi et al., 2023).⁸⁸

3.7.1.4 Potential Risks and Downsides

Environmental Impacts

The environmental impact of CAES is a critical consideration. While CAES itself is a clean storage medium, the process of compressing and expanding air can involve the use of fossil fuels, particularly in diabatic CAES systems where natural gas is used to reheat the compressed air

before expansion. This can lead to greenhouse gas emissions, negating some of the environmental benefits of using renewable energy for storage (Rabi et al., 2023).⁸⁸

Safety Concerns

Safety is another concern associated with CAES. The storage of large volumes of compressed air at high pressures poses risks of leaks or catastrophic failures. Ensuring the integrity of storage caverns and pressure vessels is paramount to prevent accidents. Moreover, the high-pressure air release process must be carefully controlled to avoid rapid depressurization, which can be hazardous (Olabi et al., 2020).

Technical Challenges

Technical challenges include managing the thermal dynamics during the compression and expansion phases. The inefficiencies due to heat loss during these processes can significantly impact the overall performance of CAES systems. Advanced technologies such as adiabatic and isothermal CAES aim to address these issues, but they are still in the experimental or early implementation phases (Kim et al., 2012).

Dependence on Fossil Fuels

Some CAES systems, particularly diabatic ones, rely on fossil fuels for reheating the compressed air before it is expanded to generate electricity. This reliance can undermine the environmental benefits of using renewable energy sources for the initial compression, as it introduces a carbon footprint into the energy storage and generation (Garvey & Pimm, 2016).⁴⁵

3.7.1.5 Strategies for Overcoming Current Limitations

To address the limitations of Compressed Air Energy Storage (CAES) technology, several strategies can be implemented. One of the primary limitations is the geographical constraint related to suitable storage sites. To overcome this, researchers are exploring alternative storage methods such as above-ground pressure vessels and the use of abandoned coal mines and other underground structures not traditionally used for CAES. For example, using abandoned coal mines for air storage could provide a viable solution in regions lacking natural salt caverns (Lutyński, 2017).⁹¹

Improving the efficiency of CAES systems is another critical area. Advanced Adiabatic CAES (A-CAES) systems, which capture and reuse heat generated during compression, offer a promising solution. Low-temperature A-CAES (LTA-CAES) approaches can avoid the technical challenges associated with high-temperature thermal energy storage, providing a more manageable and potentially more economical alternative (Wolf & Budt, 2014).⁶⁹

Additionally, Distributed CAES (D-CAES) systems can be more efficient by locating compressors near heat loads to utilize waste heat for low-grade heating needs, despite higher capital costs due to the necessary infrastructure (Safaei et al., 2013).⁷⁰

3.7.1.6 Future Research and Development Directions

Future research should focus on several key areas to enhance the performance and viability of CAES. One area is the development of more efficient thermal energy storage (TES) systems integrated with CAES. Research into packed-bed thermocline storage systems and other innovative TES solutions can significantly improve the round-trip efficiency of CAES plants by better managing the heat generated and utilized during the compression and expansion processes (Ortega-Fernández et al., 2017).⁹²

Exploring the integration of CAES with other renewable energy sources and hybrid systems can also provide valuable insights. For instance, combining CAES with liquid air energy storage (LAES) can offer flexibility and efficiency improvements, particularly in areas where geological storage options are limited (Kantharaj et al., 2015).⁷⁷

Another critical research direction is the development of modular, low-pressure CAES systems suitable for remote locations and small-scale applications. These systems can offer high efficiency and low maintenance costs, making them ideal for integrating with decentralized renewable energy installations such as wind and solar farms (Alami et al., 2017).⁹³

3.7.1.7 Policy and Regulatory Recommendations

To support the development and deployment of CAES, policymakers and regulators should consider several measures. First, providing financial incentives such as grants, subsidies, and tax credits can help offset the high initial capital costs associated with CAES projects. These incentives can make CAES more attractive to investors and developers.

Regulatory frameworks should also be adapted to facilitate the integration of CAES with the existing energy grid. This includes creating policies that recognize the unique capabilities of CAES, such as its ability to provide long-duration storage and grid stabilization services. By allowing CAES systems to participate in ancillary service markets and providing compensation for their flexibility and reliability, policymakers can encourage their adoption (Rabi et al., 2023).⁸⁸

Additionally, promoting research and development through public-private partnerships can accelerate technological advancements in CAES. Funding collaborative projects between academia, industry, and government can lead to breakthroughs that enhance the efficiency, scalability, and economic viability of CAES technology.

3.7.2 Existing Systems

According to Advanced Compressed Air Energy Storage Systems: Fundamentals and Applications⁹⁴ study there are the following CAES projects operating, started or planned:

Comparison of demonstrated projects of CAES.

Project title	Location	Year	Status	Type	Generation power
Huntorf CAES plant [18]	Germany	1978	Retrofitted in 2006	D-CAES	321 MW
McIntosh CAES plant [18]	USA	1991	Operation	D-CAES	110 MW
Illinois CAES [40]	USA	1982	Canceled	D-CAES	220 MW
Ohio Project [41]	Texas, USA	2000	Terminated in 2013	D-CAES	2700 MW
Dallas Center Project [43]	Iowa, USA	2002	Terminated in 2011	D-CAES	—
PG&E Project [45]	California, USA	2011	No recent announcement	D-CAES	300 MW/3000 MW·h
ADELE Project [18,48]	Germany	2010	Terminated in 2017	ACAES	200 MW
Seneca Lake Project [49,50]	New York, USA	2010	Canceled	D-CAES	150 MW
BEC Project [18,32]	Texas, USA	2013	No official news about the plant	D-CAES	317 MW

Figure 3.8 Demonstrated CAES projects⁹⁴

A commercial demonstration of a 10-MW ACAES system was completed and connected to the grid by IET in Feicheng City, China, in 2021 and a 100-MW ACAES system was constructed and is currently in commissioning at Zhangbei City, China. The power station successfully delivered power at one time, marking the smooth realization of grid connection of the first domestic compressed air energy storage commercial power station. The Feicheng energy storage power station equipment was developed by the Chinese Academy of Sciences. Taking full advantage of the natural advantages of good airtightness and high stability of underground salt caverns in the bordering yard of Feicheng, Tai'an, the air is compressed into the salt cavern cavity when the grid load is low, and the exhaust gas is used to drive the generator to generate electricity when the grid load peaks, so as to realize auxiliary grid reduction.

The largest grid-connected CAES project, [Hubei Yingchang](#), launched in 2024 was built in two years with a total investment of CNY1.95 billion (US\$270 million) and uses abandoned salt mines in the Yingcheng area of Hubei, China's sixth-most populous province. The plant has come online in April 2024 with 300MW/1,500MWh of capacity.

Figure 3.9 The compressed air energy storage project (CAES) project in Hubei, China. Image: China Energy Construction Digital Group and State Grid Hubei Integrated Energy Services.⁹⁵

Known on-surface CAES facilities:

A ground-level integrated diverse energy storage (GLIDES) system recently proposed at the Oak Ridge National Laboratory (USA) stores energy via gas compression. A prototype was constructed and tested.

The Goderich Energy Storage Centre, located in Goderich, Ontario, is the world's first commercially contracted Advanced-CAES facility. The facility is contracted by Ontario's Independent Electricity System Operator (IESO) for peaking capacity, ancillary services, and full participation in the merchant energy market to support grid reliability standards as set out by the IESO.

With 1.75 megawatts (MW) of peak power output, a 2.2 MW charge rating, and 10+ megawatt-hours (MWh) of storage capacity, this utility-scale commercial application of A-CAES technology is a significant achievement, conforming to all interconnection, uptime, performance and dispatch.⁹⁶

The lack of known operational above-ground facilities underlines the low Technology Readiness Level (TRL) of the technology and makes it unfeasible for consideration within the StoreMore project as a potential distributed energy storage technology.

3.7.3 Will it change everything index (WICE)

Compressed Air Energy Storage presents a compelling alternative to traditional lithium-ion batteries, particularly for large-scale and long-duration energy storage applications. To assess its potential to reshape the energy landscape, we will calculate a "Will it Change Everything Score" based on a weighted combination of key factors.

- **Energy Density:** CAES has in comparison with traditional lion bateries (our standard for comparison)a moderate energy density, 100 -200 Wh/l. It stores energy by compressing air and storing it in underground caverns or containers.⁹⁷

Score: 20

Energy Retention Period: CAES can retain energy for several hours to days, depending on the storage capacity and design. So it is standard result.

Score: 50

- **Lifetime and Life Cycles:** CAES systems typically have a long operational lifetime, with minimal degradation over cycles. From this point of view it is better than standard.
Score: 70
- **Round-Trip Efficiency (RTE):** Although CAES has a relatively high round-trip efficiency, sometimes exceeding 70% it is still lower than the reference 90-95% for Li-on bateries.⁸⁸

Score: 30

- **Technological Maturity (TRL):** underground CAES is a relatively mature technology, but its current TRL (Technology Readiness Level) is lower than that of lithium-ion batteries. While there are two operational D-CAES plants (Huntorf and McIntosh plants), the technology is still considered to be in the demonstration phase due to the limited number of projects and the ongoing research and development needed to improve efficiency and reduce costs. In contrast, lithium-ion batteries have reached TRL 9, meaning they are commercially available and widely deployed.

Score: 30

- **CAPEX:** The capital expenditure for CAES can be significant due to infrastructure costs, so the advantage is in lifetime and life cycles can have a much higher price title than Li-ion systems.

Score: 40

- **OPEX:** Compared to lithium-ion batteries, compressed air energy storage (CAES) systems generally exhibit lower operational expenditure (OPEX). This is primarily due to the minimal need for component replacement and reduced maintenance requirements of CAES, as they lack the chemical degradation processes that affect battery performance over time.

Score: 60

- **Environmental Impact:** Compared to lithium-ion batteries, CAES systems generally exhibit a lower environmental impact over their lifetime due to reduced reliance on mining and less hazardous waste generation. While above-ground CAES requires land and construction materials, its potential for repurposing existing infrastructure, such as depleted gas fields, could offset some of these concerns. Conversely, underground CAES, while more limited in siting options, boasts minimal land disturbance and longer lifespans, further contributing to its lower overall environmental footprint.

Score: 70

- **Scalability:** CAES can be scaled up to large capacities but usually only in project stage. After project finalization scalability is limited.

Score: 20

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	20	2
Energy Retention Period	0.1	50	5
Lifetime and Life Cycles	0.1	70	7
Round-Trip Efficiency (RTE)	0.15	30	4.5
Technological Maturity (TRL)	0.2	30	6
Capital Expenditure (CAPEX)	0.1	40	4
Operational Expenditure (OPEX)	0.1	60	6
Environmental Impact	0.1	70	7
Scalability	0.05	20	1
Total	1		42.5

Conclusion

The WICE Score for CAES is **42,5**. On surface CAES is basically non-existent, having a very low TRL technology with lower energy density but with a good lifetime, higher investment and lower operational costs. In case that there is good natural conditions (cavern) is system also environmentally friendly. Further development is limited, technology is appropriate in case of sufficient natural conditions in selected locations.

Impact potential of technology

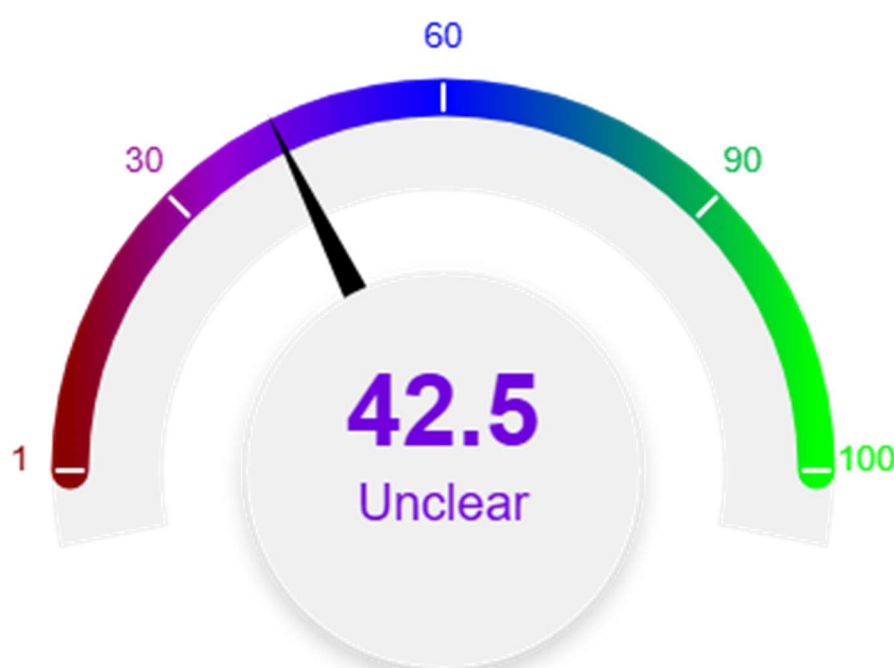


Figure 3.10 CAES WICE index

4. Liquid Air Energy Storage (LAES)

Summary of metrics

Parameter	Technology
	LAES
Energy density per unit of volume [kWh/l]	60-200
Power range [MW]	100-1000
Time of Permanent Energy Storage [hour]	4-12
Life time [cycles]	Several thousand to tens of thousands of cycles.
Life time [years]	20-40
Discharge Time [minutes]	2-12
RTE (Round-Trip Efficiency) [%]	45-70
RTE degradation	from 1% to 2% per year
Technology Maturity / Technological Readiness Level (TRL):	Developing/Demo stage with TRL 7-8
System size Energy Capacity (kWh)	Up to 10 GWh
System size Power Rating (kW or MW)	1-300 MW
CAPEX per kW of Power Capacity [EUR/kW]	From 1,400 to 3,500
CAPEX per kWh of Energy [EUR/kWh]	From 300 to 800
OPEX per kW of Power Capacity [EUR/kW/year]	1,5% of the capital cost
OPEX per kWh of Energy [EUR/kWh/year]	1,5% of the capital cost

Sources: [Comprehensive Review of Liquid Air Energy Storage \(LAES\) Technologies](#)¹⁰⁹ (Rabi et al 2023), [Liquid air energy storage \(LAES\): A review on technology state-of-the-art, integration pathways and future perspectives](#) (Vecchi et al 2021), [Compressed Air Energy Storage \(CAES\) and Liquid Air Energy Storage \(LAES\) Technologies—A Comparison Review of Technology Possibilities](#) (Burian et al 2023), [An economic feasibility assessment of decoupled energy storage in the UK](#)¹⁰⁸ (Xie et al 2018)

4.1 LAES Introduction

Liquid Air Energy Storage (LAES) is an innovative and increasingly relevant technology for addressing the challenges of integrating renewable energy sources into the electrical grid. By storing energy in the form of liquefied air at cryogenic temperatures (below -150°C), LAES offers a scalable, efficient, and location-independent means of managing fluctuations in energy supply and demand.

An energy store, a discharging system, and a charging system make up a LAES system. The charging system is an industrial air liquefaction facility that produces liquid air (also known as "cryogen") by rejecting heat from ambient air taken from the surrounding environment using electrical energy. This idea involves storing energy at cryogenic temperatures, or below -150°C , in the form of liquid air. It charges by compressing and liquefying air using extra electricity, which is subsequently stored as a liquid at temperatures close to -196°C . Because temperatures below -150°C are referred to be cryogenic, cryogenic energy storage (CES) is another term for LAES. When the liquid air discharges, it warms up and turns into a compressed gas that powers a turbine to produce energy.⁹⁸

As the energy store, the liquid air is kept at low pressure in an insulated tank. Liquid air is taken out of the tank, pumped to high pressure, and then evaporated when power is needed. This creates gaseous air that may power a turbine or piston engine to accomplish useful work that can be converted into electrical power.

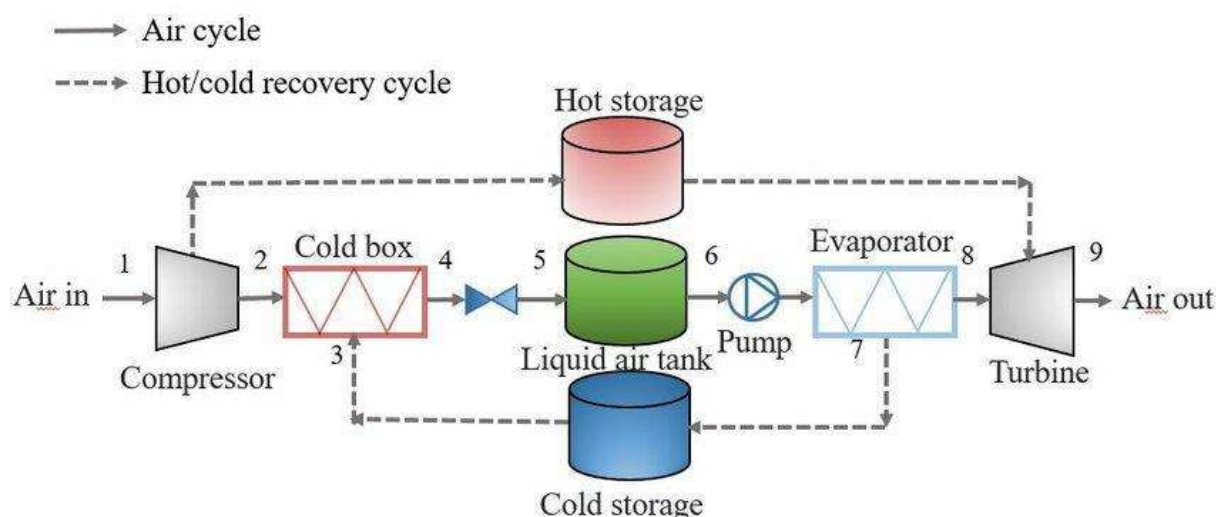


Figure 4.1 The working principle of a LAES system source: [ResearchGate](#)

Key parameters

LAES systems are among the more creative ideas for electric energy storage that have a lot of promise because they are geographically unconstrained and rely on proven technologies created for more established applications, like the gas liquefaction industry. Energy is stored in a cryogenic fluid in liquid phase, which significantly reduces the volume of the reservoir required in comparison to a more conventional Compressed-air energy storage (CAES) system.

Although this may seem like a disappointing performance, the expected round-trip efficiency of liquid air storage is between 50 and 60 percent. However, the advocates of these plants point out that the round-trip efficiency has less of an impact on the storage plant's economic performance than the investment cost as long as the total storage capacity is less than the excess power produced by intermittent RES.

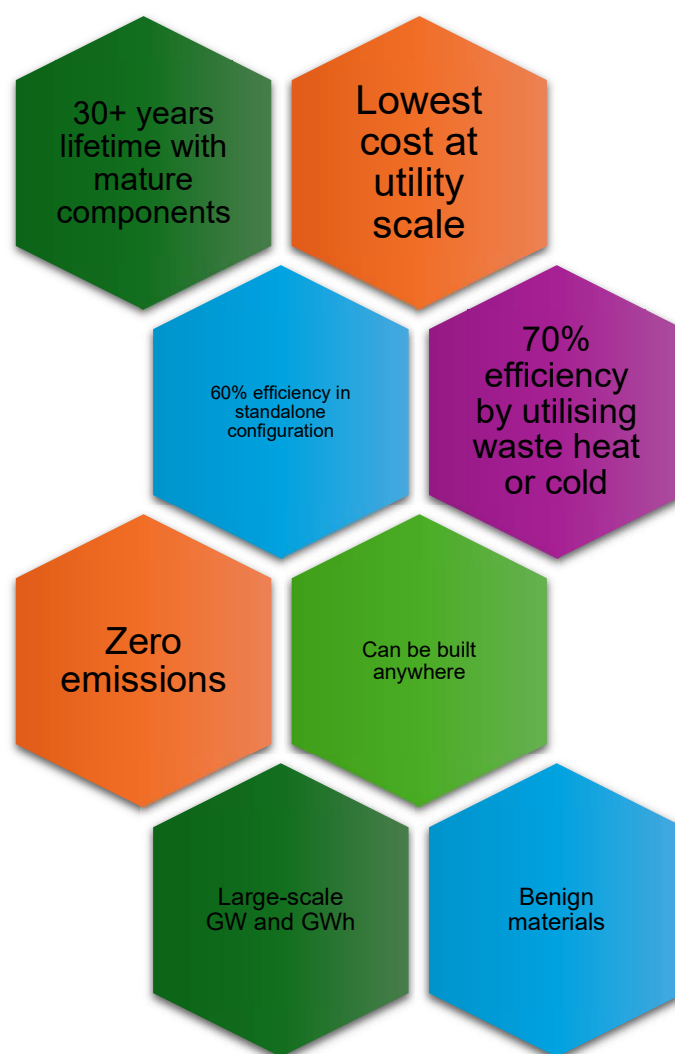


Figure 4.2 Key benefits of LAES

Physics

The physics of LAES revolves around the thermodynamic properties of air and the energy transformations involved in the charging (liquefaction) and discharging (power generation) processes.

1. Charging (Air Liquefaction)

The charging process is governed by the thermodynamic principles of compression and cooling. Ambient air is first compressed, which increases its temperature and pressure. The compressed air is then cooled using a series of heat exchangers, rejecting heat to the surroundings. As the air cools, it undergoes a phase change from gas to liquid at its boiling point, which is approximately -196°C at atmospheric pressure.

Compression: Air is first compressed to high pressures, typically around 70-250 bar. This compression process increases the air temperature significantly due to the work done on the gas. **The work done** to compress air from an initial state (P_1, V_1) to a final state (P_2, V_2) can be described using the adiabatic process formula (assuming no heat exchange with the environment). The formula is the same as for CAES:

$$W_{compression} = \frac{P_1 V_1}{\gamma - 1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]$$

where:

- P_1, V_1 are the initial pressure and volume,
- P_2, V_2 are the final pressure and volume,
- γ is the heat capacity ratio C_p / C_v ,
- The term $\gamma/(\gamma-1)$ is a constant that depends on the type of gas. For diatomic gases like air, γ is typically around 1.4. However, when dealing with liquid air, the situation becomes more complex than in the case of CAES. In the liquefaction and vaporization processes, the specific heats and phase change enthalpies (latent heat) play significant roles, which are not captured by the simple adiabatic processes described by γ .

Energy for Liquefaction:

The energy required to liquefy air is given by the specific enthalpy of liquefaction (h_f):

$$Q_{liquefaction} = m \cdot h_f$$

where:

- m is the mass of the air.
- h_f is the specific enthalpy of liquefaction.

The cooling process can be described by the heat transfer equation:

$$Q = m \cdot c_p \cdot \Delta T$$

Where:

Q = Heat removed

m = Mass of air

c_p = Specific heat capacity at constant pressure

ΔT = Temperature change

2. Storage of Liquid Air

The liquefied air is stored in insulated cryogenic tanks. During storage, it is important to minimize heat transfer to prevent boil-off and maintain the liquid state. An important concern during storage is stratification of the liquid air in the storage tank. This could result in local oxygen enrichment of the working fluid and the risk of fire or an explosion if the enriched fluid came into contact with hydrocarbons, such as the lubricating oil for the power turbine.⁹⁹

3. Expansion and Power Generation

When energy is needed, the liquid air is vaporized and expanded to drive a turbine and generate electricity. The expansion process involves heating the liquid air, turning it back into gas, and using the high-pressure gas to spin a turbine.

The vaporization process requires heat, which can be supplied from various sources, such as the heat stored during the compression phase or external heat sources.

The energy required to **vaporize liquid** air is given by the specific enthalpy of vaporization (h_v):

$$Q_{\text{vaporization}} = m \cdot h_v$$

where:

- $Q_{\text{vaporization}}$ is the heat required for vaporization
- m is the mass of the liquid air
- h_v is the enthalpy of vaporization

This heat (Q_{total}) can come from stored heat (captured during the liquefaction process) or external sources: $Q_{\text{total}} = Q_{\text{stored}} + Q_{\text{external}}$

In a well-designed LAES system, the heat generated during the compression phase can be captured and stored in a thermal storage system. This stored heat is then used during the vaporization phase, improving overall system efficiency.

Work Done During Expansion:

The work done by the expanding gas can be described using the adiabatic expansion formula (same as for CAES):

$$W_{\text{expansion}} = \frac{P_2 V_2}{\gamma - 1} \left[1 - \left(\frac{P_1}{P_2} \right)^{\frac{\gamma-1}{\gamma}} \right]$$

where:

- P_2, V_2 are the pressure and volume of the compressed air before expansion,
- P_1, V_1 are the pressure and volume after expansion.

Round-trip efficiency

The most important performance parameter is round-trip efficiency (RT). RT is simply defined as the work output in recovery mode divided by the work input in storage mode:

$$\eta_{RT} = \frac{W_{\text{expansion}}}{W_{\text{compression}}}$$

History of LAES

1883: The first liquefaction of air was achieved by Polish scientists Karol Olszewski and Zygmunt Wróblewski. This foundational work laid the groundwork for future cryogenic applications, including LAES.¹⁰⁰

1977: The first formal proposal for using liquid air as a means of energy storage was put forth by Peter Dearman, a British inventor. However, the concept did not gain significant traction at the time.

Liquid Air Energy Storage (LAES) has garnered significant attention as a large-scale energy storage solution, particularly with the rising adoption of intermittent renewable energy sources. The technology's development began in the late 1990s with companies like Mitsubishi and Hitachi leading initial efforts. Mitsubishi Heavy Industry designed the first prototype in 1998, which demonstrated a discharge system efficiency of up to 77%, though it did not account for the energy consumed by the air liquefaction plant. Following this, Hitachi, Ltd. integrated combustion with liquefaction and generation units in 2005, achieving storage efficiencies exceeding 70% in experimental settings, but without a full-scale pilot plant.

Modern innovations of LAES

Late 20th – Early 21st Century: Renewed interest in LAES emerged as concerns about climate change and the need for efficient energy storage solutions grew. Technological advancements in cryogenic processes, materials, and energy systems further contributed to the feasibility of LAES.

2011: Highview Power, a UK-based company, developed the first pilot LAES plant in Slough, UK. The plant operated at a 80MW biomass plant at Slough Heat and Power in Greater London from 2011-2014. The plant was built to prove the technology, was connected to the UK grid and complied with all the necessary regulations and inspections. This 350 kWh/2.5 MWh pilot plant became operational in 2011 at Scottish and Southern Energy's biomass plant in Slough, UK. Despite achieving a round trip efficiency of only 8% due to its small scale and inefficient cold recycle design.¹⁰¹

The pilot plant has been relocated to the University of Birmingham's new Birmingham Centre for Cryogenic Energy Storage where it will support further testing and academic research.¹⁰²

Highview Power has been backed by energy giant Centrica and the UK Infrastructure Bank to build the first commercial-scale liquid air energy storage plant in the UK, at Carrington.

The company says building work will start immediately and the plant, which got initial planning consent in 2021, should be operational by early 2026.¹⁰³

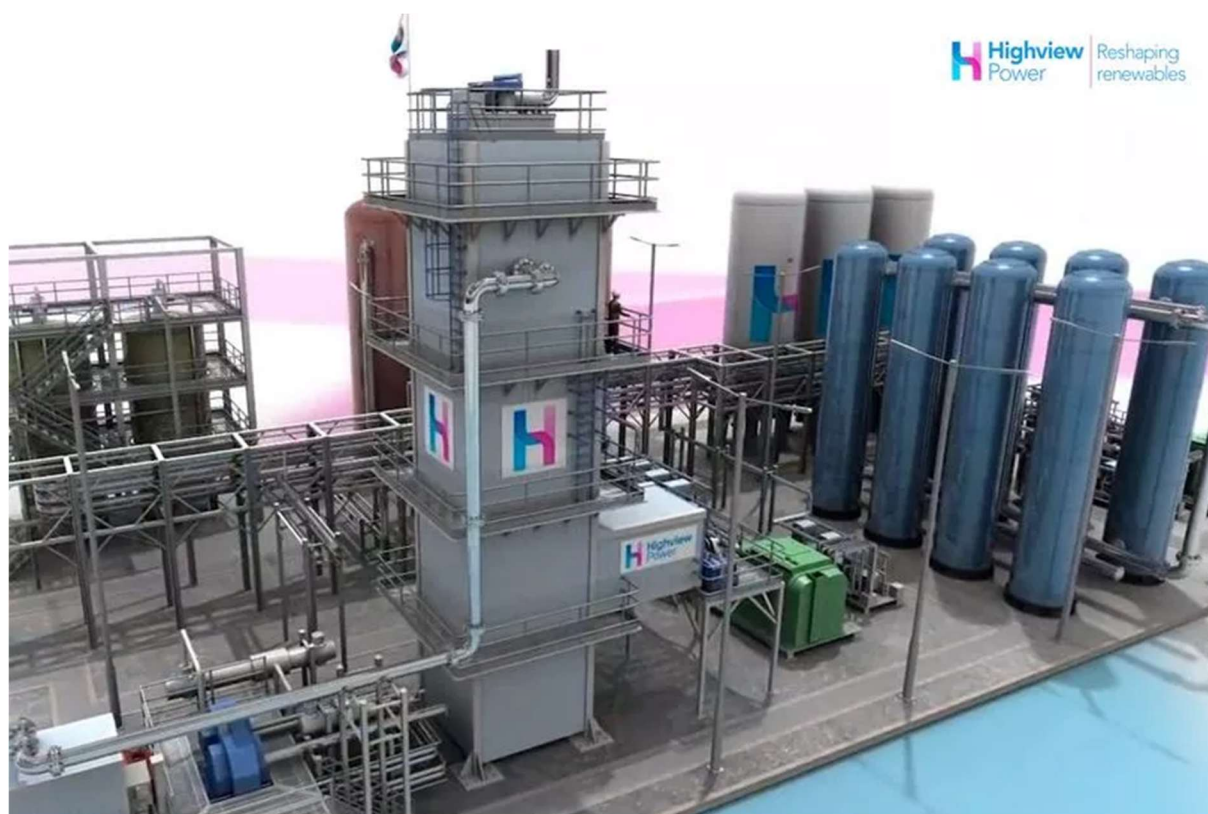


Figure 4.3 proposed energy storage plant at Carrington, Greater Manchester

A historical overview of LAES from the Comprehensive Review of Liquid Air Energy Storage (LAES) Technologies study¹⁰⁹ (Rabi et al, 2023)

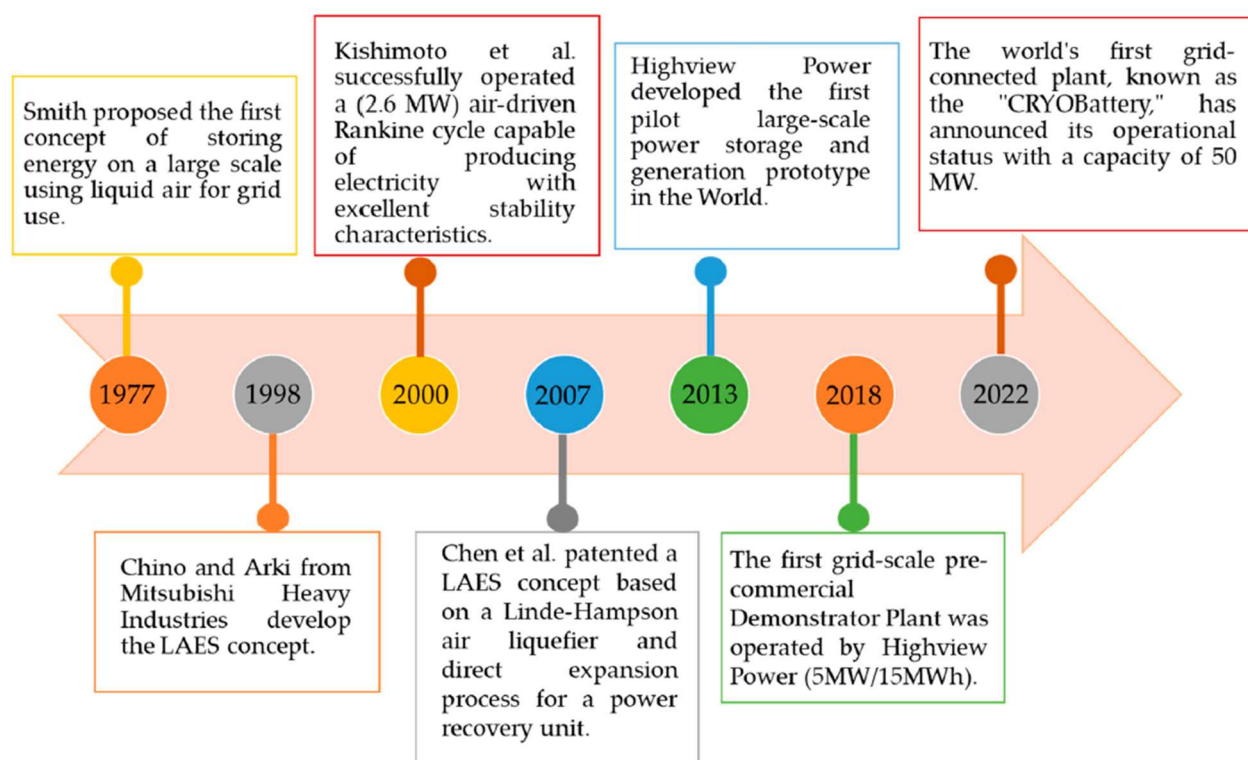


Figure 4.4 LAES historical timeline

4.1.1 Description of the process

4.1.1.1 Liquefaction phase

One of several nearly identical liquefaction cycles can be used to carry out liquefaction. When a gas is liquefied, its density increases significantly. This is advantageous because the liquefied gas can be stored inexpensively and efficiently at atmospheric pressure in smaller volumes than a gas would require. High pressure is typically required for liquefaction (up to 200 bar depending on the system). High-pressure liquefaction is preferred because it allows liquefaction to occur at higher temperatures.¹⁰⁴

Air enters the compression process at room temperature and pressure, exiting at elevated temperatures and pressures. The heat energy generated during compression significantly increases the air's temperature. This heat is usually retained for use in the subsequent power generation cycle. The hot, high-pressure gaseous air enters a heat exchanger, where it cools and condenses completely to a temperature of around -190°C (at or below the high-pressure air's

condensation temperature). The remaining high-pressure liquid passes through a throttle valve, causing it to expand and depressurize until it reaches a final temperature of about -196°C , the air's condensation temperature at atmospheric pressure. This expansion, which also causes some of the liquefied air to evaporate, results in a low-pressure, low-temperature liquid and gas mixture.

4.1.1.2 Storage

The liquid air is stored after being separated from any leftover gas. Usually, a cold storage system, often in the form of liquid refrigerants or a solid packed bed, provides the cooling needed for liquefaction. This stored cold is crucial for improving the overall efficiency of the LAES process. The liquid air is then kept in a low-pressure, insulated container to minimize heat gain and prevent boil-off until electricity production is needed. Cryogenic fluids can be stored for many months in low pressure insulated tanks, with losses as low as 0.05% by volume per day.

4.1.1.3 Power generation

The discharge process of Liquid Air Energy Storage (LAES) involves retrieving stored energy by converting liquid air back into a gaseous state to drive turbines for electricity generation. Initially, liquid air is pumped from storage tanks to high pressures using cryogenic pumps commonly employed in the liquefied natural gas (LNG) industry. This process, critical for enhancing the specific work output, typically operates at pressures ranging from 55 to 200 bar. Following pressurisation, the liquid air is gradually heated and vaporised in a series of heat exchangers, which transform the liquid into a high-pressure gas. The efficiency of these heat exchangers is paramount, often achieving effectiveness rates between 90-95%.

After vaporisation, the high-pressure gaseous air is expanded through multiple stages of turbines to produce electricity. These expansion stages are carefully designed to maximise efficiency, with turbines operating under isentropic efficiencies of 80-90%. Intermediate reheating between turbine stages is a common strategy to maintain high thermal efficiency and increase overall power output. By reheating the air, the process ensures optimal energy extraction from the gas expansion. Additionally, a recuperative heat exchanger is often employed to preheat the incoming air using the exhaust heat from the turbines, further enhancing the efficiency of the power generation cycle.

The discharge process is meticulously designed to recover and utilise thermal energy streams produced during the charging phase. High-grade cold energy, generated during the air evaporation, supports the air liquefaction process, while the heat released from compression is used for reheating during discharge. These thermal management strategies significantly improve the roundtrip efficiency of LAES, with efficiencies ranging from 40.4% to 61.6%. The integration of efficient heat exchangers, strategic reheating, and advanced turbine technology

ensures that LAES can effectively convert stored liquid air into reliable, on-demand electricity, positioning it as a competitive option in the energy storage landscape.¹⁰⁵

4.2 Main applications of LAES

(LAES technology provides a promising solution for integrating renewable energy sources into the electricity market by offering large-scale, long-duration storage capabilities. The fundamental process involves using excess electricity to liquefy air, which is then stored in insulated tanks at cryogenic temperatures. The effectiveness of LAES in the electricity market is underpinned by several key characteristics, including roundtrip efficiency, response time, and energy density.

Diferent storage technologies cover different needs. LAES sits comfortably in the middle offering medium to large scale storage solutions that can be located at the point of demand.

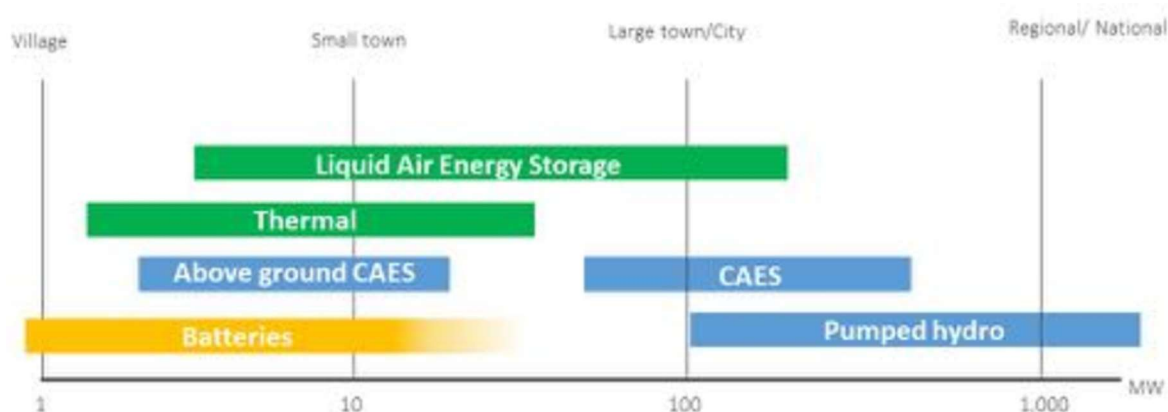


Figure 4.5 [Different energy storage technologies and the size ranges they can offer](#)

Grid-Scale Energy Balancing

One of the primary applications of LAES is grid-scale energy balancing. Due to its long-duration storage capability (hours to days) and scalability (MW to GW), LAES can effectively address the intermittency of renewable energy sources like wind and solar. By storing excess energy during periods of high generation and releasing it during periods of high demand or low generation, LAES can help maintain grid stability and reliability. The round-trip efficiency of LAES, typically between 50% and 60%, is a key consideration for economic viability in this application.

Ancillary Services

LAES can also provide a range of ancillary services to the grid, such as frequency regulation, spinning reserve, and voltage support. These services are essential for maintaining grid stability and ensuring reliable power delivery. The fast response time of LAES, demonstrated to be within seconds to minutes, makes it well-suited for these applications.

Peak Shaving and Load Shifting

LAES can be used for peak shaving and load shifting, reducing the need for expensive peaking power plants and lowering overall electricity costs. By storing energy during off-peak hours and discharging it during peak demand periods, LAES can help flatten the load curve and optimize the utilization of generation assets.

Integration with Other Technologies

LAES can be integrated with other technologies, such as liquefied natural gas (LNG) terminals and industrial processes, to create hybrid systems that offer additional benefits. For example, LAES can utilize the cold energy released during LNG regasification to improve its liquefaction efficiency, while also providing grid services. This integration can enhance the overall efficiency and economic viability of both LAES and the coupled process.

4.3 Technological barriers, regulatory framework and scalability

Technology barriers

Liquid Air Energy Storage faces several technology barriers that must be overcome to realise its full potential as a large-scale energy storage solution. One of the primary barriers is the system's round-trip efficiency. Although theoretical efficiencies can reach up to 60%, practical implementations often fall short due to technical limitations in the components and processes. For instance, initial pilot projects like Highview Power's demonstrated efficiencies as low as 8%, attributed to the small scale and suboptimal design of cold recycling mechanisms. To improve efficiency, advancements in heat exchange processes and the integration of waste heat recovery are necessary, but these improvements add complexity and cost to the system.

Another significant barrier is the energy density of LAES systems. While LAES boasts a higher energy density compared to some traditional storage methods like Compressed Air Energy Storage (CAES), it still lags behind technologies such as lithium-ion batteries. The energy density of LAES ranges between 50 to 200 Wh/L, which, while substantial, necessitates large storage volumes and robust infrastructure. The storage tanks and associated cryogenic components require significant capital investment and meticulous maintenance to prevent thermal losses and ensure operational safety. This high initial cost and the need for large physical footprints can limit the widespread adoption of LAES, especially in regions with space constraints.

The economic feasibility and scalability of LAES remain challenging. The cost of building and maintaining LAES infrastructure is high, and while economies of scale can reduce specific costs, the initial investment is still substantial. The integration of LAES with existing energy systems and the development of hybrid configurations, such as combining LAES with thermochemical energy storage, can improve performance and reduce costs, but also introduce additional technical and logistical hurdles. Moreover, the supply chain for critical components, such as advanced heat

exchangers and cryogenic pumps, needs to be robust and reliable. Addressing these barriers requires concerted efforts in research, development, and policy support to create a favourable environment for LAES deployment on a larger scale.

Scalability

The scalability LAES is one of its most promising features, especially given the increasing need for large-scale energy storage solutions to support the integration of renewable energy sources into the grid. LAES systems are inherently scalable due to their reliance on widely available materials such as steel and aluminium, and their use of conventional industrial components like compressors and turbines. Unlike technologies that depend on rare or environmentally problematic materials, LAES can be expanded to meet growing energy storage needs without significant supply chain constraints. This scalability is demonstrated by the progression from the first grid-scale liquid air energy storage project of Highview Power with its 5MW/15MWh plant¹⁰⁶, to proposed configurations with capacities reaching 100 MW/600 MWh, highlighting the potential for substantial growth.

However, the economic feasibility of scaling up LAES systems presents notable challenges. Larger LAES installations benefit from economies of scale, which reduce the specific costs of components and infrastructure. The cost per unit of energy stored decreases as the system size increases, making large-scale deployments more economically viable. Despite this, the initial capital investment required for large LAES plants is substantial, necessitating significant upfront funding and long-term financial planning. The integration of waste heat sources, as seen in Highview Power's 5 MW/15 MWh demonstration plant at Pilsworth Landfill, can enhance the overall efficiency and economic performance of larger systems. Nevertheless, the financial and logistical hurdles associated with constructing and maintaining extensive cryogenic storage and heat exchange infrastructure remain significant barriers to widespread scalability.

Technological advancements are critical to overcoming these scalability challenges. Enhancing the round-trip efficiency of LAES systems is essential to their economic and operational viability at larger scales. Current research focuses on improving heat exchange processes, optimising the cold recycling design, and integrating hybrid systems such as the combination of LAES with thermochemical energy storage (TCES). These advancements can lead to higher efficiencies and reduced operational costs, making large-scale LAES deployments more attractive. Additionally, policy support and incentives for renewable energy storage solutions can accelerate the adoption of LAES technology on a larger scale. By addressing these technical, economic, and regulatory challenges, LAES can become a cornerstone of the future energy landscape, providing reliable and efficient large-scale energy storage.

4.4 Raw material restriction

Liquid Air Energy Storage (LAES) systems, while presenting a promising solution for large-scale energy storage, rely on widely available materials such as steel and aluminium, and their use of conventional industrial components like compressors and turbines.

Air

The primary raw material, air, is universally abundant and poses no direct supply chain risks. However, the energy-intensive liquefaction process necessitates robust infrastructure and efficient components to ensure the system's effectiveness.

Containment Materials

High-strength steel or concrete with specialized insulation are essential for constructing the cryogenic tanks that store liquid air at extremely low temperatures. While these materials are generally abundant, their production can be energy-intensive and contribute to greenhouse gas emissions. Additionally, geopolitical tensions or fluctuations in global demand could lead to supply chain disruptions and price volatility, particularly for specific steel alloys or advanced insulation materials.

Expanders and Turbines

These components, crucial for converting stored energy into electricity, rely on materials like [steel](#), copper, and potentially [rare earth elements](#) for high-performance motors and generators. While steel and copper are relatively abundant, the availability of rare earth elements can be subject to geopolitical risks and supply chain vulnerabilities, as their extraction and processing are concentrated in a few countries and often associated with environmental damage. Identified **copper resources** are located in South America (38%), North America (23%), Asia (18%) and only 6% in Europe.¹⁰⁷

Refrigerants

LAES systems may utilize refrigerants like propane, methanol, or hydrofluorocarbons (HFCs) in the liquefaction process and thermal storage. The availability and environmental impact of these refrigerants vary. Propane and methanol are widely available, but their flammability requires careful handling. HFCs, while non-flammable, are potent greenhouse gases with high global warming potential. The production and use of these refrigerants should be carefully managed to minimize environmental harm.

Summary

While the primary raw material for LAES, air, is abundant, the system's reliance on specialized materials and components introduces potential vulnerabilities in the supply chain and environmental concerns related to their extraction, processing, and use. To ensure the sustainable deployment of LAES technology, it is crucial to prioritize the use of abundant and

recyclable materials, explore alternatives with lower environmental impact, and develop robust supply chains that minimize geopolitical risks.

4.5 Energy storage costs of LAES

Unfortunately, there's no abundance of use cases and operating LAES plants to demonstrate a well established calculation of OPEX and CAPEX of LAES. However, a study from the University of Birmingham (An economic feasibility assessment of decoupled energy storage in the UK - Xie, Chunping; Hong, Yan; Ding, Yulong; Li, Yongliang; Radcliffe, Jonathan)¹⁰⁸ provides a comprehensive analysis of economic feasibility.

The financial aspects of implementing LAES systems can be broken down into capital expenditure (CAPEX) and operational expenditure (OPEX). These costs vary significantly depending on the scale of the system.

Capital Expenditure (CAPEX) for LAES Systems

The initial investment cost for a LAES system is divided into three main components: the liquefaction unit, the cryogenic storage tanks, and the power recovery unit. The cost of each component is a function of its capacity.

- **Liquefaction Unit:** The cost of the liquefaction unit increases with increasing liquefaction capacity. For example, increasing the capacity from 480 MWh/day to 1185 MWh/day raises the cost from €140 million to €196 million.
- **Cryogenic Tanks:** The cost of the cryogenic tanks also increases with increasing storage capacity. For instance, with a constant liquefaction capacity and discharge power rating, increasing the storage capacity from 110 MWh to 400 MWh increases the cost from €127 million to €140 million.
- **Power Recovery Unit:** The cost of the power recovery unit increases with increasing discharge power rating. For example, with a constant liquefaction capacity and storage capacity, increasing the discharge power rating from 100 MW to 245 MW raises the cost from €140 million to €171 million.

The paper notes that the cost of the liquefaction unit is the most significant contributor to the overall CAPEX, representing a major constraint on the profitability of LAES systems.

Calculations based on the [study](#) for the smallest and largest examined systems:

50 MW System

Storage capacity: 5,800 tonnes ≈ 580 MWh Power output: 50 MW

CAPEX: €49.80 million

CAPEX per kWh of storage: €49.80 million / 580,000 kWh = €85.86/kWh
CAPEX per kW of power output: €49.80 million / 50,000 kW = €996.00/kW

Annual OPEX: €0.75 million Annual OPEX per kWh of storage: €0.75 million / 580,000 kWh = €1.29/kWh/year Annual OPEX per kW of power output: €0.75 million / 50,000 kW = €15.00/kW/year

200 MW System

Storage capacity: 25,300 tonnes $\approx$ 2,530 MWh Power output: 200 MW

CAPEX: €129.95 million

CAPEX per kWh of storage: €129.95 million / 2,530,000 kWh = €51.36/kWh CAPEX per kW of power output: €129.95 million / 200,000 kW = €649.75/kW

These calculations demonstrate the economies of scale in LAES systems. The larger 200 MW system has significantly lower costs per unit of storage capacity and power output compared to the 50 MW system.

It's important to note that these figures are based on systems using 150°C waste heat. The costs would be different for systems without waste heat or with different levels of waste heat utilization. Additionally, the relationship between storage capacity and power output is not linear across different system sizes, which affects the per-unit costs.

Operating Expenditure (OPEX) for LAES Systems

The operating and maintenance (O&M) costs for a LAES system are estimated to be 1.5% of the initial investment cost per annum. In addition to this fixed cost, there are variable costs associated with purchasing electricity for the liquefaction process and the cost of any additional materials needed for storage.

The paper does not provide specific figures for the variable O&M costs, but it does highlight the importance of waste heat utilization in improving the round-trip efficiency and overall economic viability of LAES systems. By integrating with industrial processes or other sources of waste heat, LAES plants can significantly reduce their electricity consumption during liquefaction, thereby lowering operating costs.

These operational costs include routine maintenance, labor, energy losses during the storage cycle, and other recurring expenses. As with CAPEX, OPEX tends to be lower per unit for larger systems due to more efficient operations and maintenance practices.

The costs of LAES systems are significantly influenced by system size, the degree of waste heat utilization, and the chosen operating strategy. Larger systems tend to be more economically viable due to economies of scale. The use of waste heat increases the initial CAPEX but improves the system's efficiency and economic performance over its lifetime. The choice between operating strategies has a minimal impact on CAPEX but affects the revenue streams and overall profitability of the system.

These cost considerations play a crucial role in determining the economic feasibility of LAES as a grid-scale energy storage solution. As the technology matures and costs potentially decrease, LAES could become an increasingly attractive option for supporting the integration of renewable energy sources into the power grid.

4.6 Environmental impact of LAES

Materials and Supply Chain

LAES technology primarily relies on common industrial materials such as steel for tanks, aluminium for heat exchangers, and conventional refrigerants like liquid nitrogen. These materials are widely available, and their supply chains are well-established, reducing the risk of supply shortages. Compared to lithium-ion batteries, which require rare and often environmentally damaging materials like lithium, cobalt, and nickel, LAES uses more environmentally benign and recyclable materials. The reliance on widely available materials positions LAES as a less disruptive technology in terms of raw material extraction and processing. Additionally, the end-of-life management of LAES components is simpler and less hazardous than that of lithium batteries, which require careful handling and recycling to prevent toxic leaks. Overall, LAES technology, with its scalable, non-toxic, and recyclable nature is less disruptive to the environment than lithium-ion batteries.

Construction and Operation

The construction of LAES plants involves standard industrial processes, with no need for rare materials or specialised infrastructure. The impact on the environment during construction is similar to that of other industrial plants, involving land use, energy consumption, and emissions associated with construction activities. However, unlike lithium-ion battery facilities, LAES plants do not involve the handling of toxic chemicals, reducing the potential for environmental contamination. During operation, LAES systems have a relatively low environmental footprint. They emit no pollutants, as they rely on air liquefaction and expansion processes that do not produce harmful byproducts. Additionally, the ability to utilise waste heat from industrial processes can further enhance their environmental benefits by improving overall system efficiency and reducing the need for additional heat sources.

To get a precise estimate of CO₂ emissions reduction from the usage of LAES systems, one would need to analyze specific data on the energy inputs, efficiency, and emissions associated with the entire lifecycle of the system, including manufacturing, operation, and decommissioning. This analysis would likely be case-specific and depend on factors such as the scale of the installation, the local energy mix, and the specific application of the stored energy. StoreMore project will concentrate a comprehensive environmental impact analysis in case LAES is selected for further examination.

4.7 Conclusion: advantages, disadvantages and recommendations for LAES

4.7.1 Pros and cons

LAES systems have numerous advantages such as:

1. While not as high as some chemical batteries, the energy density of liquid air is relatively high compared to other forms of mechanical storage (PHS, GS and CAES)¹¹⁸, allowing for substantial energy storage in a relatively small volume.
2. LAES systems are well-suited for long-duration energy storage. They can store energy for extended periods without significant losses, making them ideal for balancing seasonal variations in energy supply and demand.
3. Unlike pumped hydro storage, which requires specific geographical features, LAES systems can be located almost anywhere. This flexibility allows them to be deployed close to where energy storage is needed, reducing transmission losses and infrastructure costs.
4. LAES systems can be scaled up or down to meet varying energy storage needs. They are suitable for both grid-scale applications and smaller, localized storage needs.
5. LAES systems do not produce direct emissions during operation, making them environmentally friendly. They also have minimal environmental impact compared to other storage technologies like pumped hydro, which can have significant ecological and geographical impacts.
6. The components used in LAES systems, such as cryogenic tanks and compressors, have long lifespans and are relatively durable. This contributes to lower long-term maintenance costs and reliability over many years of operation.
7. LAES leverages established cryogenic and thermal technologies, which means it can benefit from existing industrial expertise and supply chains. This can reduce development costs and facilitate faster deployment.
8. Unlike batteries, which can degrade over time and with repeated charge-discharge cycles, LAES systems do not suffer from significant degradation. This results in a stable performance over the lifespan of the system.
9. LAES systems can be integrated with industrial processes to utilize waste heat and cold, improving overall system efficiency. This makes them particularly attractive for industrial applications where such waste streams are available.
10. LAES systems use inert air as the storage medium, which poses no risk of fire or explosion, enhancing the safety profile compared to batteries and some of the aforementioned storage systems where explosion risks were mentioned.

11. Unlike some battery technologies that rely on rare or environmentally sensitive materials (e.g., lithium, cobalt), LAES systems primarily use common materials, reducing supply chain and environmental concerns.

The development of energy storage systems that are not limited by geography and are also reasonably efficient, cost-effective, and safe for the environment is necessary. Lately, LAES have drawn interest from both the academic and business communities. These systems are not limited by geography and are based on widely used, industry-standard components.

Liquid air can be heated to cryogenic temperatures, so that readily available heat sources at room temperature can power the power generating cycle. This not only removes the requirement for burning and the corresponding carbon emissions, but it also makes it possible for low-temperature streams, such as waste heat, to be recovered inside the LAES process. Integration with outside heat and/or cold sources allows for energy synergies and symbiosis with other processes, including industrial locations close to the LAES process area.

LAES systems, among the more creative ideas for electric energy storage that have a lot of promise because they are geographically unconstrained and rely on proven technologies created for more established applications, like the gas liquefaction industry. Energy is stored in a cryogenic fluid in liquid phase, which significantly reduces the volume of the reservoir required in comparison to a more conventional Compressed-air energy storage (CAES) system.

LAES systems have several disadvantages, including:

1. LAES systems typically have a round-trip efficiency of about 50-60%, which is lower than other energy storage technologies like lithium-ion batteries or pumped hydro storage, which can achieve efficiencies of around 80-90%.
2. Significant energy losses occur during the liquefaction and regasification processes. These losses make LAES less efficient compared to other storage methods.
3. The initial capital cost for LAES can be high due to the need for complex infrastructure, including cryogenic storage tanks, heat exchangers, and compressors. This can make it less economically attractive, especially for smaller scale or short-term storage applications.
4. LAES systems require sophisticated technology to handle the extreme temperatures involved in liquefying and storing air. This increases the complexity of the system and the need for specialized maintenance, potentially leading to higher operational costs.
5. Effective thermal management is crucial to improving the efficiency of LAES systems. The need to capture and reuse waste heat adds complexity and can limit the overall performance if not managed properly.

6. While LAES does not have the same geographic limitations as pumped hydro storage, it does require significant space for the cryogenic storage tanks and associated infrastructure, which can be a constraint in densely populated or space-limited areas.

Advantages and Disadvantages of LAES: A Balanced Perspective

Liquid Air Energy Storage (LAES) systems present numerous advantages that make them a promising solution for energy storage needs, particularly in scenarios requiring long-duration storage. One of the key benefits is their relatively high energy density compared to other mechanical storage options, allowing substantial energy storage within a smaller footprint. LAES systems are versatile in their deployment, not being limited by specific geographical features like pumped hydro storage, which makes them suitable for urban and industrial settings. Additionally, they are well-suited for balancing seasonal energy supply and demand, given their capability to store energy for extended periods without significant losses. The environmental benefits are also notable, as LAES systems produce no direct emissions during operation and have minimal ecological impacts compared to other technologies.

Despite these advantages, LAES systems do face several challenges that can hinder their widespread adoption. The round-trip efficiency of LAES, typically around 50-60%, is lower than that of lithium-ion batteries and pumped hydro storage, which can achieve efficiencies of 80-90%. This lower efficiency is partly due to significant energy losses during the liquefaction and regasification processes. Moreover, the initial capital costs for LAES can be high, driven by the need for complex infrastructure, including cryogenic storage tanks, heat exchangers, and compressors. The technology also requires sophisticated handling of extreme temperatures, adding to the complexity and potential operational costs. Effective thermal management is crucial, as the system's efficiency heavily relies on capturing and reusing waste heat, which adds another layer of complexity.

Compared to CAES however, LAES poses comparative advantages:

CAES typically has an efficiency of 40-55%, with large installations like the Huntorf and McIntosh plants demonstrating this range. One major challenge in CAES is the energy lost during the compression and expansion phases, especially in systems that rely on natural gas for reheating, which introduces carbon emissions. In contrast, LAES has slightly higher potential efficiency, with round-trip efficiencies between 50-60%. LAES benefits from higher energy density, as it uses liquefied air stored at cryogenic temperatures, which overcomes the geographical constraints of CAES, making it deployable in a broader range of locations (Rabi et al., 2023)¹⁰⁹.

Environmental and Geographical Factors: LAES has a significant advantage in terms of environmental impact because it does not require specialized geological conditions, unlike CAES, which relies on large underground caverns for air storage. Moreover, LAES systems can be easily hybridized with other energy sources, such as waste heat recovery, to enhance performance.

However, CAES remains competitive due to its well-established infrastructure and lower upfront capital costs, despite its lower energy density and geographical limitations (Salem & Khaira, 2023)¹¹⁰.

Overall, while LAES systems have some disadvantages, their advantages in terms of flexibility, scalability, and environmental impact can outweigh these drawbacks when properly applied. The ability to deploy LAES systems in diverse locations, coupled with their use of common materials and established industrial technologies, positions them as a viable option for large-scale energy storage. The key to maximizing their potential lies in integrating them with industrial processes to utilize waste heat, thereby improving efficiency and economic feasibility. In scenarios where long-duration storage and geographical flexibility are critical, the benefits of LAES can significantly surpass its limitations, making it a valuable component in the transition to a sustainable energy future.

4.7.3 WICE index

Scoring LAES

To compare LAES and lithium-ion batteries, we need to consider several factors including energy density, efficiency, scalability, cost, environmental impact, and suitability for different applications. Each of these factors can significantly influence the overall score for each technology.

Energy Density

LAES generally has lower energy density with its presumed value of 60-200 Wh/l compared to lithium-ion batteries with [their 250-700Wh/l density](#).

Score: 20

Energy Retention Period

LAES have very long energy retention period. Since LAES stores energy in the form of liquefied air at cryogenic temperatures, it can retain energy for days to weeks with minimal losses.

Score: 80

Lifetime and Life Cycles

LAES have generally long lifetime and high number of lifecycles. LAES systems have fewer degradation issues compared to batteries, leading to a longer operational lifespan.

Score: 60

Round-Trip Efficiency (RTE)

LAES typically have a round-trip efficiency around 50-70%. LAES has lower efficiency due to the energy losses involved in liquefying air and later regasifying it to generate electricity

Score: 30

Technological Maturity (TRL)

LAES is relatively new and is in the early stages of commercial deployment, with some pilot projects and initial commercial installations. It is generally considered to be at TRL 7-8.

Score: 70

Capital Expenditure (CAPEX)

Generally, LAES systems have high initial capital costs due to the complex infrastructure required for cryogenic storage and conversion systems. However, these costs can be offset by lower operational costs and longer lifespans.

Score: 40

Operational Expenditure (OPEX)

LAES systems generally have lower operational costs compared to batteries. They require maintenance of mechanical and cryogenic systems, but these costs are spread over a long operational life with fewer replacements needed.

Score: 60

Environmental Impact

Generally lower environmental impact compared to batteries. LAES uses air as the storage medium and has fewer issues related to toxic materials and resource extraction. However, the construction and operation of cryogenic facilities can have some environmental footprint.

Score: 80

Scalability

LAES systems are highly scalable and well-suited for large-scale, grid-level energy storage. They can be designed to store large amounts of energy, making them ideal for balancing supply and demand on a grid scale.

Score: 70

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	20	2

Energy Retention Period	0.1	80	8
Lifetime and Life Cycles	0.1	90	6
Round-Trip Efficiency (RTE)	0.15	30	4.5
Technological Maturity (TRL)	0.2	70	14
Capital Expenditure (CAPEX)	0.1	40	4
Operational Expenditure (OPEX)	0.1	60	6
Environmental Impact	0.1	80	8
Scalability	0.05	70	3.5
Total	1		56.00

Conclusion

The WICE Score for LAES is 56.00 LAES technology shows promise for large-scale, long-duration energy storage applications, particularly due to its high scalability and ability to store energy for extended periods with minimal losses. However, it faces challenges in energy density and round-trip efficiency, which are lower compared to lithium-ion batteries. LAES systems have a long operational lifespan and relatively low operational costs, offsetting their high initial capital expenditure. Environmentally, LAES has a lower impact, as it primarily uses air as the storage medium and avoids reliance on toxic materials. While the technology is still emerging, with a TRL of 7-8, it is well-suited for grid-level applications and has significant potential to contribute to renewable energy integration and grid stability. Further developments are needed to improve efficiency and reduce costs, but its strengths in scalability and environmental sustainability make it a competitive option in the energy storage landscape.

Impact potential of technology

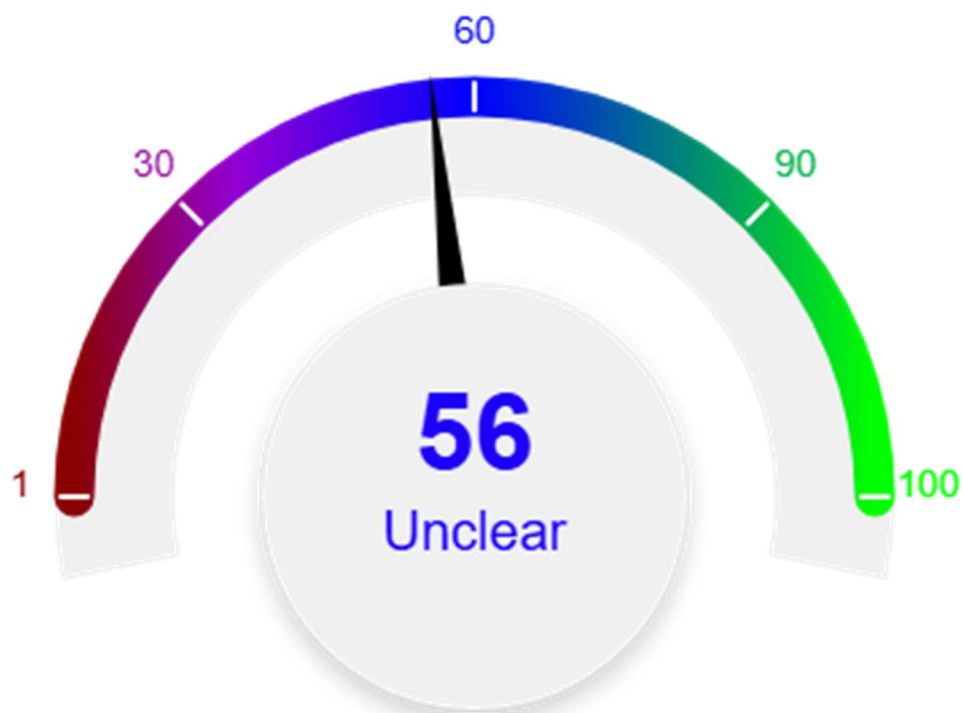


Figure 4.6 LAES WICE index

5 Flywheel Energy Storage

Summary of Metrics

Parameter	Technology
	Flywheel Energy Storage
Energy density per unit of volume [kWh/kg]*	19 Wh/kg for 10000 RPM, 171 Wh/kg for 30000 RPM
Power range [MW]	kWs to 100s of MWs due to modular design
Time of Permanent Energy Storage [hour]	hours to a few days
Life time [years/cycles]	30 years
Discharge Time [minutes]	minutes to 4 hours
RTE (Round-Trip Efficiency) [%]	85% - 95%
RTE degradation	0.14% / year ¹¹
Technology Maturity / Technological Readiness Level (TRL):	9
System size Energy Capacity (kWh)	kWhs to hundreds of kWhs for a single unit, scalable
CAPEX per kWh of Energy [EUR/kWh]	1350**
OPEX per kWh of Energy [EUR/kW/year]	0.7** (365 cycle/year)

* in case of a flywheel we use specific energy the amount of energy a flywheel can store per unit of mass of the rotating mass itself. Tripling the rotation speed means 9 times of energy due to the formula of kinetic energy.

** [data provided by Amber Kinetics](#)

5.1 Flywheel ES introduction

Flywheel energy storage systems (FESS) offer an interesting and efficient method of storing energy by utilizing the kinetic energy of a rotating mass. The basic principle involves accelerating a flywheel to a very high speed and maintaining the energy in the system as rotational energy. When energy is needed, the flywheel's rotational energy is converted back into electrical energy through a generator.

Flywheel energy storage systems are composed of a rotating mass, or rotor, which is spun at very high speeds. The energy is stored as kinetic energy in the spinning rotor, and this energy can be extracted as needed by slowing down the rotor and converting its rotational energy into electrical energy.

Physics

Formula for Kinetic Energy: Kinetic energy (in joules) stored in a rotating flywheel can be calculated using the following formula:

$$KE = \frac{1}{2} I \omega^2$$

where:

- **KE** represents the **kinetic energy** of the flywheel (in joules)
- **I** is the moment of **inertia** of the flywheel (in kilogram square meters)
- **ω** is the **angular velocity** of the flywheel (in radians per second) The moment of inertia **I** for a solid cylindrical flywheel can be expressed as:

$$I = \frac{1}{2} m r^2$$

- **m** is the **mass** of the flywheel (in kilograms)
- **r** is the **radius** of the flywheel (in meters)

Flywheels are characterized by their high power density and ability to provide quick bursts of energy. They are commonly used in applications where rapid energy discharge and recharge are required, such as in uninterruptible power supplies (UPS), grid stability, and frequency regulation.

For comparison, to achieve the same energy density with a flywheel as a 1kg lithium-ion battery (assume 300Wh/kg energy density) given an 1 cm thick cylinder made of steel:

Cylinder radius= 6.3678 cm

Inertia of the flywheel = $0.5\text{kg} * r^2 = 0.00202 \text{ kg square meters}$

KE = 300 Wh = 1,080,000 Joules

$$\omega^2 = KE / I / 2 = 1,065,376,901 \text{ rad}^2/\text{s}^2 \rightarrow \omega = 5,194,835 \text{ rev/s}$$

$$\text{RPM} = 311\,690$$

So the flywheel with the same mass has to reach 311,690 RPM for the same energy density, while the fastest spinning object known in the Universe (outside the world of nanoparticles) is the PSR J1748–2446ad pulsar, at 716 Hz (times per second), or 42,960 revolutions per minute.

This RPM means a 67,787,690.5 N centrifugal force which equals a stress (σ) of 33.84 GPa, while the tensile strength of steel ranges from 400 – 1200 MPa.

Given these calculations, the stress exerted on the flywheel made of steel would indeed exceed its tensile strength, making it impractical with current materials. However, modern flywheels use carbon fibers with much higher tensile strength, enabling higher rotational speeds and more competitive energy densities compared to lithium-ion batteries.

It's worth noting from the Kinetic Energy formula that increasing the angular velocity (ω) has a quadratic effect on the flywheel's stored energy, while increasing the mass only increases it linearly.

Flywheel energy storage systems act as mechanical batteries, storing electrical energy as kinetic energy in a rotating mass. When electricity is supplied to the system, an electric motor accelerates the flywheel to high speeds. The flywheel, typically made of lightweight and strong materials like carbon fiber, spins in a near-frictionless environment, often a vacuum or low-pressure chamber, to minimize energy losses. This stored kinetic energy can be maintained for extended periods. When electricity is needed, the process reverses: the spinning flywheel drives an electric generator, converting the kinetic energy back into electrical energy, which can then be fed into the power grid or used to power devices. This ability to rapidly absorb and release energy makes flywheels suitable for various applications, from stabilizing power grids and providing backup power to enhancing the performance of electric vehicles.

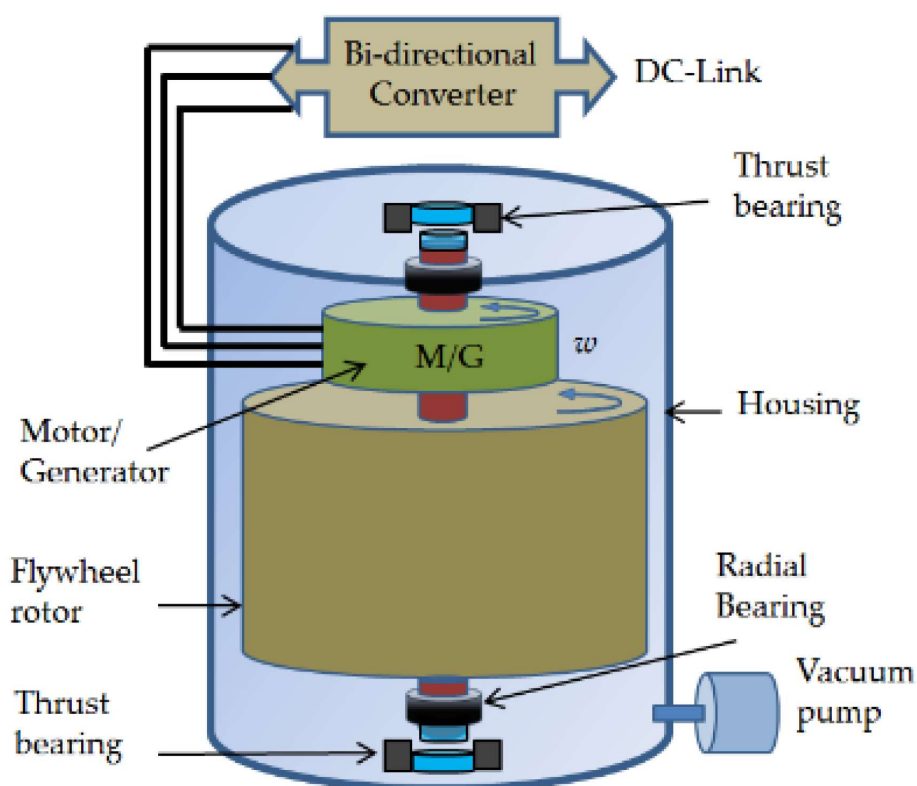


Figure 5.1 Structure and components of a flywheel¹¹²

The Motor-Generator (MG) and Converter

In principle, any power rating of MG can be attached to a given flywheel rotor according to the needs of the application in terms of its charge-discharge duration. High efficiency is always desirable, as is low electromagnetic drag during standby, particularly for applications with longer idling periods. The MG must be structurally capable of operating to maximum design speed, transfer power efficiently, and have minimum standby loss torque. The MG is almost certainly classified as high speed, operating in the 10s of thousands rpm unless the flywheel is particularly large or of low energy density. The MG must be brushless, with AC current being generated by the inverter for motoring, and then AC current is converted back to DC in generator mode. In most cases, the MG is connected directly to the flywheel rotor and operates in vacuum, which makes rotor cooling a challenge.¹¹³

Permanent magnet synchronous motors tend to be the most commonly used electrical machines on flywheel energy storage systems because of their 95.5% efficiency, high power density, and low intrinsic losses. Beyond the motor-generator limits, the maximum speed limit at which the flywheel rotor can operate is also determined by the tensile strength of the material it's made from. As the rotor RPM increases, and hoop stresses within the rotor exceed the tensile strength limits of the material, the rotor will begin to break apart. The cast iron flywheels used

on early steam engines were far too weak for high RPM use. Better-performing alloys made of titanium, magnesium, aluminum, and steel were developed, offering up to 20 times more tensile strength. Composites such as glass fiber and carbon fiber-reinforced polymers pushed flywheel tensile strength even further, easily doubling the capabilities of high-performance metals, though at greater cost.¹¹⁴

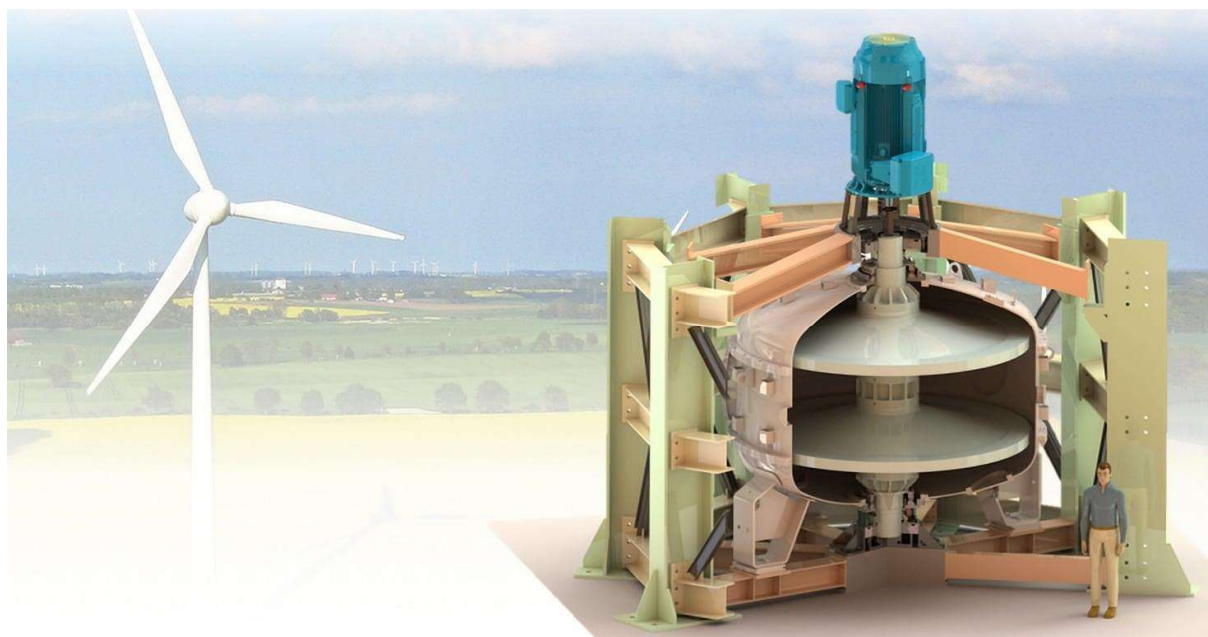


Figure 5.2 The comparison with a human shows in this graphic the size of the memory and the rotating disks. Image rights: Endowed Professorship for Construction Machinery

History

Flywheel energy storage systems have a rich history that dates back to ancient civilizations, where they were initially used for practical mechanical purposes rather than energy storage. The principle behind flywheels—storing energy in the form of rotational kinetic energy—has been understood and utilized for centuries, evolving significantly over time.

Early Uses and Developments

The concept of flywheel energy storage was one of man's first forms of storing mechanical energy. It can be traced back to the potter's wheel, one of the earliest and most enduring applications of flywheels, dating back to ancient Mesopotamia around 2000 BCE. These early flywheels were simple discs that stored kinetic energy, helping to maintain a consistent rotational speed for shaping pottery. Another early application was in the spindle wheels used in textile manufacturing, which relied on the inertia of the flywheel to maintain a steady spinning motion. The energy storage characteristics of a flywheel provided a relatively smooth, even source of rotation from the irregular force applied to it. These spinning wheels from the Middle Ages would eventually evolve in the 18th century.

Industrial Revolution

The Industrial Revolution marked a significant period of innovation and application for flywheels. During the 18th and 19th centuries, flywheels became integral components in steam engines and other machinery. The word “flywheel” came across during the industrial revolution in 1784. In factories, flywheels function as energy accumulators and are also used on steam engines and boats. They were used to smooth out the fluctuations in torque and speed, ensuring more consistent and reliable operation of mechanical systems. James Watt, a prominent figure of the Industrial Revolution, incorporated flywheels into his steam engines to regulate their speed and improve efficiency.

20th Century: The Birth of Flywheel Energy Storage

The potential of flywheels for energy storage began to be explored more thoroughly in the 20th century. In the 1950s and 1960s, research into flywheel energy storage gained momentum, driven by the need for efficient and reliable energy storage solutions for various applications, including aerospace and industrial machinery. Developed by the Swiss company Oerlikon in the fifties, gyroscopes were used for approximately 7 years at Yvernon and Grandson in Switzerland, Léopoldville in Belgian Congo, and in Gand in Belgium. The technology uses an electric engine powered by a large flywheel, weighing 1500kg (one flywheel). Once the flywheel is launched, its kinetic energy is converted into electric energy and supplied to the propulsion engine. During passengers' ascent and descent, the flywheel is reloaded, then put back into rotation. This system could reach a speed of 50-60 km per hour for an autonomy of about 6km.¹¹⁵ The development of high-strength materials and advances in bearings technology allowed for flywheels that could spin at higher speeds and store more energy.

Modern Innovations in Flywheel Storage

Recent advancements in flywheel technology have led to the development of more efficient and durable systems. For example, modern flywheels often utilize advanced materials such as carbon fiber to reduce weight and increase rotational speed, thereby enhancing energy storage capacity.

Beacon Power: This company has developed flywheel energy storage systems for grid stabilization and frequency regulation. Their flywheels can store energy and release it quickly to help balance supply and demand on the electrical grid.

Temporal Power: Based in Canada, Temporal Power has developed high-performance flywheel systems that offer rapid response times and high efficiency, making them ideal for grid applications and renewable energy integration.

Amber Kinetics: This company has developed flywheels that can store energy for longer durations, up to several hours, which makes them suitable for a wider range of applications,

including renewable energy storage. The Amber Kinetics flywheel is the first commercialized four-hour discharge, long-duration FESS solution powered by advanced technology that stores 32 kWh of energy in a two-ton steel rotor. According to the company, individual flywheels can be scaled up to tens or even hundreds of megawatts.

The **QuinteQ** flywheel relies on an ultra-fast, lightweight carbon rotor that is 100 % magnetically levitated. They use carbon fiber rotors can reach speeds of 22.500 RPM. To ensure the best efficiency in the market, the design uses superconductive crystals to make our flywheel completely frictionless. These unique magnets are also used for bullet trains and hyperloop designs. This superconductive magnetic field allows to create the only fully magnetically levitated flywheel in the world with a passive stability bearing. This creates a high roundtrip efficiency (>98%) with the lowest stand-by energy losses in the market (<0.1% per hour). The flywheel is held in a special safety vessel that is developed by the Boeing company, making it safe and applicable for a containerized solution.

Researchers from [Aarhus University](#), [Danish Technological Institute](#) and the several Danish companies have joined forces in order to optimise and advance this technology in the **project MagFly**. In the MagFly project, the existing technology will be improved so that the narrow cylinder is kept in the air by new nanomagnets, where all dimensions – from the atomic structures and up to millimeter scale – will be controlled with huge precision. By improving these aspects, the flywheels will be designed in a way that can store energy for up to 24 hours.¹¹⁶

The **NASA** "Envisioned Future Priorities" document outlines several applications for flywheel energy storage systems (FESS) to support future lunar and Martian missions. These applications focus on providing reliable and efficient energy storage solutions in challenging environments, where traditional batteries and other energy storage technologies might fall short. NASA is exploring the use of flywheel energy storage systems for both lunar and Mars surface operations. On the Moon, flywheels would provide long-duration, reliable power for industrial-scale activities like resource extraction, even during extended periods of darkness. On Mars, they could offer robust energy storage for human habitats and exploration, ensuring a consistent power supply despite the challenging environmental conditions. The high cycle life, rapid charge/discharge capability, and resilience to extreme temperatures make flywheels a promising energy storage solution for both lunar and Martian endeavors.¹¹⁷

FES systems are also used in physics laboratories and fusion experiments, where short bursts of high power are needed. For example, the **Joint European Torus** plasma physics experiment uses two large flywheels with a mass of 775 tons to deliver up to 400 megawatts of power in seconds.

An interesting innovation of Flywheel Energy Storage Systems (FESS) is the use of **concrete**¹¹⁸. Traditional flywheels are typically made of steel or carbon fiber, but concrete offers a low-cost

alternative for energy storage, reducing costs by a factor of ten. By compressing the concrete with a surrounding material to counteract its poor tensile strength, it can be used to store kinetic energy efficiently. These concrete flywheels can spin at high speeds, storing excess solar energy during the day and releasing it at night, addressing the intermittence problem of renewable energy. This development offers a sustainable and cost-effective solution for energy storage, making renewable sources more viable without the need for expensive batteries.

5.1.1 Main branches of FESS

Classification of Flywheel Energy Storage Technologies

Flywheel energy storage systems vary significantly in design, materials, and application, catering to diverse energy storage needs. A comprehensive understanding of these variations is crucial for evaluating their suitability for different scenarios. This section presents a classification of flywheel technologies based on their construction, bearing technology, operating conditions, rotational speed, and power output.

1. Flywheel Materials¹¹⁹

Flywheels are a critical component of Flywheel Energy Storage Systems (FESS), responsible for storing kinetic energy. The materials used in constructing flywheels significantly affect their energy storage capabilities, mechanical properties, cost, and suitability for different applications. Modern flywheels are typically constructed using two types of materials: **metallic materials** (predominantly high-strength steel) and **composite materials** (such as carbon fibre). Both categories offer distinct advantages and challenges.

- **Composite Flywheels:** Composite materials, particularly carbon fibre, are widely used in modern flywheel systems due to their high specific energy (energy per unit mass). The key advantage of composite flywheels is their high tensile strength combined with low density, allowing them to achieve higher rotational speeds without significant material stress. This results in a higher energy storage capacity compared to steel flywheels.

However, composite materials are anisotropic, meaning they have different strengths in different directions. While they exhibit excellent tensile strength along the fibre direction, they are weaker in the radial direction, which can limit their overall performance. To mitigate this, multiple layers or rims of composite materials are often shrink-fitted to reduce radial stress and increase durability.

The manufacturing process for composite flywheels is more complex and costly compared to metallic counterparts. Despite this, composite flywheels remain a preferred choice for high-performance applications, such as those requiring rapid charge and discharge cycles or lightweight designs in aerospace and automotive sectors.

- **Steel Flywheels:** Historically, steel flywheels were regarded as low-speed, less efficient options compared to composite ones. However, recent developments in high-strength steel have revived interest in metallic flywheels, particularly for ground-based and large-scale applications. Steel flywheels are typically less expensive to manufacture and more recyclable, making them an attractive option for applications where cost-effectiveness and system robustness are critical.

Steel flywheels, while heavier, provide high energy density (energy per unit volume) due to the high density of steel itself. This makes them suitable for stationary systems where space is a greater constraint than weight. Furthermore, steel flywheels benefit from a well-understood material behaviour, with more readily available data on fatigue life and failure modes, making them a reliable choice for long-term use.

In terms of energy storage efficiency, steel flywheels operate at lower speeds compared to composite ones but offer enhanced durability and robustness. They are also easier to manufacture in large quantities, leading to lower production costs.

Choosing the Right Material

The choice of material for a flywheel depends on the specific application requirements. For mobile or high-speed applications, such as electric vehicles or aerospace, composite materials are favoured due to their higher energy-to-weight ratios. Conversely, for stationary applications like grid-scale energy storage, where cost and recyclability are important, steel flywheels may offer a more practical solution.

2. Rotor Bearing Technology¹²⁰

The bearing technology in a flywheel energy storage system is crucial for its efficiency, lifespan, and overall performance. The choice of bearing type significantly influences these factors and depends on the specific application requirements.

- **Permanent Magnet Bearings (PMBs):** PMBs utilize the force of permanent magnets to levitate the flywheel rotor, eliminating physical contact and friction. This results in minimal energy loss and wear, leading to high efficiency and a long lifespan. PMBs are often favored in high-performance flywheel systems, particularly for grid-scale energy storage, due to their low losses and cost-effectiveness. However, they cannot sufficiently dampen movement on all axes and are typically used in conjunction with other bearing types.
- **Active Magnetic Bearings (AMBs):** AMBs employ electromagnets and a feedback control system to actively adjust the magnetic field and maintain the rotor's position. This active control allows for precise rotor positioning and vibration damping, enhancing the system's stability. AMBs are well-suited for applications requiring high speeds and heavy

loads, such as in large-scale industrial FESS. However, they require a complex control system and external power, which can increase costs and complexity.

- **Superconducting Magnetic Bearings (SMBs):** SMBs utilize superconducting materials to generate a strong and stable magnetic field for levitation. They offer the lowest friction and energy loss among all bearing types, making them ideal for high-speed applications where efficiency is paramount. SMBs have demonstrated exceptional performance in flywheel systems, particularly in research and development projects [80]. However, they necessitate cryogenic cooling to maintain superconductivity, adding complexity and cost to the system.

The choice of bearing technology depends on various factors, including the desired speed and power output of the flywheel, the required efficiency and lifespan, and overall system cost considerations. While permanent magnet bearings offer superior performance in many aspects, their higher cost and complexity might not be suitable for all applications.

3. Rotational Speed ^{121 122}

The rotational speed of a flywheel significantly influences its energy storage capacity, power output, and application suitability. Flywheel systems are broadly classified into two categories based on their speed: low-speed and high-speed.

- **Low-Speed Flywheels (<10,000 RPM):** Low-speed flywheels are typically larger and heavier, often constructed with steel or other high-density metals. They rotate at speeds below 10,000 revolutions per minute (RPM) and generally utilize mechanical bearings due to the relatively low friction and wear at these speeds. These flywheels are primarily employed in industrial settings where robustness and long life are paramount. They often serve as **uninterruptible power supplies (UPS) for critical equipment**, ensuring continuous operation during power outages. Their lower energy density and slower response times make them less suitable for grid-scale energy storage applications requiring rapid power delivery.
- **High-Speed Flywheels (>10,000 RPM):** High-speed flywheels are designed to spin at much higher speeds, typically exceeding 10,000 RPM and often reaching 60,000 RPM or more. They utilize advanced composite materials like carbon fiber for their rotors, allowing for a higher strength-to-weight ratio and greater energy storage capacity. To minimize friction at these high speeds, magnetic bearings are often employed, along with vacuum chambers to reduce air resistance. The high energy density and fast response times of high-speed flywheels make them well-suited for grid-scale energy storage applications, including **Frequency Regulation** (Rapidly injecting or absorbing power to stabilize grid frequency), **Peak Shaving** (Storing excess energy during low-demand periods and releasing it during peak demand to reduce strain on the grid), **Renewable**

Energy Integration (Smoothing out the variability of renewable energy sources like wind and solar).

Challenges: The higher rotational speeds of these flywheels demand advanced engineering and materials, leading to increased complexity and costs compared to low-speed systems.

Choosing the Right Speed:

The choice between low-speed and high-speed FESS depends on the specific requirements of the application:

Low-speed flywheels are ideal for situations where robustness, cost-effectiveness, and long-term reliability are prioritised over rapid energy delivery. Applications include industrial power backups and other stationary systems where energy density is less critical.

High-speed flywheels, on the other hand, are designed for high-performance applications requiring rapid energy storage and discharge, such as grid-level energy smoothing, electric vehicle propulsion, and renewable energy integration. While more expensive, they provide greater energy efficiency and faster response times.

5.2 Main applications of FESS

Flywheel Energy Storage Use Cases

Flywheel Energy Storage systems are versatile, finding application across various sectors due to their unique ability to rapidly deliver and absorb energy. **However, the Critical Review of Flywheel Energy Storage System** study¹²² focuses on transport and industry applications, their role in ensuring grid stability, supporting renewable energy integration, and providing uninterrupted power supply is becoming increasingly crucial.

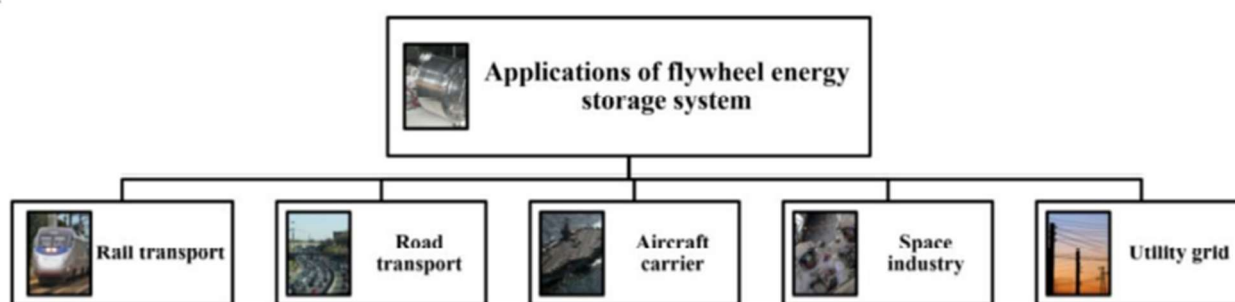


Figure 5.3 Applications of flywheel energy storage system- Source: ¹²¹

Lets focus first on Utility grid applications as these are the focus of our Energy Outlook study.

5.2.1 Grid Stability and Frequency Regulation:

- **Purpose:** Flywheels rapidly respond to fluctuations in grid frequency, caused by imbalances between electricity generation and consumption. By injecting or absorbing power within milliseconds, they maintain the grid's frequency within safe operational limits.¹²¹
- **Ideal Solution:** High-speed flywheels with permanent magnet bearings (PMBs) are best suited for this application due to their fast response times, high power density, and ability to withstand frequent charge/discharge cycles.

5.2.2. Uninterruptible Power Supplies (UPS):

- **Purpose:** Flywheels provide instantaneous backup power during sudden power outages, bridging the gap until primary power sources can be restored or backup generators can start up. This is critical for data centers, hospitals, industrial facilities, and other operations where power interruption can have severe consequences.¹²²
- **Ideal Solution:** Low-speed flywheels with mechanical bearings are often used in UPS systems due to their cost-effectiveness and durability. They can provide reliable backup power for several minutes, which is typically sufficient for most UPS scenarios.

5.2.3 Renewable Energy Integration:

- **Purpose:** Flywheels can improve system stability, thereby aiding the penetration of wind and solar energy into power systems. Their fast response characteristics make them suitable for frequency regulation in applications involving renewable energy sources. Power oscillations due to solar and wind sources are mitigated by storing the energy during sunny or windy periods and supplying it back when demanded. Flywheels can counteract wind oscillations and improve the system frequency. In solar systems, they can be integrated with batteries to improve system output and extend the battery's operational lifetime. Flywheels offer a significant benefit by backing up solar PV, as they can handle the high cycling caused by passing clouds while still providing "ride-through" capability, as long as standby losses are kept low.
- **Ideal Solution:** High-speed composite flywheels with PMBs can be ideal for this application due to their high efficiency, rapid response times, and ability to handle frequent cycling.

5.3.4 Additional Use Cases:

Power Quality Improvement

Flywheels can mitigate voltage sags and swells, improving power quality for sensitive equipment. (Ideal Solution: High-speed flywheels with PMBs).

Transportation

Flywheels can be used in electric and hybrid vehicles for regenerative braking, capturing kinetic energy during deceleration and using it for acceleration, thus improving efficiency. (Ideal Solution: High-speed composite flywheels with PMBs). Flywheels find use in various industries, including manufacturing, oil and gas, and aerospace, for providing stable power, absorbing shock loads, and managing energy fluctuations in machinery.

Industrial Applications

Flywheels can be used in manufacturing processes to provide short bursts of high power or to stabilize power delivery to machinery. (Ideal Solution: Low-speed flywheels with mechanical bearings for cost-effectiveness)

Flywheel energy storage systems represent a versatile technology with a wide range of applications. Their unique characteristics make them ideal for high-power, rapid-response scenarios, supporting grid stability, renewable energy integration, and critical power needs across various sectors. As the technology continues to advance, flywheels are likely to become an even more integral part of the future energy landscape.

5.3 Technological barriers, regulatory framework and scalability

Flywheel energy storage systems (FESS) are increasingly recognized for their potential to support renewable energy integration and grid stability. However, the adoption and scaling of FESS face several challenges, including technological limitations, regulatory hurdles, and issues related to scalability.

Technological Barriers

Material and Design Limitations: The performance of flywheel systems is heavily influenced by the materials used. Traditional flywheels made of steel or other dense metals are durable but offer lower energy densities due to speed limitations. Recent advancements in composite materials, such as carbon fiber, allow for higher rotational speeds and energy densities. However, these materials are expensive and require sophisticated manufacturing processes, which can limit the widespread adoption of high-speed flywheels.

Energy Efficiency and Operational Losses: Flywheels exhibit high round-trip efficiency, often exceeding 90%. However, maintaining this efficiency over long periods necessitates minimizing friction and aerodynamic losses. Technologies such as magnetic bearings and vacuum enclosures are used to reduce these losses, but they add complexity and cost to the system. Ongoing research aims to enhance the durability and efficiency of these components to make FESS more economically viable.

Integration with Renewable Energy Systems: Flywheels are well-suited for applications requiring rapid energy discharge and recharge, such as frequency regulation and renewable

energy integration. However, integrating FESS with existing grid infrastructure poses technical challenges. Advanced power electronics and control systems are essential to manage the high power outputs and fast response times of flywheels. Effective integration strategies are crucial for optimizing the benefits of flywheels in renewable energy systems.

Regulatory Barriers and Scalability of Flywheel Energy Storage in the EU

Flywheel energy storage systems (FESS), as behind-the-meter solutions, are primarily regulated under the existing frameworks for distributed energy resources (DERs) and energy storage systems in the European Union. These frameworks cover various aspects, including:

1. **Grid Connection:** FESS, like other DERs, must adhere to the technical requirements and standards for grid connection outlined in the EU network codes and relevant national regulations. This ensures the safe and stable operation of the grid and prevents any adverse impacts on power quality.
2. **Safety and Performance:** General safety standards and regulations for electrical installations and equipment apply to FESS as well. This includes compliance with electrical safety codes, electromagnetic compatibility (EMC) requirements, and any specific safety guidelines for energy storage systems.
3. **Energy Market Participation:** FESS can participate in energy markets under the existing rules and regulations for energy storage systems. This allows them to provide ancillary services, such as frequency regulation and voltage support, and get compensated for their contribution to grid stability.

Scalability Considerations

Flywheel energy storage systems (FESS) offer a modular and scalable solution for energy storage needs across various applications. The scalability of these systems is achieved through the deployment of standard units that can be connected and controlled to meet increasing energy demands. This chapter explores the mechanisms of scaling up flywheel systems, the economic implications, and the considerations regarding different types of flywheels, including their speed, materials, and bearings.

Modular Design and Scalability

Standard Units and Modular Deployment: Manufacturers of flywheel systems typically produce standard units, each with a specific energy storage capacity. These units are designed to be modular, meaning that additional units can be seamlessly integrated into an existing system to scale up its total energy storage capacity. The modular nature of flywheel systems allows for flexibility in deployment, enabling systems to be tailored to the specific needs of different applications, from small-scale backup power supplies to large grid stabilization projects.

Connection and Control: The integration of multiple flywheel units into a cohesive energy storage system involves both physical and electronic connections. Physically, the flywheels are arranged in parallel or series configurations, depending on the desired performance characteristics. Electronically, a central control system manages the operation of all connected flywheel units. This control system coordinates the charging and discharging cycles, monitors the health and performance of each unit, and ensures balanced load distribution to optimize the overall efficiency and lifespan of the system.

Economic Implications of Scaling

Economies of Scale: The modular nature of FESS allows for incremental capacity expansion, which can be advantageous in terms of cost management. Instead of investing in a large, upfront capital expenditure for a high-capacity system, project developers can start with a smaller system and gradually add more units as needed. This approach can reduce the initial financial burden and allow for better alignment of the investment with the actual energy storage requirements.¹²³

However, the cost per unit of energy stored in a flywheel system does not necessarily decrease linearly with increasing capacity. While some economies of scale can be achieved in manufacturing and installation, other factors, such as the need for more sophisticated control systems and power electronics for larger systems, can offset some of the cost benefits.

5.4 Raw material restrictions

The construction of flywheel energy storage systems relies on various raw materials, each with its unique supply chain dynamics, geopolitical considerations, and environmental footprint. Understanding these factors is crucial for assessing the long-term sustainability and scalability of flywheel technologies.

Steel and other Metals

Steel is a fundamental material used in the construction of lower-speed flywheels, containment vessels, and structural components. While iron ore, the primary raw material for steel, is relatively abundant globally, the steel industry's supply chain is susceptible to disruptions due to its energy-intensive nature and reliance on fossil fuels.

Other metals like aluminum and copper are also used in flywheel systems for rotors, bearings, and electrical components. These metals have more geographically concentrated supply sources, with a handful of countries accounting for a significant portion of global production.

Composite Materials

High-performance flywheels often incorporate advanced composite materials like carbon fiber reinforced polymers (CFRPs) and glass fiber reinforced polymers (GFRPs) for their high strength-

to-weight ratios. The raw materials for these composites, including carbon fibers, resins, and reinforcing fibers, are derived from petroleum products and specialized precursor materials.

The supply chains for these composite materials are relatively complex and concentrated in a few countries, primarily in Asia and Europe. It is notable, that while not the largest producers globally, both Germany and Hungary feature among the top countries for carbon fiber production capacity according to this data. Their presence in the Danube Region could potentially provide a localized source of **carbon fiber materials** for composite flywheel manufacturers operating in that geographic area.¹²⁴

Rare Earth Elements

Certain types of high-performance permanent magnet bearings (PMBs) used in some flywheel designs require rare earth elements (REEs) like [neodymium and dysprosium](#). These critical materials have highly concentrated supply sources, with China currently dominating global production, leading to potential supply risks and geopolitical concerns.

5.5 Cost of FESS systems

While initial capital expenditure (CAPEX) for flywheel systems can be high, primarily due to the cost of advanced materials like carbon fiber and sophisticated bearing systems, the operational expenditure (OPEX) is relatively low. Flywheels have long lifespans, require minimal maintenance, and have high efficiency, which contributes to lower overall lifetime costs. As the number of units increases, the incremental cost of adding each additional unit decreases, making large-scale flywheel systems economically attractive.

Types of Flywheels and Their Impact on Scalability

Speed and Material Considerations:

- **Low-Speed Flywheels:** Typically made from steel, these flywheels are robust and cost-effective but offer lower energy density. They are suitable for applications where space is not a constraint and cost is a primary consideration.
- **High-Speed Flywheels:** Made from advanced composite materials like carbon fiber, these flywheels can achieve much higher energy densities due to their ability to spin at higher speeds. High-speed flywheels are more expensive but are essential for applications requiring compact, high-capacity storage.

Bearing Systems:

- **Mechanical Bearings:** Used in traditional flywheel designs, these bearings are simpler and cheaper but introduce friction losses and require regular maintenance.
- **Magnetic Bearings (Maglev):** These bearings levitate the flywheel using magnetic fields, eliminating physical contact and significantly reducing friction. Magnetic bearings are

more expensive but offer higher efficiency and lower maintenance (levitation eliminates the need for lubrication like greases or oils), making them suitable for high-performance applications.

- **Hybrid Bearings:** Some flywheels use a combination of mechanical and magnetic bearings to balance cost and performance.

According to a technology company, due to high lifespan of flywheels and no degradation during operation, FESS OPEX is very competitive with Li-ion and Flow batteries.

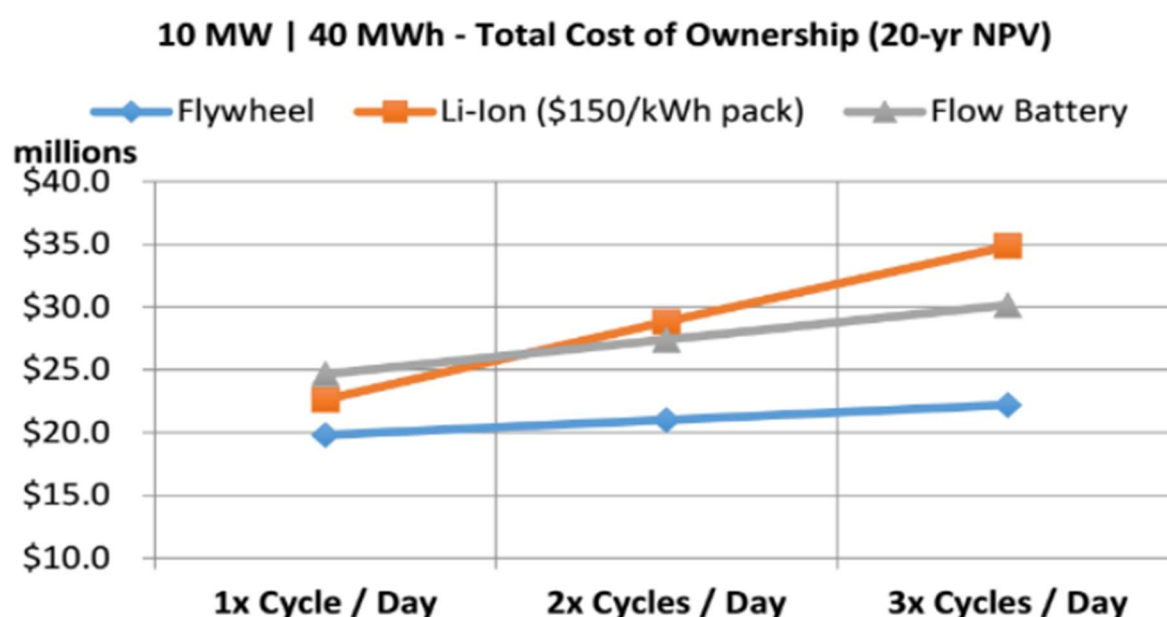


Figure 5.4 Based on projected scaled manufacturing and installation pricing models Amber Kinetics Fresno FESS Proposal¹²⁵

The modular nature of FESS allows for incremental capacity expansion, which can be advantageous in terms of cost management. Instead of investing in a large, upfront capital expenditure for a high-capacity system, project developers can start with a smaller system and gradually add more units as needed. This approach can reduce the initial financial burden and allow for better alignment of the investment with the actual energy storage requirements.

5.6 Environmental impact of FESS

While FESS are generally considered a greener alternative to traditional chemical batteries, a comprehensive assessment is crucial to understand their overall environmental footprint.

The extraction, processing, and manufacturing of raw materials for flywheels can have significant environmental impacts, including greenhouse gas emissions, water and air pollution, and ecosystem degradation. The energy-intensive nature of steel and composite production, as well as the mining of rare earth elements, can contribute to these environmental burdens.

Furthermore, the end-of-life management and recycling of flywheel systems can pose challenges due to the complexity of separating and recovering different materials, particularly composite components.

1. Material Extraction and Processing

- **Steel:** Steel, a common material in flywheel construction, involves energy-intensive extraction and processing, contributing to greenhouse gas emissions and potential habitat disruption. The environmental impact varies depending on the source and production methods of the steel. Moreover, FESS made of steel is fully recyclable.¹⁶³
- **Carbon Fiber Composites:** High-performance flywheels often utilize carbon fiber composites, which offer high strength-to-weight ratios. However, the production of carbon fiber is energy-intensive and involves the use of potentially harmful chemicals. The extraction of precursor materials and the manufacturing process can generate significant emissions and waste.
- **Rare Earth Elements:** Some flywheel designs, particularly those with magnetic bearings, incorporate rare earth magnets (Some advanced flywheel systems use rare earth magnets (like [neodymium magnets](#), which are the strongest permanent magnets known) due to their strong magnetic fields.). The mining and processing of rare earth elements are associated with severe environmental consequences, including deforestation, water pollution, and the release of toxic substances.

2. Manufacturing and Assembly

- **Energy Consumption:** The manufacturing and assembly of flywheel components require energy, contributing to the overall carbon footprint of the system. The energy intensity of the manufacturing process depends on the materials used, the complexity of the design, and the efficiency of the manufacturing facilities.
- **Waste Generation:** Manufacturing processes can generate waste, including scrap materials, chemicals, and packaging. Proper waste management and recycling practices are essential to minimize the environmental impact of FESS production.

3. Operational Phase

- **Minimal Emissions:** During operation, FESS produce minimal emissions, as they do not involve chemical reactions or combustion processes. This is a significant advantage over fossil fuel-based power generation and some battery technologies.

4. End-of-Life and Disposal

- **Recycling Potential:** The recyclability of flywheel components varies depending on the materials used. Steel is readily recyclable, while carbon fiber composites and rare earth

magnets pose greater challenges for recycling due to their complex composition and the difficulty of separating materials.

- **Waste Management:** Proper disposal of flywheel components that cannot be recycled is essential to prevent environmental contamination. This includes managing hazardous materials, such as those used in some magnetic bearings, in accordance with regulations.

5. Life Cycle Assessment (LCA)

A comprehensive life cycle assessment (LCA) is a valuable tool for evaluating the overall environmental impact of FESS. LCA considers all stages of the flywheel's life, from raw material extraction to end-of-life disposal, and quantifies the environmental impacts associated with each stage. This allows for a holistic assessment of the environmental performance of FESS and identification of areas for improvement.

Hybrid energy storage system (HESS)

Hybrid energy storage system (HESS) allows for the integration of different energy storage technologies to create a system that can provide a range of different services in one solution. The combination of different technologies allows the system to optimize the use of the available energy storage resources, and to provide a more reliable and cost-effective energy storage solution. Combining technologies can allow for an extension of the life of the more sensitive energy storage technologies.

Batteries have a high energy density but a low power density, while flywheels have a high power density but a low energy density. HESS can combine the two to balance the energy and power requirements. Doing so, a flywheel system can help increase the lifetime of batteries in the HESS by acting as a shock absorber and deliver the many small cycles, for 'grass' or 'spikes'.

Applications where HESS can be used are for example for balancing grids and microgrids, increasing renewable energy uptake, reducing curtailment, energy trading, utility sites, events.¹²⁶

5.7 Conclusions: advantages, disadvantages, and recommendations for FESS

5.7.1 Pros and cons

Flywheel energy storage systems (FESS) offer a unique set of advantages and disadvantages compared to other energy storage technologies. Understanding these pros and cons is crucial for evaluating their suitability for various applications and making informed decisions about their deployment.

The comparative analysis study *Development and prospect of flywheel energy storage technology: A citespace-based visual analysis*¹⁶⁶ highlights strengths and weaknesses of FESS compared to CAES and PHS:

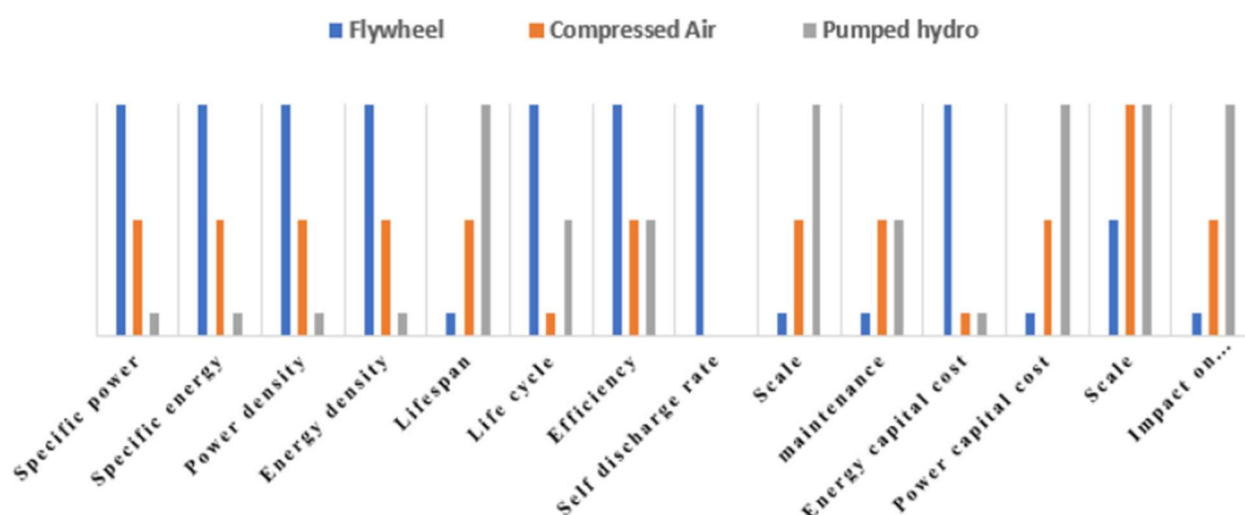


Figure 5.5 Comparison of mechanical energy storage system – [Source](#)

Pros

- **High Specific power and specific energy:** Flywheels have a significantly higher specific power **compared to other mechanical energy storage** systems like Compressed Air and Pumped Hydro (and Gravity Storage). However, these factors are significantly less favorable when compared to chemical storage options.
- **High Cycle Life and Long Lifespan:** Flywheels can endure tens of thousands of charge-discharge cycles without significant degradation, offering a long operational life of over 20 years. This makes them a durable and reliable energy storage solution compared to chemical batteries, which degrade over time and require replacement.
- **Rapid Response and High Power Density:** FESS can respond to changes in power demand within milliseconds, making them ideal for applications requiring fast response times, such as frequency regulation and voltage support. They also have high power density, meaning they can deliver large amounts of power quickly.
- **High Efficiency:** Flywheels have high round-trip efficiency, typically in the range of 90-95%, meaning minimal energy is lost during the storage and retrieval process. This makes them an efficient energy storage solution compared to some other technologies.
- **Low Environmental Impact:** FESS are generally environmentally friendly, producing no emissions during operation, highly recyclable and utilizing non-toxic materials. ^[121, 122] They can contribute to reducing greenhouse gas emissions and promoting a cleaner energy system.

- **Flexible Operation:** Flywheels can be charged and discharged rapidly and frequently without affecting their lifespan or performance. They are also not affected by the depth of discharge, offering flexibility in operation.

Cons:

- **High Initial/power capital cost:** The initial investment cost for FESS can be high (Capital Energy Capacity cost predicted for 2025 is €2145 / kW)¹¹³ due to the specialized materials and precision engineering involved in their construction. This can be a barrier to their widespread adoption, especially for smaller-scale projects. The cost of high-speed flywheels, which utilize advanced materials like carbon fiber composites, can be up to five times higher than that of low-speed flywheels made of steel.
- **Self-Discharge:** Flywheels experience self-discharge due to friction and aerodynamic drag, leading to a gradual loss of stored energy over time. This limits their suitability for long-duration energy storage applications. While operating the flywheel in a vacuum can mitigate these losses, it adds complexity and cost to the system.
- **Limited Energy Density:** Compared to chemical batteries, flywheels have lower energy density, meaning they require more space to store the same amount of energy. This can be a constraint in applications with space limitations.
- **Safety Concerns:** High-speed flywheels can pose safety risks due to the potential for catastrophic failure if not properly designed and maintained. Robust containment structures and safety protocols are essential to mitigate these risks.

Overall, FESS offer a compelling energy storage solution with numerous advantages, including long lifespan, fast response, high efficiency, and low environmental impact. However, their high initial cost, self-discharge, and limited energy density are important factors to consider when evaluating their suitability for specific applications. Ongoing research and development efforts are focused on addressing these challenges and further improving the performance and cost-effectiveness of FESS technology.

5.7.2 Existing systems

Amber Kinetics has 10 functioning flywheel storage installations in the United States, Australia, Japan, Taiwan, Tibet and the Philippines.



Figure 5.6 West Boylston Municipal Lighting Plant 128kW/512kWh flywheel energy system ¹²⁷

Beacon Power operates three flywheel energy storage plants that provide frequency regulation service in three different US markets. There are more than 400 flywheels in commercial operation today helping grid operators safely and efficiently balance power grid supply and demand to ensure reliability. Stephentown, New York is the site of Beacon Power's first 20 MW plant (40 MW overall range) operating with 200 flywheels and provides frequency regulation service.¹²⁸ A similar system is operating in Hazle Township, Pennsylvania.



Figure 5.7 Stephentown flywheel system in New York interconnected at 115kV transmission system

The Max Planck Institute – Flywheel Energy Storage System is a 387,000kW flywheel energy storage project located in Garching, Bavaria, Germany. The rated storage capacity of the project is 770kWh. The facility utilizes three flywheel generator systems for on-site power that is required for high energy fusion experiments.

However, it is notable, that Flywheel systems are out of reach for study visits because of their location or research characteristics.

5.7.3 WICE index

Scoring Flywheels

Flywheel energy storage systems represent a compelling alternative to traditional lithium-ion batteries, offering a unique set of advantages and challenges. To assess their potential to revolutionize the energy storage landscape, we will calculate their "Will it Change Everything Score" based on a weighted combination of key factors. This score will provide a comprehensive evaluation of FESS's disruptive potential, considering not only their technical capabilities but also their environmental impact, scalability, and market viability compared to the current dominant technology, lithium-ion batteries.

1. Energy Density

Flywheels generally have lower energy density compared to lithium-ion batteries.

Score: 30

2. Energy Retention Period

Flywheels have a high self-discharge rate, which means they are not ideal for long-term energy storage. However, this discharge rate is not worse than the baseline value for Li-ion batteries

Score: 50

3. Lifetime and Life Cycles

Flywheels can offer a very high number of cycles with minimal degradation deserving the maximum score.

Score: 100

4. Round-Trip Efficiency (RTE)

Flywheels typically have a round-trip efficiency of about 90-95% which is similar to Li-ion batteries.

Score: 50

5. Technological Maturity (TRL)

Flywheels are relatively mature, having a TRL level of 9, but less so compared to lithium-ion batteries. There are certainly not as many market actors offering flywheel technology than battery manufacturers.

Score: 45

6. Capital Expenditure (CAPEX)

Flywheels have much higher initial costs compared to lithium-ion batteries.

Score: 30

7. Operational Expenditure (OPEX)

Flywheels have lower operational costs due to minimal maintenance.

Score: 80

8. Environmental Impact

Flywheels are environmentally friendly due to fewer toxic materials and superior recyclability. Additionally, their lower risk of accidents reduces the chance of environmental contamination.

Score: 90

9. Scalability

Flywheels are scalable but face limitations in large-scale applications. Overall their scalability parameter is similar to batteries.

Score: 50

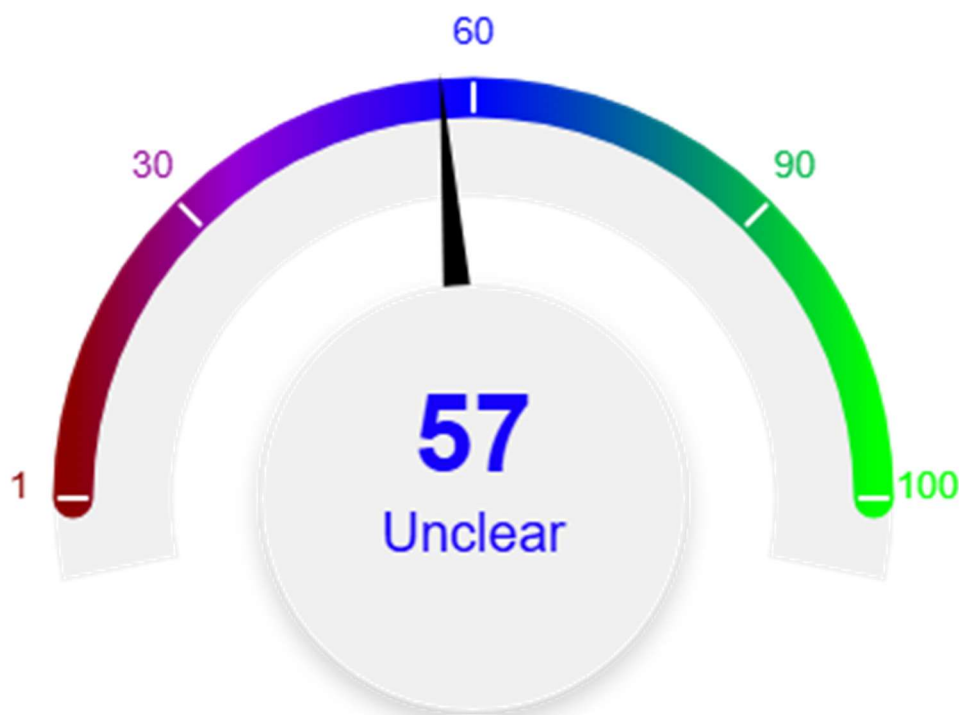
Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	30	3
Energy Retention Period	0.1	50	5
Lifetime and Life Cycles	0.1	100	10
Round-Trip Efficiency (RTE)	0.15	50	7.5
Technological Maturity (TRL)	0.2	45	9
Capital Expenditure (CAPEX)	0.1	30	3
Operational Expenditure (OPEX)	0.1	80	8
Environmental Impact	0.1	90	9
Scalability	0.05	50	2.5
Total	1		57.0

Conclusion

The WICE Score for FESS is **57**. Flywheels offer significant advantages in terms of long lifespan and high cycle durability, making them ideal for applications requiring frequent charge-discharge cycles. Their high round-trip efficiency is comparable to that of lithium-ion batteries. However, flywheels have lower energy density and a high self-discharge rate, making them less suitable for long-term energy storage. Additionally, the initial capital expenditure for flywheels is higher, though their operational costs are lower due to minimal maintenance requirements. Environmentally, flywheels perform well, with fewer toxic materials and easier recyclability, but their scalability is somewhat limited for large-scale grid applications. While they are mature in terms of technological development, flywheels remain less prevalent in the market compared to lithium-ion batteries. As a result, they are best suited for niche applications such as short-term power quality control and frequency regulation.

Impact potential of technology



6. Chemical Energy Storage – Hydrogen (H₂ES)

Summary of Metrics

Parameter	Technology
	Hydrogen Energy Storage
Energy density per unit of volume [Wh/kg]	39405.6 Wh/kg / 3300.0 Wh/m ³ (HHV) ¹²⁹ 33313.9 Wh/kg / 2800.0 Wh/m ³ (LHV) ¹³⁰
Power range [MW]	kWs to 100s of MWs due to modular design
Time of Permanent Energy Storage [hour]	24 hours to years depending on the technology
Life time [years/cycles]	5-10 years for electrolyzers and fuel cells, 10-15 years for storage
Discharge Time [minutes]	from minutes up to hours
RTE (Round-Trip Efficiency) [%]	Around 30 % to 50 % depending on technology
RTE degradation	< 2% / 1000 hours
Technology Maturity / Technological Readiness Level (TRL):	6-8
System size Energy Capacity (kWh)	kWh to hundreds of kWh for a single unit, scalable
System size Power Rating (kW or MW)	800 - 1200 EUR/kW
CAPEX per kWh of Energy [EUR/kWh]	7,8 - 40 EUR/kW/year, depending on technology
OPEX per kWh of Energy [EUR/kW/year]	0,3-2,8 EUR/kW/year

Sources: <https://www.mdpi.com/1996-1073/13/18/4835>¹⁷⁵, <https://doi.org/10.1093/ce/zkac083>

6.1 Introduction – Hydrogen: Production, Storage, Utilization

After discussing mechanical energy storage options in chapters 2-5, we transition to a different storage technology: chemical energy storage. The following three chapters delve into hydrogen,

various battery types, and flow cell energy storage, dedicated to the latter due to its unique characteristics.

Hydrogen as an energy carrier has the potential to revolutionize the shift towards sustainable energy systems. This chapter examines the production, storage, and utilization of hydrogen, emphasizing its importance in reducing emissions. Key production methods include electrolysis, steam methane reforming (SMR), and biomass conversion, each with unique benefits and challenges. Hydrogen storage options such as compressed gas, liquid, and metal hydrides are crucial for its application, each with specific advantages and safety considerations. Hydrogen's use in energy generation, industrial applications, and integration with renewable energy sources showcases its versatility and significant role in future energy systems.

Chemistry - The Basics

Hydrogen is the simplest and most abundant element in the universe. It has the highest energy content per unit mass of any fuel:

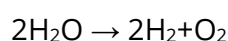
Energy content per unit mass:

141,86 MJ/kg / 39405.6 Wh/kg / 3300.0 Wh/m³ (HHV)

119.93 MJ/kg / 33313.9 Wh/kg / 2800.0 Wh/m³ (LHV)

However, storing hydrogen efficiently is a challenge due to its low density in both gas and liquid forms. Here's where chemistry steps in to offer innovative storage solutions.

In the context of StoreMore, the most relevant method of Hydrogen production is electrolysis. The electrolysis process splits water into hydrogen and oxygen. The balanced chemical equation for electrolysis is:



From this equation, we see that 2 moles of water produce 2 moles of hydrogen gas.

1. Molecular Weights:

- H₂O: 18 g/mol
- H₂: 2 g/mol

2. Water Required for Hydrogen Production:

- Through electrolysis of water, to produce 1 kg of hydrogen, approximately 9 kg of water is needed according to the stoichiometric ratio. Therefore, for 2 kg of hydrogen, one would need approximately 18 kg of water (or 18 liters at room temperature).

Forms of Hydrogen Storage

Compressed Gas:

Hydrogen can be stored as a compressed gas at high pressures (typically 350-700 bar)¹³¹.

Energy Density = (Energy content per unit mass * Density) / Volume

For hydrogen at 700 bar, the density is approximately 42 kg/m³, leading to an energy density of:

Energy Density $\approx 120 \times 42 = 5040 \text{ MJ / m}^3 = 1,400 \text{ kWh / m}^3$

Liquid Hydrogen:

Storing hydrogen as a liquid requires cooling it to cryogenic temperatures (-253°C).

Energy Density = 8.5 MJ/l = 2.361111 kWh/l

Solid-State Storage:

Hydrogen can be stored in solid materials like metal hydrides or chemical compounds (e.g., Magnesium Hydride, MgH₂), where the energy content of 1 kg of MgH₂ is approximately 2849.25 kJ or 0.791667 kWh

For comparison, a 1 kg lithium-ion battery with an energy density of 300 Wh/kg stores 300 Wh of energy, making it compact but relatively heavy. In contrast, to store the same 300 Wh of energy using hydrogen, which has an energy density of approximately 33,000 Wh/kg, only about 0.009 kg (or 9 grams) of hydrogen is needed. However, hydrogen gas requires significant volume: 9 grams of hydrogen at 1 bar occupy approximately 101.24 litres. When compressed at 700 bar, this 9 grams would occupy about 0.21 litres. Therefore, while lithium-ion batteries are denser and more practical for everyday devices, hydrogen offers superior weight efficiency but presents storage and handling challenges due to its low volumetric density.

History of H₂ES

In the late 17th century, around 1670, Irish alchemist Robert Boyle made a crucial observation. He noted that when iron interacted with dilute acids, it produced flammable gases. This discovery laid the groundwork for future research.

Nearly a century passed before English scientist Henry Cavendish, in 1766, identified this substance as a distinct chemical element. Cavendish delved deep into the element's chemical characteristics, proposing that the "combustible air" originated from the metals themselves rather than the acids. He dubbed this element "metal phlogiston," drawing on the contemporary belief in a fire-like element called "phlogiston."

When combined with oxygen, this flammable gas produced a water-like substance, a phenomenon previously demonstrated by British chemist Joseph Priestley. It was French chemist Antoine Lavoisier who later gave the element its current name. Lavoisier coined the term "hydrogen" (represented as H on the periodic table) by combining Greek words meaning "water" and "I bring forth," essentially calling it a "water maker."

In 1800, a significant scientific breakthrough occurred when British researchers William Nicholson and Sir Anthony Carlisle discovered electrolysis. This process allowed for the production of pure hydrogen and oxygen through the application of electricity to water.

Approximately four decades later, in 1839, German-Swiss scientist Christian Friedrich Schönbein identified the fuel cell effect during his experiments with platinum, hydrogen, and oxygen. This process essentially reversed electrolysis, combining hydrogen and oxygen to generate water and electricity.

Shortly after Schönbein's discovery, British scientist Sir William Robert Grove applied these findings to create the "gas voltaic battery." Grove's device employed two platinum sulfate electrodes, with one end immersed in hydrogen gas and the other sealed in a hydrogen container placed within an oxygen container. This practical application of the fuel cell principle led to Grove being recognized as the "Father of the Fuel Cell."

The domestic applications of hydrogen have undergone significant transformation since its initial household uses. During the 1800s, the predominant residential use was for illumination, where hydrogen produced from iron filings and sulfuric acid reactions provided gas lighting. This application became obsolete with the advent of electrical lighting systems.

The early 20th century saw hydrogen being utilized in residential heating systems, though this was later superseded by natural gas. While hydrogen's residential applications declined, it found crucial applications in aerospace, particularly as rocket fuel during the Space Age, and in industrial processes for manufacturing chemicals like ammonia and methanol.

In contemporary times, hydrogen has experienced a residential revival through fuel cell technology. These systems generate electricity through hydrogen-oxygen reactions, producing only water and heat as byproducts, offering a potential pathway to zero-emission home power generation. Despite interest in expanding hydrogen's residential uses to include heating and cooking, widespread adoption faces challenges related to production costs, storage complexities, and safety considerations regarding its high flammability.¹³²

Current Research Trends

Current research in hydrogen technology is driven by the need to address the challenges of cost, efficiency, and scalability. One significant trend is the development of integrated systems that combine renewable energy sources with hydrogen production and storage technologies. For instance, the integration of photovoltaic (PV) and wind power with electrolyzers for hydrogen production is being explored to create more sustainable and cost-effective energy systems (Liu et al., 2020).¹³³

Another research trend is the focus on improving the materials used in hydrogen storage and fuel cells. Advanced materials such as carbon nanotubes, graphene, and novel metal alloys are

being studied for their potential to enhance the performance and safety of hydrogen storage systems. Additionally, the development of new catalysts and membrane materials for fuel cells aims to reduce costs and improve efficiency (Chanchetti et al., 2016).¹³⁴

Hydrogen production methods are also evolving, with significant research into biomass gasification and waste-to-hydrogen technologies, which offer sustainable and cost-effective alternatives to traditional fossil fuel-based methods. These technologies can leverage existing waste streams and biomass resources to produce hydrogen with a lower environmental footprint (Holladay et al., 2009).¹³⁵

Future Advancements

Technological advancements in hydrogen production, storage, and utilization are crucial for the widespread adoption of hydrogen as a sustainable energy carrier. In hydrogen production, future advancements are expected to focus on improving the efficiency and cost-effectiveness of electrolysis, particularly through the development of advanced catalysts and membrane technologies. Photocatalytic water splitting and high-temperature thermochemical cycles, which use solar energy to produce hydrogen, are also areas of active research that promise to reduce costs and improve efficiency (Liu et al., 2020).¹³³

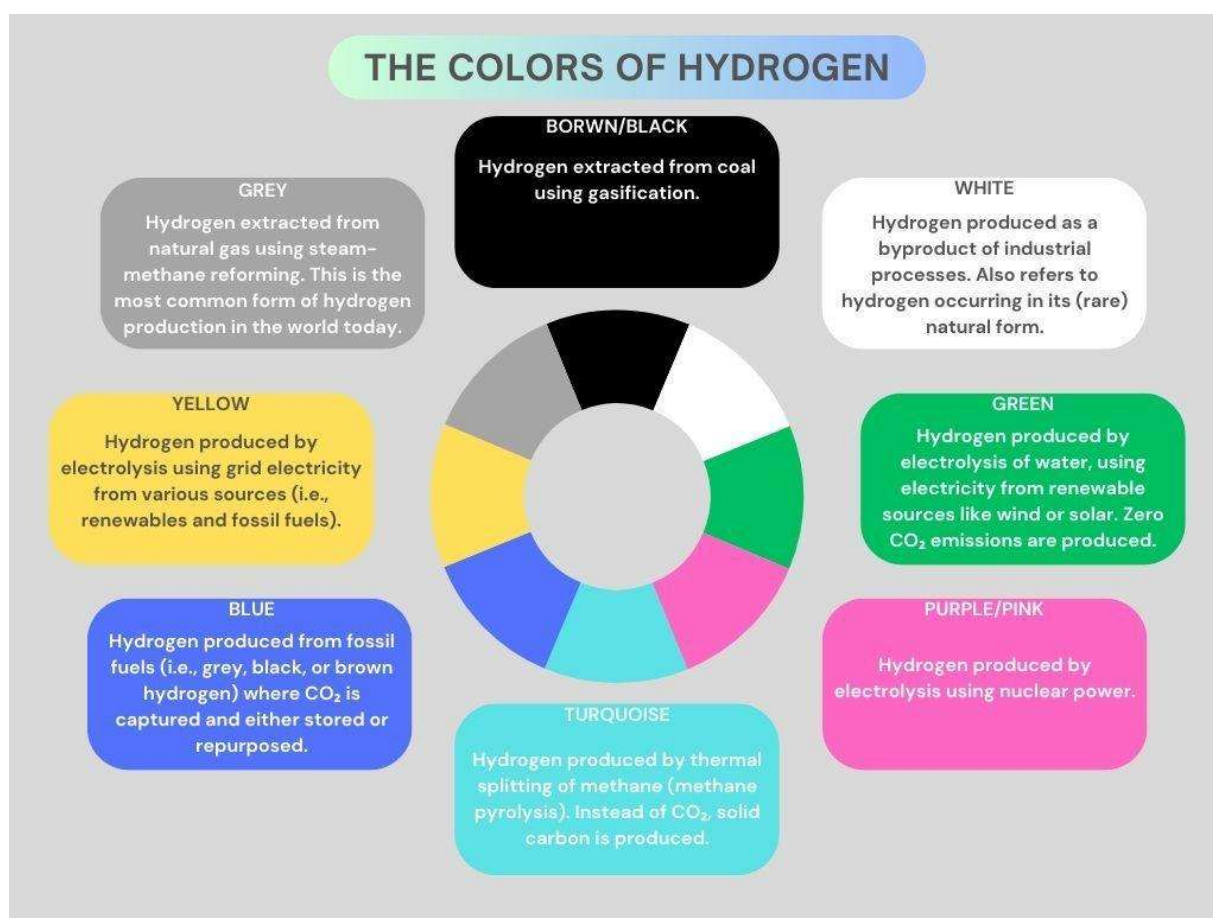
For hydrogen storage, innovations are directed towards developing materials with higher hydrogen storage capacities and better safety profiles. Metal-organic frameworks (MOFs) and chemical hydrogen storage materials like ammonia borane and liquid organic hydrogen carriers (LOHCs) are being investigated for their potential to store hydrogen at lower pressures and ambient temperatures. These advancements could make hydrogen storage more practical and economical (Preuster et al., 2017).¹³⁶

In terms of utilization, advancements in fuel cell technology, particularly in polymer electrolyte membrane fuel cells (PEMFCs), are expected to improve their efficiency, durability, and cost. Research is also focusing on high-temperature fuel cells, such as solid oxide fuel cells (SOFCs), which offer higher efficiency and can utilize a broader range of fuels, including hydrogen (Davoodabadi et al., 2021).¹³⁷

6.1.1 Production of Hydrogen

Hydrogen can either be found in natural form (white hydrogen) or produced through multiple primary methods. These methods are gasification, electrolysis, pyrolysis, steam methane reforming, and biomass conversion. Each method has unique processes, advantages, disadvantages, and efficiency yields.

The colors of Hydrogen is a vivid representation of the concept



Electrolysis

Electrolysis involves splitting water (H₂O) into hydrogen (H₂) and oxygen (O₂) using an electric current. This method can be powered by renewable energy sources, making it a clean and sustainable option for hydrogen production. „Water electrolysis accounts for just 0.1% of today's global hydrogen production, but installed capacity and the number of announced projects have been growing rapidly in recent years. About 600 projects with a combined capacity of more than 160 GW have been announced since the GHR 2022. By the end of 2022, the global installed water electrolyser capacity for hydrogen production reached almost 700 MW, a 20% increase compared to the previous year.” (IEA Global Hydrogen Review 2023)¹³⁸

Advantages: Produces high-purity hydrogen, can use renewable energy, and has low environmental impact when powered by green electricity (Kato et al., 2005).¹³⁹

Disadvantages: High operational costs and energy requirements, especially if not using low-cost renewable energy sources (Alzahrani & Dincer, 2021).¹⁴⁰

Efficiency and Yield: Generally has an energy efficiency of about 66%, with significant potential for improvement as technology advances (Yao et al., 2017).¹⁴¹



Figure 6.2 Modular electrolyzer from Enapter – source: [pv magazine](https://www.pv-magazine.com)

Steam Methane Reforming (SMR)

SMR is the most common method for hydrogen production, involving the reaction of methane (CH_4) with steam (H_2O) at high temperatures to produce hydrogen and carbon monoxide (CO), which is then converted to CO_2 and more hydrogen in a water-gas shift reaction.

Advantages: Well-established technology with high hydrogen yield and relatively low production costs compared to other methods (Frieden & Leker 2024).¹⁴²

Disadvantages: Produces significant CO_2 emissions, contributing to greenhouse gas effects unless coupled with carbon capture and storage (CCS) (Fan & Xiao, 2021).¹⁴³

Efficiency and Yield: SMR has an energy efficiency of about 70-80% and a high hydrogen yield, making it the most efficient current method for large-scale hydrogen production (Balasubramanian et al., 1999).¹⁴⁴

Biomass Conversion

Biomass conversion involves gasifying biomass materials to produce a hydrogen-rich gas mixture, which can then be processed to extract pure hydrogen. This method includes processes like pyrolysis, gasification, and steam reforming of biomass.

Advantages: Utilizes renewable resources, has the potential for carbon-neutral production, and can use a wide variety of biomass feedstocks (Demirbaş, 2016).¹⁴⁵

Disadvantages: Lower hydrogen yield compared to SMR, higher complexity in processing, and variability in feedstock quality and availability (Hulteberg & Karlsson, 2009).¹⁴⁶

Efficiency and Yield: Biomass gasification has an energy efficiency of about 38.9%, with potential improvements as technology develops (Yao et al., 2017).¹⁴¹

6.1.2 Storage of Hydrogen

Hydrogen, as a promising energy carrier, necessitates efficient and safe storage solutions, especially for mobile applications. Several technologies have been developed, each with its own advantages and drawbacks.

Compressed Hydrogen Gas

This is the most established method, where hydrogen is stored under high pressure (350-700 bar) in robust tanks. This method offers fast refueling times and simple infrastructure, making it the current industry standard for fuel cell electric vehicles like the Toyota Mirai. However, the high pressure requires heavy and expensive tanks, limiting the gravimetric energy density.

Pros:

- Mature technology with established infrastructure.
- Fast refueling times comparable to gasoline or diesel vehicles.
- Simple and well-understood storage mechanism.

Cons:

- High-pressure storage requires heavy and expensive tanks.
- Lower gravimetric energy density compared to liquid fuels.
- Safety concerns associated with high-pressure gas storage.

Safety Considerations:

Compressed hydrogen storage involves high pressures, typically 350-700 bar, which necessitates robust tank design and stringent safety protocols. Potential risks include leaks, ruptures, and the rapid release of hydrogen gas, which is explosive. Safety measures such as pressure relief valves, leak detection systems, and proper handling procedures are essential to mitigate these risks.

Liquid Hydrogen

Hydrogen is liquefied at extremely low temperatures (-253 °C) for storage. While this method offers higher volumetric energy density than compressed gas, it suffers from significant boil-off losses due to heat transfer. The energy-intensive liquefaction process and the need for heavily insulated tanks also pose challenges for widespread adoption.

Pros:

- Higher volumetric energy density than compressed hydrogen gas.
- Suitable for applications requiring large amounts of hydrogen.

Cons:

- Significant boil-off losses due to heat transfer.
- Energy-intensive liquefaction process.
- Requires heavily insulated and costly storage tanks.

Safety Considerations:

Liquid hydrogen storage involves extremely low temperatures (-253 °C), posing risks of frostbite and cold burns. Additionally, the boil-off of hydrogen gas can create flammable atmospheres, requiring proper ventilation and leak detection systems. The cryogenic nature of liquid hydrogen also necessitates specialized handling procedures and equipment.

Cryo-Compressed Hydrogen

This hybrid approach combines compression and cooling to store hydrogen at high pressure and low temperature. It aims to mitigate boil-off losses while maintaining a reasonable energy density. However, the technology is still under development and requires specialized infrastructure.

Pros:

- Combines the advantages of compressed and liquid hydrogen storage.
- Aims to reduce boil-off losses compared to liquid hydrogen.

Cons:

- Technology still under development.
- Requires specialized infrastructure for refueling and storage.
- Cost and complexity of tank design.

Safety Considerations:

Cryo-compressed hydrogen storage involves both high pressure and low temperature, combining the safety concerns of both compressed and liquid hydrogen. The design of tanks must address the challenges of maintaining structural integrity under extreme conditions while minimizing heat transfer to prevent boil-off.

Material-Based Storage (Metal Hydrides, MOFs, Carbon Nanostructures)^{147 148}

Various materials, such as metal hydrides, metal-organic frameworks (MOFs), and carbon nanostructures, are being explored for hydrogen storage. These materials can adsorb or absorb hydrogen, offering potential advantages in terms of safety and volumetric density. However, challenges like slow kinetics, high operating temperatures, and complex thermal management systems need to be addressed.

Pros:

- Potential for higher volumetric energy density than compressed gas.

- Safer storage due to lower operating pressures.
- Some materials offer reversible storage through adsorption/absorption.

Cons:

- Slow kinetics for hydrogen uptake and release in some materials.
- High operating temperatures or cryogenic conditions may be required.
- Complex thermal management systems needed for some materials.

Safety Considerations:

The safety of material-based storage depends on the specific material used. Metal hydrides, for example, can be reactive and require careful handling. MOFs and carbon nanostructures are generally considered safer but may still pose risks of dust inhalation or release of adsorbed gases.

Liquid Organic Hydrogen Carriers (LOHCs)

LOHCs are organic compounds that can be hydrogenated and dehydrogenated to store and release hydrogen. They offer the advantage of using existing infrastructure for liquid fuels. However, the energy-intensive hydrogenation/dehydrogenation processes, the need for catalysts, and potential toxicity concerns limit their applicability for mobile applications.

Pros:

- Leverages existing infrastructure for liquid fuels.
- Easier handling and transportation than compressed or liquid hydrogen.

Cons:

- Energy-intensive hydrogenation and dehydrogenation processes.
- Requires catalysts, often based on expensive noble metals.
- Potential toxicity and environmental concerns associated with some LOHCs.

Safety Considerations:

The safety of LOHCs depends on the specific compound used. Some LOHCs may be flammable, toxic, or pose environmental risks. Proper handling, storage, and spill prevention measures are essential. The use of catalysts also raises concerns about their potential environmental impact and the need for safe disposal or recycling.

Chemical Hydrogen Storage

This involves converting hydrogen into other chemical compounds like methane or ammonia, which are easier to store and transport. However, the conversion processes are often energy-intensive and may require specialized infrastructure. Additionally, the use of these compounds as fuels may involve different technologies than pure hydrogen.

Pros:

- Leverages existing infrastructure for natural gas or ammonia.
- Higher volumetric energy density than compressed hydrogen gas.
- Easier handling and transportation than compressed or liquid hydrogen.

Cons:

- Energy-intensive conversion processes (methanation, Haber-Bosch process).
- Round-trip efficiency losses due to conversion steps.
- Requires specialized infrastructure for conversion back to electricity (e.g., SOFCs).
- Safety concerns associated with the storage and handling of methane and ammonia.

Safety Considerations:

Methane is a highly flammable gas, and its storage and transportation require stringent safety measures to prevent leaks and explosions. Ammonia, while not as flammable, is toxic and corrosive, necessitating careful handling and storage to avoid exposure and environmental contamination. Both methane and ammonia can pose risks to human health and the environment if not managed properly.

Storage Methods overview

Method	Gravimetric Energy Density (wt %)	Volumetric Energy Density (MJ/L)	Temperature (K)	Pressure (barg)	Remarks
Compressed	5.7	4.9	293	700	Current industry standard
Liquid	7.5	6.4	20	0	Boil-off constitutes major disadvantage
Cold/cryo compressed	5.4	4.0	40–80	300	Boil-off constitutes major disadvantage
MOF	4.5	7.2	78	20–100	Attractive densities only at very low temperatures.
Carbon nanostructures	2.0	5.0	298	100	Volumetric density based on powder density of 2.1 g/mL and 2.0 wt % storage capacity.
Metal hydrides	7.6	13.2	260–425	20	Requires thermal management system.
Metal borohydrides	14.9–18.5	9.8–17.6	130	105	Low temperature, high pressure thermal management required
Kubas-type	10.5	23.6	293	120	
LOHC	8.5	7	293	0	Highly endo/exothermal requires processing plant and catalyst. Not suitable for mobility
Chemical	15.5	11.5	298	10	Requires SOFC fuel cell.

Figure 6.3 Source: Hydrogen Storage for Mobility: A Review MDPI¹⁴⁹

6.2 Main applications of Hydrogen

Hydrogen, as a versatile energy carrier, finds application across various sectors due to its high energy content and clean combustion properties. This section explores hydrogen's use in energy generation through fuel cells and combustion, its industrial applications, and the benefits and challenges associated with its utilization.

6.2.1 Applications in Energy

Hydrogen, as an energy storage medium, offers a unique blend of benefits and challenges, positioning it as a key player in the renewable energy landscape. Its versatility is evident in the wide range of potential applications, from fuel cells to industrial processes.

A summary graph of H₂ production and transport supply chain

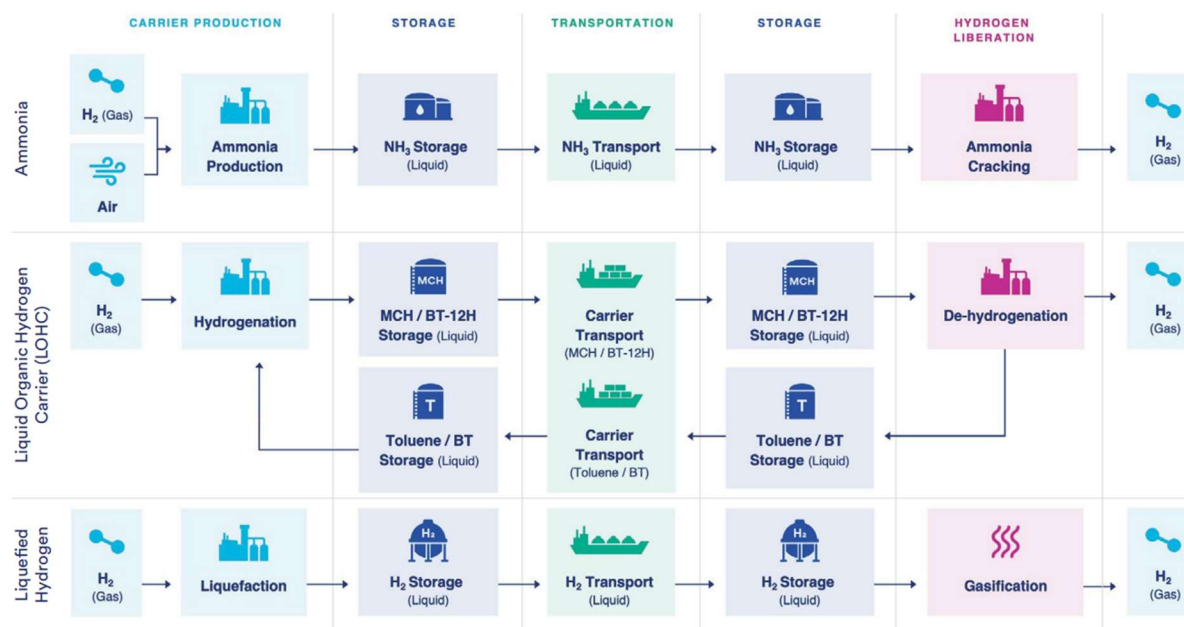


Figure 6.4 Source: [Clean Air Task Force](#)¹⁵⁰

- In the ammonia pathway, hydrogen gas (H₂) is synthesized with air to produce ammonia, which is then stored and transported as a liquid. Upon reaching its destination, ammonia is cracked back into hydrogen gas. However, the production costs of ammonia are substantially elevated due to the requirement of extracting and purifying nitrogen gas from air through the Haber-Bosch process, making this method significantly more expensive than alternative approaches.
- For LOHC, hydrogen is hydrogenated into carriers like methylcyclohexane (MCH) or toluene, stored and transported in liquid form, and dehydrogenated back to hydrogen gas at the usage site.
- In the liquefied hydrogen pathway, hydrogen gas is liquefied, stored, and transported in its liquid form, and then gasified back to hydrogen gas for usage. Each method involves distinct processes for converting hydrogen into a more stable and transportable form, ensuring efficient storage and transportation before conversion back to hydrogen gas for end-use.

H2ES parameters

Main characteristics and suitable applications of different systems according to the Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives study from Hassan et al (2023)¹⁵¹

Storage system	Suitable applications	Gravimetric density	cost	Energy consumption	Response /kinetics	Purification /filter	Gravimetric density	Energy consumption	Response /kinetics	Purification /filter
A : Compressed Gas H₂							L-M	M	FR ⁽¹⁾	NA
Type I	stationary	VL	L	L	FR ⁽¹⁾	NA				
Type II	stationary	L	M	H	FR ⁽¹⁾	NA				
Type III	Industrial and vehicular	M	H	H	FR ⁽¹⁾	NA				
Type IV	- vehicles - industrial purposes (at high pressures)	H	VH	VH	FR ⁽¹⁾	NA				
B : liquid and Cryo-compressed H₂							H	H	FR	NA
L H ₂ systems	aerospace	H	H	VH	FR	NA				
cryo-compressed	vehicles	VH	H	H	FR	NA				
C : Material based H₂ Storage							L-H	L	L	require
MOFs	- stationary - vehicles(near targets)	H ⁽²⁾	M ⁽³⁾	L	MK	require				
Elemental hydrides	- stationary applications - Thermally (CHP)	L	-	L	SK	require				
Intermetallic hydrides	- stationary applications (like nuclear) - Thermally (heating + air conditioning) - MH batteries	VL	-	L	FK	require				
complex hydrides	- stationary applications - Thermally	M	H ⁽³⁾	L	MK	require				
chemical hydrides	- energy/Hydrogen carrier - single fuel use (vehicles) - direct combustion	H	M ⁽³⁾	L	FK	require				

Table symbols : V: very, L : low, M : medium, H : high, F : fast, R : response, K : kinetics, L- M : low to medium.

Figure 6.5: source: <https://doi.org/10.1016/j.rser.2021.111311>

1. Response Time

Hydrogen storage systems exhibit varying response times depending on the specific technology employed. Compressed hydrogen storage systems generally offer rapid response times, typically in the range of seconds to minutes. This makes them suitable for quick-response applications like grid balancing and supporting variable renewable energy sources.

Liquid hydrogen storage systems often have slower response times compared to compressed gas systems. This is due to the need for regasification before use, which can take several minutes to hours depending on the system size and design.

Solid-state storage systems, such as metal hydrides, can have a wide range of response times. Some advanced metal hydride systems can release hydrogen quite rapidly (within minutes), while others may take longer. The response time depends on the specific material used, system design, and operating conditions.

2. Energy Density

Hydrogen has one of the highest energy densities by weight among known energy storage mediums. Its higher heating value (HHV) is approximately 39,405.6 Wh/kg, while its lower heating value (LHV) is about 33,313.9 Wh/kg. However, its volumetric energy density remains relatively low, creating challenges for storage. Compressed hydrogen at 700 bar achieves about 3,300 Wh/m³ (HHV) or 2,800 Wh/m³ (LHV). Liquid hydrogen, with a volumetric energy density of approximately 2,360 Wh/L (8.5 MJ/L), provides a higher density but necessitates cryogenic temperatures of around -253°C, adding significant complexity and cost to its storage.

3. Flexibility and Duration

Hydrogen's versatility as an energy storage medium is indeed notable. It can be stored in multiple forms—primarily as compressed gas, cryogenic liquid, or in solid-state materials—each suited to different applications and infrastructure requirements. Compressed gas is most common for general use, while liquid storage offers higher density but requires significant energy for liquefaction and maintenance. Solid-state storage, such as metal hydrides, is still developing but promises safer, denser storage.

This flexibility allows hydrogen to be used for both short-term energy buffering (hours to days) and long-term seasonal energy storage (months), addressing a range of energy needs. However, each storage method has distinct efficiency levels, costs, and technical challenges.

For short-term storage, compressed gas or advanced solid-state systems are often preferred due to their quicker response times. Long-term and large-scale storage might utilize underground caverns or liquid storage, trading some efficiency for capacity. See: Figure 6.5

While hydrogen's flexibility is significant, it's important to note that each storage method has specific infrastructure requirements and energy losses associated with conversion and storage processes.

4. Losses During Storage

Hydrogen storage indeed faces challenges regarding energy efficiency and losses, which vary depending on the storage method:

Compressed Hydrogen Storage:

Compression energy: Typically requires 10-15% of the hydrogen's energy content for compression to 350-700 bar.

Leakage: Modern storage systems have minimal leakage rates, often less than 1% per year, but this can accumulate over time.

Liquid Hydrogen Storage:

Liquefaction energy: Requires about 30-40% of the hydrogen's energy content for the liquefaction process.

Boil-off: Cryogenic storage (at -253°C) leads to unavoidable heat ingress, causing boil-off rates of 0.1-1% per day, depending on tank size and insulation quality.

Solid-state Storage Systems (e.g., metal hydrides):

Absorption/desorption losses: Energy is required for both processes, typically 10-20% of the hydrogen's energy content.

Thermal management: Maintaining optimal temperature for hydrogen release can lead to additional energy expenditure.

Fuel cells and combustion engines

Hydrogen is prominently used as an energy carrier in fuel cells and combustion processes. Fuel cells, particularly proton-exchange membrane fuel cells (PEMFCs), convert hydrogen into electricity through an electrochemical reaction. This technology is gaining traction in the automotive industry, especially for fleet vehicles like buses, taxis, and logistic vehicles, due to its high efficiency and minimal environmental impact (Fan et al., 2021).¹⁵² PEMFCs generate electricity by combining hydrogen and oxygen, producing water and heat as by-products. This makes them a clean energy source with no harmful emissions, making them suitable for both stationary and mobile applications.

In combustion, hydrogen can be burned directly in internal combustion engines (ICEs) or used in gas turbines. Hydrogen combustion produces water as the primary emission, eliminating carbon dioxide emissions. However, challenges such as flame stability and nitrogen oxide (NOx) emissions need to be addressed to make hydrogen combustion more viable (Kobayashi et al., 2019).¹⁵³

Applications in Renewable Energy Storage

Grid Energy Storage: Hydrogen can play a pivotal role in grid energy storage, absorbing excess electricity generated from renewable sources and converting it back to electricity when demand exceeds supply. This application helps to stabilize the grid, manage peak loads, and integrate a higher share of renewables into the energy mix.

Peak Shaving and Load Levelling: Hydrogen storage systems can be deployed for peak shaving, storing energy during off-peak times and releasing it during peak demand periods. This helps to reduce the need for peaker plants and enhances overall grid efficiency.

Backup Power Systems: For critical infrastructure and remote locations, hydrogen storage provides a reliable backup power source. It ensures uninterrupted power supply during outages or when renewable generation is insufficient.

Seasonal Energy Storage: Hydrogen is one option for seasonal storage. However, this storage method faces significant efficiency challenges, with considerable energy losses during the conversion and storage processes. While this capability could contribute to renewable energy systems, it's worth noting that there are various other seasonal storage methods available, though most face similar efficiency limitations. The path to 100% renewable energy systems may require accepting these inefficiencies while working to improve storage technologies.

Renewable Energy Curtailment Avoidance: Hydrogen storage helps to avoid curtailment of renewable energy. When production exceeds grid capacity, the excess energy can be converted to hydrogen, stored, and later converted back to electricity or used in other applications, thus maximizing the utilization of renewable resources.

6.2.2 Transportation

Hydrogen is increasingly being recognized as a viable alternative fuel for the transportation sector, primarily through its application in hydrogen fuel cell vehicles (HFCVs). These vehicles use hydrogen gas to power an electric motor via a fuel cell that generates electricity through an electrochemical reaction between hydrogen and oxygen, with water and heat as the only by-products. This technology is being applied across various types of vehicles, including passenger cars, buses, trucks, trains, and even aircraft (Hassan et al., 2023).¹⁵⁴

HFCVs offer several advantages over traditional internal combustion engine vehicles (ICEVs) and even battery electric vehicles (BEVs). For instance, they have a higher energy density compared to batteries, which translates to longer driving ranges and shorter refueling times, similar to the refueling experience with gasoline or diesel. Hydrogen fuel cells also provide higher efficiency rates, typically converting about 60% of the energy in hydrogen into electrical power, compared to around 25-30% for ICEVs (Hosseini & Butler, 2020).¹⁵⁵

6.2.3 Industrial Applications

Hydrogen is extensively used in various industrial applications due to its unique chemical properties and clean energy potential. One of the primary industrial applications of hydrogen is in the chemical manufacturing sector. Hydrogen is a critical feedstock in the production of ammonia through the Haber-Bosch process, which is essential for the global fertilizer industry. Ammonia production is one of the largest consumers of hydrogen, utilizing it to react with

nitrogen to produce ammonia, which is subsequently used to manufacture fertilizers (Kamali, 2020).¹⁵⁶

Another significant application of hydrogen is in oil refining. In refineries, hydrogen is used in hydrocracking and hydrotreating processes to break down heavy crude oil into lighter, more valuable products such as gasoline, diesel, and jet fuel. These processes help remove sulfur and other impurities, producing cleaner fuels that meet stringent environmental regulations (Chen et al., 2022).¹⁵⁷

The steel industry is also exploring hydrogen as a means to decarbonize its production processes. Traditionally, steel production relies heavily on carbon-intensive methods such as blast furnaces, which emit large amounts of CO₂. Hydrogen can be used as a reducing agent in steelmaking to produce direct reduced iron (DRI) through a process that significantly reduces CO₂ emissions. For instance, the use of hydrogen in direct reduction processes and as part of hydrogen-enriched blast furnaces is gaining traction as a sustainable alternative to conventional methods (Liu et al., 2021).¹⁵⁸

6.2.3 Residential and Commercial Use

Hydrogen is increasingly being considered as a viable energy source in residential and commercial sectors for heating, power generation, and combined heat and power (CHP) systems. In residential settings, hydrogen can be used in fuel cells to provide both electricity and heat. Solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs) are among the most commonly used types. These fuel cells convert hydrogen into electricity and heat, offering an efficient and clean solution for residential energy needs. For instance, hydrogen fuel cells can power household appliances and provide heating, significantly reducing greenhouse gas emissions compared to traditional fossil fuels (Hosseini et al., 2013).¹⁵⁹

In commercial buildings, hydrogen is used in larger-scale CHP systems, which generate electricity and capture the byproduct heat for space heating and hot water. This integration not only improves energy efficiency but also reduces operational costs by utilizing waste heat. Hydrogen can also be stored on-site in tanks or through advanced storage methods like Liquid Organic Hydrogen Carriers (LOHCs), enabling the efficient use of surplus renewable energy. This flexibility makes hydrogen an attractive option for energy storage in commercial applications, ensuring a reliable energy supply even during peak demand periods or when renewable sources are intermittent (Teichmann et al., 2012).¹⁶⁰

6.3 Technological barriers, regulatory framework and scalability

6.3.1 Technical Challenges

Efficiency and Energy Loss

Hydrogen production, storage, and utilization face several technical challenges that impact efficiency and energy loss. In hydrogen production, especially via electrolysis, the primary challenge is the high energy requirement. Electrolysis of water is inherently energy-intensive, and the efficiency of current electrolyzers ranges between 60-80% (Rolo et al., 2023).¹⁶¹ Significant energy losses occur during the conversion of electrical energy to chemical energy in hydrogen, necessitating advancements in electrolyzer technology to enhance efficiency. Solid oxide electrolyzers, for example, can achieve higher efficiencies, but they operate at high temperatures and have issues with durability (Acar & Dincer, 2019).¹⁶²

Storage of hydrogen also presents efficiency challenges. Compressed hydrogen storage requires substantial energy to compress the gas to high pressures, typically around 700 bar, resulting in an energy loss of approximately 10-15% (Edwards et al., 2008).¹⁶³ Liquid hydrogen storage, which involves cooling hydrogen to cryogenic temperatures, suffers from even greater energy losses, with around 30-40% of the energy content of hydrogen lost during liquefaction due to the energy required for cooling (Ghorbani et al., 2023).¹⁶⁴ Additionally, boil-off losses during storage further reduce the efficiency of liquid hydrogen.

In terms of utilization, fuel cells, which convert hydrogen back into electricity, face efficiency challenges as well. Proton exchange membrane fuel cells (PEMFCs) have efficiencies of about 40-60%, while solid oxide fuel cells (SOFCs) can achieve higher efficiencies but suffer from issues related to high operating temperatures and material degradation (Hananto et al., 2023).¹⁶⁵ The overall efficiency of hydrogen as an energy carrier is affected by these cumulative losses in production, storage, and utilization stages, making it imperative to develop more efficient technologies across the hydrogen value chain.

Material Challenges

The production and utilization of hydrogen require specialized materials that present their own challenges. Electrolyzers, essential for hydrogen production, depend heavily on critical raw materials such as platinum, iridium, and ruthenium. These materials are not only rare and expensive but also concentrated in geopolitically sensitive regions like South Africa, Russia, and Zimbabwe ([Hydrogen Tech World.com](https://hydrogentechworld.com), [Hydrogen Tech World.com](https://hydrogentechworld.com)). This reliance on scarce materials poses a significant supply chain risk and can lead to price volatility.

Safety and Reliability

Safety and reliability are critical concerns in hydrogen technologies due to hydrogen's high flammability and the potential for leaks. Hydrogen's low ignition energy and wide flammability

range make it a hazardous substance to handle, store, and transport (Chen et al., 2022).¹⁵⁷ Ensuring the safe operation of hydrogen systems requires robust materials and engineering solutions that can withstand high pressures and prevent leaks. For instance, high-pressure hydrogen storage tanks must be designed with materials that resist hydrogen embrittlement, a phenomenon where hydrogen weakens metals and causes cracks (Moradi & Groth, 2019).¹⁶⁶

Reliability issues are also prevalent in hydrogen technologies. Electrolyzers, especially high-temperature ones, face durability issues due to the harsh operating conditions, which can lead to degradation of components and reduced lifespan (Ahmed et al., 2023).¹⁶⁷ Similarly, fuel cells, particularly PEMFCs, suffer from membrane degradation and catalyst poisoning, which affect their long-term reliability and performance (Béthoux, 2020).¹⁶⁸ Addressing these reliability issues involves developing more durable materials and components that can withstand the operational stresses of hydrogen technologies.

Mitigating safety risks involves implementing stringent safety protocols and technologies. For hydrogen storage, this includes using advanced sensors and control systems to detect leaks and prevent accidents. Safety valves and pressure relief devices are essential to manage the risks associated with high-pressure hydrogen storage (Ratan & Wolfson, 2005).¹⁶⁹ For liquid hydrogen storage, specialized insulation and containment systems are necessary to manage the cryogenic temperatures and prevent boil-off losses (Sharma, 2019).¹⁷⁰

Enhancing the reliability of hydrogen technologies requires continuous monitoring and maintenance. Regular inspections and the use of predictive maintenance technologies can help identify potential failures before they occur, thereby improving the overall reliability of hydrogen systems. Additionally, advancements in material science, such as the development of hydrogen-resistant alloys and durable membranes, are crucial to overcoming the current reliability challenges (Ali, 2019).¹⁷¹

6.3.2 Legal and Regulatory Barriers (and incentives)

The development and deployment of hydrogen technologies face numerous legal and regulatory challenges that impact the availability and accessibility of resources. One significant barrier is the lack of standardized regulations and codes for hydrogen production, storage, and distribution. The absence of harmonized international standards creates inconsistencies and uncertainties for investors and developers, hindering the large-scale adoption of hydrogen technologies (Dolci et al., 2019).¹⁷²

In many regions, existing energy policies are still heavily skewed towards fossil fuels, providing subsidies and incentives that make renewable energy and hydrogen less competitive. Reforming these policies to support hydrogen production from renewable sources is crucial. For example, the European Union has made strides in this direction by setting targets for renewable energy adoption and creating frameworks to support green hydrogen initiatives. However, similar

efforts are needed globally to create a conducive environment for hydrogen technologies (Chechel et al., 2022).¹⁷³

Safety regulations related to hydrogen production and handling also pose significant challenges. Hydrogen is highly flammable, and its storage and transport require stringent safety measures. Developing comprehensive safety standards and ensuring their consistent application across different regions is essential to mitigate risks and build public trust in hydrogen technologies (Litvinenko et al., 2020).¹⁷⁴

Infrastructure development for hydrogen distribution and refueling is another area where regulatory support is critical. Establishing hydrogen pipelines, storage facilities, and refueling stations requires significant investment and coordinated planning. Regulatory frameworks need to facilitate these developments by providing clear guidelines and financial incentives. The integration of hydrogen infrastructure with existing energy systems, such as natural gas grids, also requires regulatory adjustments to ensure safe and efficient operations (Sacconi et al., 2020).¹⁷⁵

The EU Hydrogen Strategy

On a positive note, the EU has adopted its Hydrogen Strategy in July 2020. The document is a plan to make Europe a leader in clean hydrogen. It sets out ambitious goals to:

- Develop an investment agenda to mobilize €470 billion in public and private investments in hydrogen by 2030.
- Boost demand for hydrogen by creating a market for clean hydrogen products and services.
- Design an enabling framework with clear regulations, standards, and permitting procedures.

The strategy unfolds in three phases. The first phase (2020-2024) aims to install 6 GW of renewable hydrogen electrolyzers and produce up to 1 million tonnes of renewable hydrogen, focusing on decarbonizing existing production and initial industrial and transport applications. The second phase (2025-2030) targets installing 40 GW of electrolyzers and producing up to 10 million tonnes of renewable hydrogen, expanding its use in more industrial applications and transport. The third phase (2030 onwards) envisions deploying hydrogen at scale in hard-to-decarbonize sectors and using it for balancing renewable electricity and energy storage.

The Strategy defines [20 key action points](#). These actions focus on establishing a robust investment framework via the European Clean Hydrogen Alliance, which includes over 750 projects. The strategy supports strategic investments in clean hydrogen within the EU's recovery plan, encouraging its use in transport and industry, and setting common standards and certification for low-carbon hydrogen. Additionally, the strategy prioritizes infrastructure planning, market rules, and innovation through various EU initiatives and funding mechanisms,

ensuring the widespread adoption and integration of hydrogen as a sustainable energy storage solution.

By facilitating hydrogen's role in energy systems integration, the EU aims to boost demand and scale up production while ensuring a comprehensive supportive framework. Actions include planning hydrogen infrastructure within Trans-European Networks, accelerating refuelling infrastructure deployment, and designing market rules to promote efficient hydrogen infrastructure development. The strategy also emphasizes international cooperation, supporting pilot projects and the development of key hydrogen value chains through programs like Horizon 2020 and the Clean Hydrogen Partnership, which combines significant EU and industry funding to drive innovation and competitive pricing in renewable hydrogen technologies.

REPowerEU

The REPowerEU initiative is a major driver in promoting hydrogen as an energy carrier through the establishment and expansion of Hydrogen Valleys across Europe. These Hydrogen Valleys are integrated ecosystems where renewable hydrogen production aligns with local demand, thus fostering regional energy self-sufficiency and reducing reliance on fossil fuels. The European Commission has committed an additional €200 million to the Clean Hydrogen Joint Undertaking, aiming to accelerate the development of these projects. This funding supports early-stage Hydrogen Valleys, facilitating innovation and the creation of infrastructure necessary for hydrogen production and utilization.

Furthermore, the initiative includes the establishment of a Clean Hydrogen Knowledge Hub, which aims to consolidate and disseminate best practices, technical knowledge, and data on hydrogen technologies. Additionally, the European Hydrogen Academy has been launched to provide comprehensive education and training, ensuring the development of skilled professionals in the hydrogen sector. These efforts are designed to create a robust hydrogen economy within the EU, contributing to the overarching goals of energy security, sustainability, and economic growth by fostering local production and consumption of clean hydrogen. ([Repowering the EU with Hydrogen Valleys: Commission presents progress towards a European hydrogen economy](#))

Accelerating the rollout of renewables

A massive **scaling-up and speeding-up of renewable energy** in power generation, industry, buildings and transport will accelerate our independence, give a boost to the green transition, and reduce prices over time. The Commission proposes to **increase the headline 2030 target for renewables from 40% to 45%** under the Fit for 55 package. Setting this overall increased ambition will create the framework for other initiatives, including:

- **Setting a target of 10 million tonnes of domestic renewable hydrogen** production and 10 million tonnes of imports by 2030, to replace natural gas, coal and oil in hard-to-

decarbonise industries and transport sectors. To accelerate the hydrogen market increased sub-targets for specific sectors would need to be agreed by the co-legislators. The Commission is also publishing **two Delegated Acts on the definition and production of renewable hydrogen** to ensure that production leads to net decarbonisation. ([REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition](#))

6.3.3 Scalability

Scalability and Integration

The scalability of hydrogen technologies is a critical factor in their integration into existing energy systems. Current hydrogen technologies vary in their scalability, with some, like steam methane reforming (SMR), already deployed at large scales, while others, such as electrolysis and advanced storage materials, are still developing.

For large-scale hydrogen production, centralized production facilities that use renewable energy sources are being developed. These facilities can produce hydrogen at lower costs and with fewer emissions than smaller, decentralized systems. However, decentralized systems, which produce hydrogen close to the point of use, can offer flexibility and reduce the need for extensive hydrogen transportation infrastructure (Olabi et al., 2021).¹⁷⁶

Integration of hydrogen into existing energy systems involves developing infrastructure for hydrogen production, storage, and distribution. This includes building pipelines, refueling stations, and storage facilities that can handle large volumes of hydrogen safely and efficiently. The use of hydrogen in existing natural gas infrastructure, through blending hydrogen with natural gas, is also being explored as a transitional strategy to reduce emissions and facilitate the adoption of hydrogen technologies (Ratnakar et al., 2021).¹⁷⁷

Hydrogen can also enhance the stability and resilience of energy grids by acting as an energy storage medium. This is particularly important for integrating intermittent renewable energy sources like wind and solar, which can produce excess energy during periods of high generation. By converting this excess energy into hydrogen, it can be stored and later converted back into electricity when needed, thus balancing supply and demand and enhancing grid stability (Wieliczko & Stetson, 2020).¹⁷⁸

Pilot to Commercial Scale

Scaling up hydrogen technologies from small pilot projects to large-scale commercial operations presents several challenges. One of the primary issues is the high cost associated with the production, storage, and distribution of hydrogen. In pilot projects, the focus is often on demonstrating the technical feasibility of hydrogen systems, but these projects typically benefit from subsidies, grants, and other forms of financial support that are not sustainable at

commercial scales (Dzhusupova & Vis, 2023).¹⁷⁹ As the scale increases, the costs of infrastructure, including electrolyzers, storage tanks, and distribution networks, can become prohibitively expensive without substantial financial investment and market incentives.

Another challenge in scaling up is the efficiency of hydrogen production and utilization. Pilot projects often operate under optimal conditions, but real-world applications at commercial scales can encounter various inefficiencies. For example, hydrogen production via electrolysis requires significant amounts of electricity, and current electrolyzer technologies are not yet efficient enough to make this process economically viable at a large scale. The energy losses during the conversion and storage processes can be substantial, leading to higher costs per unit of hydrogen produced (Caponi et al., 2022).¹⁸⁰ Additionally, scaling up requires overcoming technical barriers related to the durability and reliability of hydrogen systems, which may perform well in controlled pilot environments but face challenges in more varied and demanding commercial operations (Wang, 2015).¹⁸¹

The integration of hydrogen into existing energy and industrial systems also poses logistical challenges. For hydrogen to be a viable large-scale energy carrier, it must be efficiently integrated into the current energy infrastructure, including power grids and transportation networks. This integration requires significant modifications to existing systems, such as upgrading pipelines and refueling stations to handle hydrogen safely and efficiently. Moreover, establishing a widespread hydrogen refueling infrastructure is critical for the adoption of hydrogen fuel cell vehicles and other applications, but this infrastructure is currently limited and requires substantial investment to expand (Blazquez-Diaz, 2019).¹⁸²

Economic and Logistical Factors

The economic factors involved in scaling up hydrogen technologies are complex and multifaceted. The initial capital investment required for building large-scale hydrogen production facilities, storage systems, and distribution networks is substantial. These costs are often higher than those for traditional fossil fuel-based systems, making it challenging to attract investment without significant government support and incentives. Economic models suggest that achieving economies of scale is crucial for reducing the levelized cost of hydrogen (LCOH), but this requires large-scale deployment and continuous technological advancements to improve efficiency and reduce costs (Kuehn, 2023).¹⁸³

Another economic challenge is the current market demand for hydrogen. While there is significant interest in hydrogen as a clean energy carrier, the market for hydrogen is still relatively small compared to other energy sources. Building a robust market demand is essential to justify the investments needed for scaling up. This involves fostering partnerships between governments, industry stakeholders, and consumers to create a stable and growing market for hydrogen technologies. Long-term offtake agreements and supportive policies can provide the necessary market stability and encourage investment (Agarwal, 2022).¹⁸⁴

Logistical challenges also play a significant role in scaling up hydrogen technologies. Transporting hydrogen from production sites to end-users involves complex logistics, especially given hydrogen's low energy density by volume. Hydrogen must be compressed or liquefied for efficient transport, requiring specialized infrastructure and increasing costs. Additionally, the safe handling and transport of hydrogen pose significant logistical challenges, as hydrogen is highly flammable and can cause material embrittlement. Developing robust safety protocols and standards is essential to address these issues (Gerboni & Salvador, 2009).¹⁸⁵

The development of a reliable and extensive hydrogen distribution network is necessary to support large-scale deployment. This includes pipelines, refueling stations, and storage facilities that can handle the increased volumes of hydrogen required for commercial applications. The conversion of existing natural gas pipelines to hydrogen transport is being explored, but this requires significant modifications and safety measures to ensure compatibility and safety (Li et al., 2008).⁷³

The European Hydrogen Backbone (EHB) initiative

The EHB initiative aims to accelerate Europe's decarbonisation journey by defining the critical role of hydrogen infrastructure – based on existing and new pipelines – in enabling the development of a competitive, liquid, pan-European renewable and low-carbon hydrogen market.

The initiative seeks to foster market competition, security of supply, security of demand, and cross-border collaboration between European countries and their neighbours.

Since its founding in 2020, the European Hydrogen Backbone (EHB) initiative has contributed to the development of a European hydrogen market through the publications of its flagship EHB maps, with a vision of a pan-European hydrogen transport infrastructure.

The accelerated EHB vision shows that by 2030 an initial 28,000 km pipeline network could emerge, connecting industrial clusters, ports, and hydrogen valleys – and laying the foundation for future large-scale hydrogen supply corridors. The hydrogen infrastructure can then grow to become a pan-European network, with a length of 53,000 km by 2040. (Source: <https://ehb.eu/>)



Figure 6.6 EHB – Map of the developing Hydrogen backbone

6.4 Raw material restrictions

Hydrogen production, particularly through electrolysis and biomass conversion, requires specific natural resources and is influenced by geographical and climatic conditions. Understanding these requirements is essential for optimizing hydrogen production processes and ensuring their sustainability.

The global availability of resources needed for hydrogen production varies significantly, influenced by regional differences in natural resources and infrastructure. Water is the primary resource for hydrogen production via electrolysis, and its availability is generally sufficient worldwide. However, regions experiencing water scarcity may face challenges in allocating this vital resource for hydrogen production, particularly where water demand for agriculture and human consumption is high (Abdalla et al., 2018).¹⁸⁶ Countries with abundant water resources, such as those with extensive river systems or coastal access, are better positioned to implement large-scale electrolysis projects.

Raw Materials for production and storage equipment

The efficient storage of hydrogen as an energy medium involves several critical components, each demanding specific raw materials. These components include electrolyzers, tanks,

compressors, and pipes. Below is a detailed examination of the essential raw materials for each component, their accessibility, and supply chains to Europe.

Electrolyzers

Electrolyzers are crucial for splitting water into hydrogen and oxygen, and they require a range of raw materials.

Main Elements found in Electrolyzers (and Hydrogen Fuel Cells), Metal Hydrides and Lithium-ion Batteries

@Bruno G. Pollet

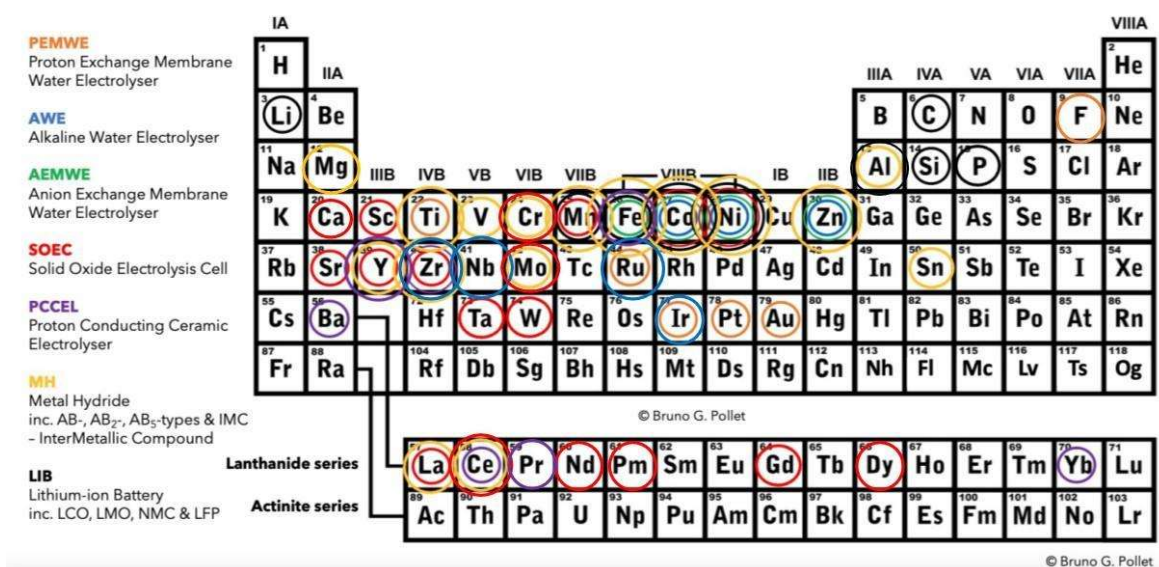


Figure 6.7 Hydrogen Tech World - [Critical raw materials in the hydrogen sector](#)¹⁸⁷

- **Platinum Group Metals (PGMs):** Platinum (Pt), Iridium (Ir), and Ruthenium (Ru) are essential for Proton Exchange Membrane (PEM) electrolyzers due to their catalytic properties. These metals are rare and expensive, with most of the global supply and [reserves](#) of platinum concentrated in South Africa and Russia.

World **iridium supply** is currently dominated by South Africa, as a by-product of platinum and palladium production. In 2018 South Africa accounted for 87% of global iridium production, with a further 8% coming from Zimbabwe and 3% each from Russia and Canada, according to the [US Geological Survey](#).

- **Nickel (Ni) and Cobalt (Co):** Used in Alkaline Water Electrolyzers (AWE) and Anion Exchange Membrane Water Electrolyzers (AEMWE) for their electrochemical properties. Nickel is more abundant and less expensive than PGMs, but its supply chain is also concentrated in a few countries, namely Indonesia, Russia, Canada, New Caledonia.¹⁸⁸

- **Titanium (Ti):** Commonly used in PEM electrolyzers for its corrosion resistance. Titanium reserves concentrate in China, Australia, India, Canada, Brazil, Norway adding up to 88% of total global reserves in 2023.¹⁸⁹
- **Stainless Steel:** Utilized in various components for its durability and resistance to corrosion.

Tanks:

- **Carbon Fiber:** A lightweight and strong material used in Type IV composite pressure vessels for compressed hydrogen storage. Carbon fiber production is energy-intensive and relies on precursor materials like polyacrylonitrile (PAN) derived from fossil fuels.
- **Polymers:** High-strength polymers like epoxy resins are used as binders in composite tanks. These polymers are typically derived from petrochemicals.
- **Metals:** Steel or aluminium liners are used in some types of pressure vessels. These metals are widely available, but their production can have environmental impacts.

Compressors:

- **Steel:** Used for the casing, impellers, and other structural components of compressors. Steel is widely available, but its production is energy-intensive and contributes to greenhouse gas emissions.
- **Copper:** Used for electrical wiring and motor components in compressors. Copper is a relatively abundant metal, but its extraction and processing can have environmental impacts.

Pipes:

- **Steel:** The most common material for hydrogen pipelines due to its strength and durability. However, hydrogen embrittlement can be a concern, requiring specialized steel grades or coatings.
- **Thermoplastics:** Emerging as an alternative for shorter-distance hydrogen pipelines due to their resistance to embrittlement and lower cost. However, their long-term performance and safety under high pressures need further validation.

Europe faces challenges in accessing some of these raw materials, particularly PGMs, which are primarily sourced from outside the region. The concentration of PGM supply in a few countries raises concerns about price volatility and supply security. Efforts are underway to diversify supply chains and develop alternative catalyst materials to reduce reliance on PGMs.

Other raw materials like steel, copper, and polymers are more readily available within Europe, but their production and transportation can contribute to environmental impacts. The increasing demand for these materials in the growing hydrogen sector may put additional pressure on supply chains and necessitate sustainable sourcing practices.

The development of a robust and sustainable supply chain for raw materials is crucial for the successful deployment of hydrogen energy storage systems in Europe. This involves not only securing access to resources but also promoting responsible mining practices, recycling, and the development of alternative materials to mitigate environmental and geopolitical risks.

6.5 Energy Storage Costs

6.5.1 Initial Investment and Infrastructure

Cost Breakdown

The initial investment required to set up hydrogen production, storage, and distribution infrastructure is substantial and involves several key components. Hydrogen production can be achieved through various methods, including steam methane reforming (SMR), electrolysis, and biomass gasification. Each of these methods has distinct cost structures. For example, the capital expenses for electrolyzers used in water electrolysis are particularly high. A technoeconomic analysis of renewable hydrogen production using solar energy indicated that the base-case capital expenses for photoelectrochemical (PEC) and photovoltaic-electrolytic (PV-E) systems can range from \$160 million to \$260 million for a capacity of 10,000 kg H₂ per day, with levelized costs of hydrogen production (LCOH) between \$6.1 and \$12.1 per kg (Shaner et al., 2016).¹⁹⁰

Storage infrastructure costs are also significant. Hydrogen can be stored as compressed gas, liquid hydrogen, or in metal hydrides. Compressed hydrogen storage requires high-pressure tanks, which involve high material and safety costs. Liquid hydrogen storage necessitates cryogenic facilities, which are expensive due to the need for advanced cooling and insulation technologies. A study on hydrogen delivery scenarios found that the infrastructure costs for hydrogen storage and distribution can vary widely, with levelized costs of delivery ranging from \$2.73 to \$8.02 per kg H₂ depending on the method and scale (Demir & Dincer, 2018).¹⁹¹

Distribution infrastructure includes pipelines, transport trucks, and refuelling stations. Building a network of hydrogen pipelines is capital-intensive but offers cost efficiencies at scale. Alternatively, hydrogen can be transported via cryogenic liquid tankers or high-pressure gas trailers, which also incur significant costs. A comprehensive evaluation of hydrogen infrastructure for transportation in Germany estimated that the most cost-efficient hydrogen supply could be achieved through a combination of cavern storage and pipeline transport in high-demand scenarios, with costs ranging from €6.7 to €7.5 per kg H₂ (Emonts et al., 2019).¹⁹²

Comparison with Other Technologies

When compared to other energy storage technologies, the initial investment for hydrogen infrastructure is generally higher. Battery storage systems, such as lithium-ion batteries, have lower initial capital costs and are widely used for short-term energy storage applications. However, batteries have limitations in terms of energy density and lifecycle, making them less

suitable for large-scale or long-term storage compared to hydrogen. For instance, the cost of installing large-scale battery storage can range from \$300 to \$600 per kWh, which is competitive for short-duration storage but not for applications requiring high energy density and long-term storage (Bogart, 2002).¹⁹³

Pumped hydro storage, another common energy storage technology, involves lower operational costs once the initial infrastructure is in place. The capital costs for pumped hydro are typically in the range of \$1,000 to \$2,500 per kW of installed capacity. However, the geographical and environmental constraints of pumped hydro limit its scalability and application flexibility compared to hydrogen, which can be produced and stored virtually anywhere with access to water and energy sources (Liemberger et al., 2019).¹⁹⁴

The levelized cost of storage (LCOS) for hydrogen is generally higher than that for batteries and pumped hydro. A study comparing hydrogen and electricity production systems with CO₂ capture and storage found that hydrogen production costs with CCS range from 6 to 9 €/GJ, which is competitive with fossil fuels under certain conditions but higher than battery storage costs on a per-kWh basis (Damen et al., 2006).¹⁹⁵

In summary, while hydrogen infrastructure requires higher initial investments compared to batteries and pumped hydro, its advantages in terms of scalability, energy density, and long-term storage potential make it a critical component of future energy systems, particularly for applications that require large-scale and long-term energy storage.

6.5.2 Operational and Maintenance Costs

Long-term Costs

The long-term operational and maintenance costs of hydrogen technologies are influenced by several factors, including the type of hydrogen production method, the scale of operation, and the technological advancements in the field. One of the significant long-term costs is associated with the maintenance and replacement of critical components in hydrogen production and utilization systems. For instance, electrolyzers used in water electrolysis require regular maintenance to ensure efficient operation, and their components, such as membranes and catalysts, need periodic replacement due to wear and degradation (Granovskii et al., 2007).¹⁹⁶ The high temperatures involved in some hydrogen production methods, like steam methane reforming and solid oxide electrolyzers, exacerbate material degradation, leading to higher maintenance costs over time (Ahmed et al., 2023).¹⁶⁷

Hydrogen storage systems, particularly those involving high-pressure tanks or cryogenic storage, also incur significant long-term costs. High-pressure storage tanks must be inspected and tested regularly to ensure they can safely contain hydrogen without leaking or rupturing. Cryogenic storage, which involves maintaining hydrogen at extremely low temperatures, requires advanced insulation and continuous energy input to prevent boil-off losses, leading to ongoing

operational expenses (Ghorbani et al., 2023).¹⁶⁴ Additionally, hydrogen fuel cells, which are used to convert hydrogen back into electricity, have components like the proton exchange membrane and catalysts that degrade over time and need to be replaced, adding to the long-term operational costs (Lipman & Delucchi, 1996).¹⁹⁷

Comparison of different hydrogen production methods

Process	Energy source	Feedstock	Capital cost (M\$)	Hydrogen cost (\$/kg)
SMR with CCS	Standard fossil fuels	Natural gas	226.4	2.27
SMR without CCS	Standard fossil fuels	Natural gas	180.7	2.08
CC with CCS	Standard fossil fuels	Coal	545.6	1.63
CG without CCS	Standard fossil fuels	Coal	435.9	1.34
ATR of methane with CCS	Standard fossil fuels	Natural gas	183.8	1.48
Methane pyrolysis	Internally generated steam	Natural gas	–	1.59–1.70
Biomass pyrolysis	Internally generated steam	Woody biomass	53.4–3.1	1.25–2.20
Biomass gasification	Internally generated steam	Woody biomass	149.3–6.4	1.77–2.05
Direct bio-photolysis	Solar	Water + algae	50 \$/m ²	2.13
Indirect bio-photolysis	Solar	Water + algae	135 \$/m ²	1.42
Dark fermentation	–	Organic biomass	–	2.57
Photo-fermentation	Solar	Organic biomass	–	2.83
Solar PV electrolysis	Solar	Water	12–54.5	5.78–23.27
Solar thermal electrolysis	Solar	Water	421–22.1	5.10–10.49
Wind electrolysis	Wind	Water	504.8–499.6	5.89–6.03
Nuclear electrolysis	Nuclear	Water	–	4.15–7.00
Nuclear thermolysis	Nuclear	Water	39.6–2107.6	2.17–2.63
Solar thermolysis	Solar	Water	5.7–16	7.98–8.40
Photo-electrolysis	Solar	Water	–	10.36

Figure 6.8 Source: Kayfeci et al: Hydrogen Production¹⁹⁸

Cost-efficiency

The cost-efficiency of hydrogen technologies over their lifecycle is a critical consideration for their broader adoption. Lifecycle cost analysis (LCCA) of hydrogen technologies indicates that while the initial capital investment is high, the operational costs can be managed effectively with technological advancements and economies of scale. For example, hydrogen production through natural gas reforming is currently the most cost-efficient method due to the relatively low cost of natural gas and well-established technology. However, it is associated with high greenhouse gas emissions, necessitating the integration of carbon capture and storage (CCS) technologies to mitigate environmental impact (Granovskii et al., 2007).¹⁹⁶

Electrolysis powered by renewable energy sources offers a cleaner alternative, but it is currently more expensive due to the high cost of renewable electricity and the lower efficiencies of current

electrolyzer technologies. However, as the cost of renewable energy continues to decline and electrolyzer technologies improve, the cost-efficiency of green hydrogen production is expected to improve significantly. Advances in materials science and engineering are expected to enhance the durability and efficiency of electrolyzers, reducing their operational and maintenance costs over time (Bhandari et al., 2014).¹⁹⁹

Hydrogen storage and fuel cell technologies also demonstrate potential for improved cost-efficiency. The development of new storage materials, such as metal hydrides and liquid organic hydrogen carriers (LOHCs), aims to reduce the energy losses and operational costs associated with traditional high-pressure or cryogenic storage methods. Fuel cells, particularly PEMFCs, are becoming more cost-efficient as production scales up and materials used in their construction, such as catalysts, become cheaper and more durable (Egeland-Eriksen et al., 2021).²⁰⁰

Lifecycle cost analysis shows that while hydrogen technologies currently have higher upfront and operational costs compared to conventional fossil fuels, their long-term cost-efficiency can be competitive with continued technological advancements and supportive policies. Implementing carbon pricing and subsidies for renewable energy can further enhance the economic viability of hydrogen technologies by internalizing the environmental costs of fossil fuels and providing financial incentives for clean energy adoption (Lee et al., 2009).²⁰¹

6.5.3 Economic Feasibility

Cost-Benefit Analysis

Investing in hydrogen technologies presents both economic benefits and drawbacks. The primary economic benefit lies in the potential for hydrogen to contribute significantly to the decarbonization of the energy sector, thus addressing climate change and reducing greenhouse gas emissions. For instance, hydrogen fuel cell vehicles (FCVs) and hydrogen-based energy systems offer a cleaner alternative to fossil fuels, which can lead to reduced healthcare costs and environmental damage. Studies indicate that hydrogen fuel can become competitive with traditional fuels like gasoline if production costs decrease and economies of scale are achieved. For example, hydrogen produced via water electrolysis powered by renewable energy sources has the potential to become economically feasible with significant technological advancements and cost reductions in electrolyzers (Lee et al., 2009).²⁰¹

However, the drawbacks include high initial capital costs and the current cost of hydrogen production technologies. Hydrogen production through methods like steam methane reforming (SMR) and electrolysis is still more expensive compared to conventional fossil fuels, primarily due to the high costs of electrolyzers and renewable electricity. Additionally, hydrogen infrastructure, such as refuelling stations and storage facilities, requires substantial investment, which can be a barrier to widespread adoption (Keipi et al., 2018).²⁰² The economic feasibility of

hydrogen technologies is also influenced by the price of competing technologies and the overall market conditions for energy.

Lifecycle cost assessments have shown that while the upfront costs are high, operational costs can be managed effectively with ongoing technological improvements. For example, a study on the economic feasibility of hydrogen refuelling stations showed that subsidies on capital costs could make hydrogen cheaper than gasoline over a ten-year period for PEM electrolyzers and five years for alkaline electrolyzers (Nistor et al., 2016).²⁰³

6.6 Environmental Impact of H₂ES

Comparative Environmental Impact

Hydrogen production methods vary significantly in their environmental impacts, depending on the energy sources and technologies used. Fossil fuel-based hydrogen production, particularly through steam methane reforming (SMR), is the most common method but has significant environmental drawbacks. SMR of natural gas has the highest environmental impacts in terms of abiotic depletion, global warming potential (GWP), and other impact categories due to the substantial carbon dioxide emissions associated with the process (Sulemanet al., 2015).²⁰⁴ In contrast, renewable-based hydrogen production methods, such as water electrolysis powered by wind or solar energy, present much lower environmental impacts. Electrolysis using renewable energy sources results in near-zero GWP and minimal emissions, making it a more environmentally benign option (Dincer & Acar, 2015).²⁰⁵

Thermochemical water splitting cycles, such as the Cu-Cl cycle, offer another environmentally friendly hydrogen production method, with significantly lower GWP compared to conventional methods. These cycles require less energy and produce fewer emissions, highlighting their potential as sustainable hydrogen production technologies (Ozbilen et al., 2013).²⁰⁶ Biomass gasification, although renewable, can have higher environmental impacts related to acidification and eutrophication due to the use of agricultural feedstocks and associated land use changes (Nnabuife et al., 2023).²⁰⁷

Green Hydrogen

Green hydrogen is produced using renewable energy sources, primarily through the electrolysis of water powered by wind, solar, or hydroelectric energy. This method is considered the most sustainable and environmentally friendly, as it generates hydrogen without any direct carbon emissions. The production of green hydrogen has an environmental impact factor significantly lower than that of hydrogen produced from fossil fuels, contributing to its potential in mitigating climate change (Ota et al., 2014).²⁰⁸

The environmental benefits of green hydrogen include the reduction of greenhouse gas emissions, as the process does not rely on fossil fuels and thus avoids the carbon dioxide

emissions inherent in methods like SMR. Additionally, the use of renewable energy for hydrogen production supports the decarbonization of the energy sector, further enhancing the environmental credentials of green hydrogen. By utilizing renewable resources, green hydrogen helps in reducing the dependency on fossil fuels and contributes to energy security and sustainability (Dincer, 2012).²⁰⁹

6.7 Conclusions: Advantages, Disadvantages, and Recommendations for Hydrogen

6.7.1 Pros and cons

Key Benefits

Hydrogen offers several key advantages as an energy carrier, making it an attractive alternative to traditional fossil fuels.

- **Abundance:** Hydrogen is the most abundant element in the universe, primarily found in water. This makes it a virtually inexhaustible resource for energy storage, unlike fossil fuels with limited reserves.
- **Versatility:** Hydrogen is also highly abundant and can be produced from various sources, including water, natural gas, biomass, and even waste products. This versatility in production methods enhances energy security by reducing dependence on a single energy source and allows for the utilization of local resources, thus minimizing geopolitical risks associated with energy supply (Mazloomi & Gomes, 2012).²¹⁰
- **Clean Energy Carrier:** When produced from renewable sources, hydrogen is a clean energy carrier, emitting only water vapor when used in fuel cells. This makes it a crucial component in decarbonizing sectors like transportation and industry. When used in fuel cells, hydrogen combines with oxygen to produce electricity, with water and heat as the only by-products. This reaction does not emit greenhouse gases or other pollutants, making hydrogen a clean energy source that can significantly reduce air pollution and greenhouse gas emissions (Beschkov & Ganev, 2023).²¹¹
- **Long-Duration Storage:** Hydrogen can be stored for extended periods, from days to seasons, without significant energy loss. This is a key advantage over batteries, which are better suited for short-duration storage. Long-duration storage is essential for balancing the intermittency of renewable energy sources and ensuring a reliable energy supply.
- **Scalability:** Hydrogen storage systems can be scaled up to meet the demands of large-scale energy storage applications, such as grid-level storage or industrial processes. This scalability is crucial for accommodating the increasing penetration of renewable energy and managing fluctuations in energy demand.

- **Multiple Applications:** Hydrogen can be used in various ways, including electricity generation through fuel cells, heating, and as a feedstock for producing chemicals and synthetic fuels. This versatility makes it a valuable asset in a diversified energy system.
- **Energy Security:** Hydrogen can be produced domestically, reducing reliance on imported fossil fuels and enhancing energy security. It can also be traded internationally, providing opportunities for energy cooperation and diversification of supply sources.

Comparative Advantages

When compared to other energy storage technologies, hydrogen presents several distinct advantages. Unlike batteries, which degrade over time and have limited lifespans, hydrogen storage systems can have longer operational lives with proper maintenance. Hydrogen can be stored for long periods without significant loss of energy, making it suitable for seasonal energy storage, whereas batteries are generally better suited for short-term storage due to their higher self-discharge rates (Abe et al., 2019).²¹²

In terms of energy density, hydrogen outperforms conventional battery technologies. For instance, lithium-ion batteries have an energy density of around 0.5 MJ/kg, significantly lower than hydrogen's 120 MJ/kg. This higher energy density makes hydrogen more suitable for applications that require lightweight and high-capacity energy storage, such as in aviation and heavy-duty transportation (Burheim, 2017).²¹³

Hydrogen also offers advantages in terms of scalability and versatility. It can be used across a wide range of applications, from small-scale residential energy systems to large industrial processes and transportation. This versatility is not as easily achievable with current battery technologies, which are often designed for specific applications and have limitations in terms of scalability (Nagpal & Kakkar, 2018).²¹⁴

But, but, but!

Multiple studies demonstrate the drawbacks of Hydrogen, certain science communicators use harsher language when describing the feasibility of it ([“The most dumb thing” for energy storage: Hydrogen](#) – Sabine Hossenfelder).

Presenting both sides of the H-coin, we have to admit, that Hydrogen technologies, while promising, face several significant disadvantages and limitations.

- One of the primary drawbacks is the **high cost** associated with hydrogen production, storage, and distribution. Currently, the most economically viable method of hydrogen production is through steam methane reforming (SMR), which relies on fossil fuels and emits substantial amounts of carbon dioxide. Green hydrogen, produced via water electrolysis powered by renewable energy, remains expensive due to the high cost of renewable electricity and the low efficiency of current electrolyzer technologies. The infrastructure for hydrogen storage and distribution, including high-pressure tanks and

refuelling stations, also requires substantial investment, further increasing the overall cost of hydrogen as an energy carrier (Dagdougui et al., 2018).²¹⁵

- Another significant drawback is the **efficiency losses** associated with hydrogen technologies. The process of producing hydrogen, especially through electrolysis, involves significant energy losses. Further losses occur during the compression, liquefaction, and storage stages, as well as in the conversion of hydrogen back to electricity in fuel cells. These cumulative losses reduce the overall efficiency of hydrogen as an energy carrier compared to direct electricity use in batteries (Crowl & Jo, 2007).²¹⁶ Additionally, the energy density of hydrogen by volume is low, necessitating high pressures or cryogenic temperatures for storage, which adds complexity and cost to the storage solutions (Hwang & Varma, 2014).²¹⁷
- **Safety Concerns:** Hydrogen poses several safety risks due to its physical and chemical properties. It has a wide flammability range and can ignite at low energy thresholds, increasing the risk of fires and explosions. Hydrogen flames are also invisible and can burn with very little heat radiation, making detection and management of hydrogen fires particularly challenging. Leaks from storage and distribution systems are a major concern, as hydrogen can easily escape through small openings and has a tendency to embrittle metals, potentially leading to structural failures (Najjar, 2013).²¹⁸ Safety measures, including robust leak detection systems and advanced materials resistant to hydrogen embrittlement, are essential to mitigate these risks but add to the overall cost and complexity of hydrogen technologies (Rosyd et al., 2007).²¹⁹
- **Storage Challenges:** Hydrogen has a low energy density by volume under atmospheric pressure, requiring large storage volumes or high pressures. This poses challenges for transportation and distribution, especially for mobile applications.
- **Infrastructure Requirements:** A widespread hydrogen economy necessitates the development of new infrastructure for production, storage, transportation, and utilization. This infrastructure is currently limited and requires significant investment to establish.
- **Limited Technology Maturity:** While some hydrogen technologies are mature, others, like fuel cells and certain storage methods, are still under development. This limits their current efficiency and cost-effectiveness.
- **Embrittlement:** Hydrogen can cause embrittlement of materials, making them brittle and prone to failure. This necessitates the use of specialized materials and designs for storage tanks and pipelines, increasing costs and complexity.
- The integration of hydrogen into existing energy systems also faces technical and **regulatory challenges**. The current energy infrastructure is predominantly designed for fossil fuels, and significant modifications are required to accommodate hydrogen. Regulatory frameworks need to evolve to support the safe and efficient deployment of

hydrogen technologies, requiring coordination between governments, industry stakeholders, and regulatory bodies (Hienuki et al., 2020).²²⁰

Recommendations

Overcoming Limitations

To overcome the current limitations of hydrogen technologies, several strategies need to be employed. Firstly, the cost of hydrogen production, particularly green hydrogen, must be reduced. This can be achieved through advancements in electrolyzer technologies to improve efficiency and reduce costs. Research into new materials for electrodes and catalysts that can lower the energy requirements for water electrolysis is crucial. Additionally, scaling up production facilities can help achieve economies of scale, thereby lowering the unit cost of hydrogen production (Pantaleone & Fazioli, 2022).

Another strategy is to enhance the infrastructure for hydrogen storage and distribution. Developing advanced storage materials, such as metal hydrides and carbon nanotubes, can improve storage efficiency and safety. For transportation, building a robust network of hydrogen refuelling stations is essential. Investments in infrastructure, supported by public-private partnerships, can accelerate the deployment of hydrogen technologies in both urban and rural areas (Soboń et al., 2021).

Moreover, addressing the safety concerns associated with hydrogen requires rigorous safety standards and the development of new technologies for leak detection and prevention. Research into hydrogen-resistant materials can mitigate the issue of hydrogen embrittlement, making storage and transport safer (Najjar, 2013). Public education campaigns are also necessary to improve the perception of hydrogen safety and promote its acceptance.

Future Research and Development

Future research and development should focus on several key areas to improve hydrogen technology. One critical area is the development of more efficient and durable electrolyzers for green hydrogen production. Innovations in solid oxide and proton exchange membrane electrolyzers, as well as the exploration of new materials and designs, can enhance performance and reduce costs (Dehghanimadvar et al., 2020).

Research should also explore advanced hydrogen storage methods. The development of novel storage materials that can store hydrogen at lower pressures and temperatures while maintaining high energy density is essential. Investigating the use of chemical carriers, such as ammonia and liquid organic hydrogen carriers (LOHCs), can provide alternative storage solutions that are both safe and efficient (Christensen et al., 2006).

In addition, integrating hydrogen into renewable energy systems is a promising area for research. Developing efficient methods for coupling hydrogen production with intermittent

renewable energy sources like wind and solar can enhance energy system flexibility and stability. Research into hybrid systems that combine hydrogen with other energy storage technologies, such as batteries, can optimize the overall efficiency and resilience of the energy grid (Kovač et al., 2021).

Policy and Regulatory Recommendations

To support the development and deployment of hydrogen technologies, robust policy and regulatory measures are needed. Governments should implement policies that provide financial incentives for hydrogen production and infrastructure development. Subsidies, tax credits, and grants can encourage investment in hydrogen technologies and reduce the financial burden on early adopters (Cheng & Lee, 2022).

Introducing carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, can make hydrogen more competitive with fossil fuels by internalizing the environmental costs of carbon emissions. These mechanisms can drive the market towards cleaner energy solutions, including hydrogen (Pantaleone & Fazioli, 2022).

Regulatory frameworks need to be harmonized to facilitate the safe and efficient deployment of hydrogen technologies. Establishing international standards for hydrogen production, storage, and transport can ensure consistency and safety across borders. Governments should also support the development of hydrogen infrastructure through public-private partnerships, ensuring that refuelling stations and storage facilities are widely available and accessible (Edwards et al., 2021).

Furthermore, policies that promote research and development in hydrogen technologies are essential. Governments can fund research programs and provide grants for innovative projects that aim to improve the efficiency, safety, and cost-effectiveness of hydrogen technologies. Collaboration between academia, industry, and government agencies can accelerate technological advancements and the commercialization of hydrogen solutions (Emodi et al., 2021).

State of play in Europe

As of now, member states are actively progressing with the implementation of the EU Hydrogen Strategy. Almost all member states have included clean hydrogen plans in their National Energy and Climate Plans, with 26 countries signing the "Hydrogen Initiative" and 14 incorporating hydrogen into their alternative fuels' infrastructure frameworks. Some member states have already adopted or are in the process of adopting national hydrogen strategies.

Currently, 1.5-2.3 GW of new renewable hydrogen production projects are under construction or announced, with an additional 22 GW of electrolyser projects in the pipeline, indicating significant progress towards the strategy's goals. The European Clean Hydrogen Alliance plays a

crucial role in coordinating investments and actions across member states, supporting the development of a hydrogen supply chain through well-coordinated, large-scale investment projects.

The European Commission continues to support member states through various funding instruments and programs, such as the InvestEU programme, the European Regional Development Fund, and the Cohesion Fund. These initiatives aim to facilitate the green transition by supporting innovative solutions in renewable and low-carbon hydrogen, fostering public-private partnerships, and ensuring regional development and cohesion. The cooperation within the Clean Hydrogen Alliance and the Strategic Forum for Important Projects of Common European Interest (IPCEI) will further promote joint investments and actions across member states .

6.7.2 Existing systems

According to the [Global Hydrogen Review 2023](#) of the IEA there are several pilot projects utilising Hydrogen. These pilots are either:

- Trade pilots: projects demonstrating the feasibility of large-scale hydrogen production, storage, and transport between countries;
- Transportation fuel pilots: hydrogen fuel for rail, ships, aviation, cars, vans, trucks, forklifts, etc.;
- Building pilots: heating applications replacing natural gas;
- Electricity generation: primarily through fuel cells and gas turbines. Gas turbines can also run on hydrogen, either pure or blended with natural gas, providing a flexible option for existing power infrastructure. These systems can generate electricity at utility scale, potentially offering a low-carbon alternative to conventional fossil fuel power plants. Additionally, hydrogen-derived fuels like ammonia are emerging as promising energy carriers. Ammonia can be burned directly in modified gas turbines or used in fuel cells, potentially easing storage and transportation challenges associated with pure hydrogen.

Hydrogen as fuel in the power sector is virtually non-existent today, with a share of less than 0.2% in the global electricity generation mix.

The direct use of 100% ammonia was successfully demonstrated in a [2 MW gas turbine in 2022 in Japan](#), with efforts underway to develop a 40 MW turbine for pure ammonia use. The newly developed combustor on the 2,000-kilowatt-class gas turbine at IHI Yokohama Works, we were able to achieve a greenhouse gas reduction rate exceeding 99%, even when the ammonia fuel ratio is at 70~100%, and they verified the output of 2,000kW when mono-firing liquid ammonia.

Hydrogen and ammonia are gaining traction as potential fuels in the power sector. Utilities across North America, Europe, and Asia-Pacific are exploring hydrogen co-firing with natural gas in gas turbines, while Asian projects are investigating ammonia use in coal-fired plants. These approaches aim to reduce emissions from existing facilities in the short term, while future plants running solely on hydrogen or ammonia could provide flexibility to electricity systems, especially when paired with large-scale hydrogen storage.

Several projects combining renewable electricity-based hydrogen production with large-scale storage for later reconversion are in development. Notable examples include the Advanced Clean Energy Storage and [IPP Renewed project](#) in the United States, where gas turbines for an 840 MW combined-cycle plant with 30% hydrogen co-firing were delivered in 2022, targeting operation by 2025. In the United Kingdom, the [Saltend project](#) aims to retrofit an existing 1,200 MW natural gas-fired combined heat and power plant for 30% hydrogen co-firing by 2027.

Announced projects utilizing hydrogen and ammonia in the power sector could reach an installed capacity of 5,800 MW by 2030, a 65% increase from projections in the Global Hydrogen Review 2022. About 70% of these projects involve hydrogen use in gas turbines, 10% in fuel cells, and 3% co-firing ammonia in coal-fired plants. Geographically, these initiatives are concentrated in Asia-Pacific (39%), Europe (36%), and North America (25%).

Capacity in power generation using hydrogen and ammonia by region, historical and from announced projects, 2019-2030

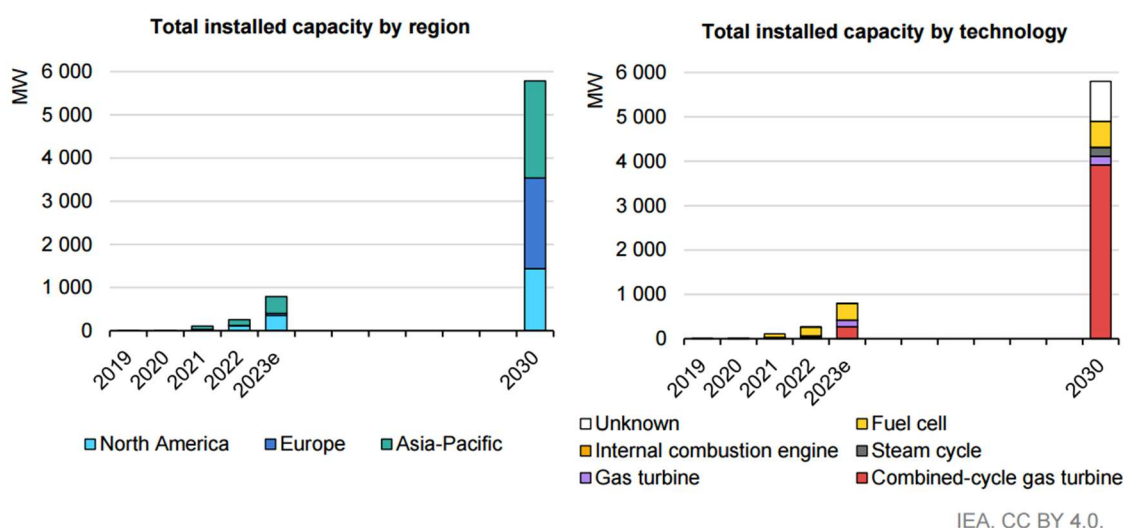


Figure 6.9 Source: [IEA Global Hydrogen Review 2023](#)

Deep Purple™ Pilot

The [Deep Purple™ pilot project](#) consortium will design, build, and test a physical, land-based pilot at TechnipFMC's Norwegian headquarters in Kongsberg. The pilot will include an electrolyser, hydrogen storage, fuel cells, and energy control system as well as the development and testing

of an advanced control and advisory system and a dynamic process simulator. The unique characteristics of the pilot is that parts of the system (Hydrogen storage) are under the ocean.

Bosch SOFC pilot

[Bosch SOFC](#) is gathering practical experience of using fuel cells as a decentralized, highly efficient, and low-emission power generation solution at various locations. Their pre-series units have already accumulated over 500,000 hours of operation across diverse pilot projects. "SOFC" stands for solid oxide fuel cell. To keep the planning and installation effort to a minimum, Bosch combines several of these SOFC units and all relevant auxiliary systems to create a plug-&-play system with an output of 100 kW. Pilot fuel cell systems are deployed at the Bosch Research and Development Center in Schwieberdingen, at the Stuttgart-Feuerbach heating plant, Erkelenz hospital Germany, at the Hydrogen Campus in Salzgitter and at the Bosch Home Comfort site in Wernau, Germany.

[USS 2030](#)

In the lead project "Underground Sun Storage 2030" (USS 2030), the safe, seasonal and large-scale storage of renewable energy in the form of hydrogen in underground gas reservoirs is being developed. In addition, all partners involved in the project will jointly gain valuable technical and economic knowledge for the development of a secure hydrogen supply. In this unique cross-sector demonstration facility, solar energy is converted into green hydrogen by water electrolysis and stored in pure form in an underground natural gas reservoir in Gampern, Upper Austria. The scale of the storage corresponds to the summer surplus of about 1,000 photovoltaic systems on family homes. In summer, this surplus energy is stored and in winter the green energy can be provided again in the form of electricity and heat.

6.7.3 WICE index

Scoring Hydrogen Energy Storage Systems

Hydrogen Energy Storage (H2ES) systems present a promising alternative to conventional energy storage technologies, offering a distinct set of advantages and challenges. To evaluate their potential to transform the energy storage landscape, we will calculate their "Will it Change Everything Score" based on a weighted combination of crucial factors. This score will provide a comprehensive assessment of H2ES's disruptive potential, taking into account not only their technical capabilities but also their environmental impact, scalability, and market viability. The analysis will compare H2ES systems to the baseline lithium-ion batteries, considering aspects such as energy density, Lifetime and life cycles, TRL, etc.

- **Energy Density:** Hydrogen has a high energy density by weight but lower by volume. Gravimetric Energy Density: Approximately 120 MJ/kg or 33.3 kWh/kg. Volumetric Energy Density: 2.99kWh/m³ under atmospheric pressure and 1,400 kWh/m³ under 700 bar.

Score: 100

- **Energy Retention Period:** Hydrogen storage duration depends on the storage method (e.g., compressed gas, liquid, or metal hydrides) but it is from days to weeks.

Score: 80

- **Lifetime and Life Cycles:** Hydrogen storage systems have varying lifetimes based on the technology. Different parts of the system have different lifetimes, typically the shortest for electrolyzers and fuel cells (5-10 years) and longer for storage units (10-15 years). On average, the lifetime of the system is higher, than the baseline Lithium batteries.

Score: 70

- **RTE:** Hydrogen storage and conversion processes can have moderate to high round-trip efficiencies. In literature is RTE between 30 – 50 %

Score: 30

- **TRL:** Hydrogen storage technologies are advancing but still evolving. Remaining problem is effective technologies for green hydrogen and lack of operating facilities on a commercial scale for electricity production. We consider a complete system as mature as the least mature part of it, which in our case are fuel cells. Overall system TRL is 6-8 in our opinion.

Score: 60

- **CAPEX:** Capital costs for hydrogen storage can be significant especially due to storage under low temperatures.

Score: 20

- **OPEX:** Hydrogen energy storage systems generally have higher OPEX compared to lithium-ion batteries, driven by the complexity and maintenance needs of electrolyzers, compressors, storage tanks, and fuel cells. In contrast, lithium-ion batteries benefit from lower operational costs and higher efficiency, making them more cost-effective for many energy storage applications.

Score: 30

- **Environmental Impact:** Hydrogen energy storage systems, particularly when integrated with renewable energy sources, can offer a more environmentally friendly alternative to lithium-ion batteries, with lower long-term impacts, especially in the use and disposal phases.

Score: 60

- **Scalability:** Hydrogen energy storage systems offer greater scalability potential than lithium-ion batteries due to their ability to store vast amounts of energy for extended durations and their flexibility in applications and geographical locations. Electrolyser available on the market are modular, storage tanks are either custom or also modular offering a very flexible scalable energy storage solution.

Score: 90

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	100	10
Energy Retention Period	0.1	80	8
Lifetime and Life Cycles	0.1	70	7
Round-Trip Efficiency (RTE)	0.15	30	4,5
Technological Maturity (TRL)	0.2	60	12
Capital Expenditure (CAPEX)	0.1	20	2
Operational Expenditure (OPEX)	0.1	30	3
Environmental Impact	0.1	60	6
Scalability	0.05	90	4,5
Total	1		57.00

Conclusion

The "Will it Change Everything Score" for Hydrogen energy storage is 57.00 it is a relatively new technology with very high energy density, with good lifetime, but lower RTE. Problematic is higher investment and still not clear legislation (grey, green, ping, blue hydrogen). Hydrogen storage is interesting for energy intensive industries (chemical, fertilizers) where is necessary store green energy for longer period (month). Economical sustainability is still not clear and depends not only on technological development but also on energy legislation and public stimulation.

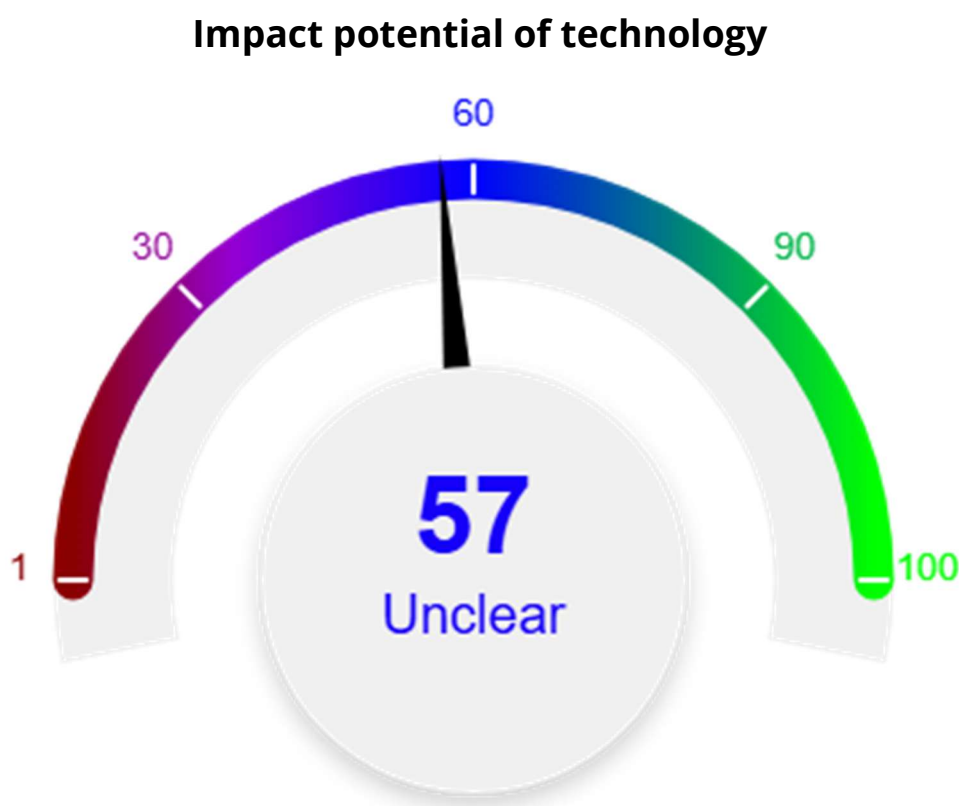


Figure 6.10

So is it The Most Dumb Thing? Yes and No (but rather no)!

Hydrogen energy storage has been heralded as both a revolutionary solution and an impractical endeavour, drawing starkly contrasting opinions.

While hydrogen energy storage faces significant challenges, particularly related to efficiency, cost, and infrastructure, it also offers considerable benefits in terms of decarbonization, versatility, and long-term storage potential. The "dumb" label primarily stems from current technological and economic barriers, but ongoing research, development, and investment may mitigate these issues over time. Therefore, hydrogen is not inherently a "dumb" solution; rather, it is a complex one that requires careful consideration and strategic implementation to unlock its full potential as a clean energy carrier.

Currently, given the limitations discussed in previous sections with respect to physical properties and potential costs, low-carbon hydrogen is best used in applications where there are simply no other good decarbonization options. These „no-regret applications“ are ammonia production, methanol production, steel manufacturing, potentially aviation, heavy-duty trucking, marine shipping.¹⁵⁰ Meanwhile, power generation remains a niche application.

The choice of hydrogen storage technology depends on the specific application, considering factors like energy density, cost, safety, and infrastructure requirements. While compressed hydrogen gas is currently the leading option for mobility, ongoing research and development in other storage technologies hold the promise of further advancements in the future.

7. Galvanic cells – Battery energy storage (BES)

7.1 Introduction to BES

Beyond lithium-based solutions, the next frontier in chemical energy storage lies in batteries crafted from alternative materials. The quest for sustainable and efficient energy storage solutions has led researchers to explore a wide range of materials beyond lithium. These alternative batteries aim to address the limitations of lithium-ion technology while offering comparable or even superior performance.

In the following sections, we'll delve deeper into the diverse world of alternative battery chemistries, exploring their unique characteristics, advantages, and challenges. We'll examine how these emerging technologies hold the potential to revolutionize energy storage and pave the way for a more sustainable and electrified future.

In this context, it's important to understand the fundamental principles of battery operation, which rely on electrochemical processes to store and release energy.

With the rise of electrical equipment and the reduction of their size, there has been an increasing demand for batteries for the portability of equipment. Their operation is typically based on electrochemical processes. Primary batteries (non-rechargeable batteries) are disposable energy stores because non-reversible chemical reactions take place during their operation (electric current flows through them). However, in the case of secondary batteries (rechargeable batteries), by pumping electrons and charges in opposite directions, the chemical reaction that takes place during immersion (discharge) can be (partially) reversed, so it can be used several times after recharging.

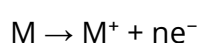
Chemistry

Battery energy storage systems are electrochemical devices that convert chemical energy into electrical energy and vice versa. At their core, all batteries consist of three main components: an anode (negative electrode), a cathode (positive electrode), and an electrolyte.

The fundamental principle of battery operation involves redox (reduction-oxidation) reactions. During discharge, the anode undergoes oxidation, releasing electrons, while the cathode accepts these electrons in a reduction reaction. The electrolyte facilitates the transfer of ions between the electrodes, maintaining electrical neutrality.

Generic half-cell reactions for a battery can be represented as:

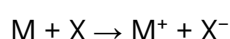
Anode (Oxidation): Anode material (M) loses electrons (e^-) and becomes positively charged ions (M^+).



Cathode (Reduction): Cathode material (X) gains electrons (e^-) and forms negatively charged ions (X^-).



Overall Reaction: The combination of these reactions results in the flow of electrons through an external circuit, generating electrical current.



Electrolyte:

The electrolyte is a crucial component that facilitates the movement of ions between the electrodes, completing the electrical circuit.¹ It can be a liquid, solid, or paste, depending on the battery chemistry.

Cell Voltage:

The potential difference between the anode and cathode, known as the cell voltage, depends on the specific chemical reactions taking place. The higher the difference in the electrochemical potential of the anode and cathode materials, the higher the cell voltage.

Major parameters of batteries are the followings:

- cell voltage (nominal, minimum, maximum) [V]
- nominal capacity (valued at 1 C) [Ah]=[C/s·h]=[3600 C]
- current load capacity [A] (in C)
- charging current [A] (in C)
- internal resistance, impedance [mΩ]
- number of charge-discharge cycles

energy density

- per unit weight [Wh/kg]
- per unit volume [Wh/dm³]
- power density [W/kg]

The parameters listed above largely depend, even for cells of the same base (for example, Ni or Li), on the exact chemical composition, and therefore also on the chemical reactions that take place in them. Below will be the main advantages-disadvantages and areas of application of the most commonly used types of batteries.

History of BES

Initially, the batteries were mainly used for residential consumers e.g. flashlight (flat battery 4.5 V), radio (C "baby" and D "goliath" size), then for consumer electronics in remote controls (AA "pencil" then AAA "small pencil" size). The terminal voltage of the elements depends on the

standard potential of the processes taking place on the anode and cathode of the chemical cell located in them, the difference of which gives the cell voltage, and the number of cells in the element. Typically, in the case of batteries, the cell voltage, 1.5 V which in many cases is also the terminal voltage of the element, however, more cells than a few element sizes are connected in series, thus increasing the terminal voltage. These element types are the 4.5 V flat element, or the element 9 V. In terms of their chemistry and structure, they can be of several types (zinc-carbon, alkaline, lithium), however, due to the compatibility, their cell voltage is typically the same (1.5 V).

Batteries spread to a lesser extent among the population at the beginning, since the first available battery was a heavy and dangerous (due to its corrosive effect) lead-acid battery. It was mainly used in cars and engines just to start them. Today, with the development of technology, the population also uses rechargeable batteries (secondary batteries) in more places, which first spread with the advent of nickel-based (NiCd and NiMH) batteries with the replacement of batteries (first AA and AAA batteries), as well as batteries for mobile phones and notebooks. These have been supplanted by lithium-based batteries with their cells with higher energy density and higher currents (Li-ion, LiPo, etc.), which have the great advantage of a small memory effect for charge-discharge cycles, as well as a much larger number of cycles, so that it can perform its task longer. Further on, the main properties of batteries will be presented.

Battery types

Most commonly used battery types:

- lead-acid battery
 - Main features:
 - production cost medium
 - moderate energy density
 - moderate self-discharge
 - negligible memory effect
 - environmental hazard due to lead
 - Use
 - car starter batteries (SLI: Starting, Lightning, Ignition)
 - Uninterruptible power supply (UPS)
 - Forklifts

They typically consist of cells containing a sulfuric acid electrolyte, with a lead dioxide positive electrode and a sponge lead negative electrode. During discharge, both electrodes undergo a chemical reaction, transforming into lead sulfate.

Lead-Acid batteries, including flooded and valve-regulated lead-acid (VRLA) batteries, share similar operational principles. VRLA batteries require further research to fully realize their commercial potential.

These batteries exhibit a relatively long lifecycle, typically between 1200 and 1800 cycles, depending on the depth of discharge. Their efficiency generally ranges from 75% to 80%, and their lifespan typically falls within 5 to 15 years. However, these characteristics are significantly influenced by operating temperature. While higher temperatures can improve efficiency and capacity, they also accelerate battery degradation. Conversely, low temperatures can significantly reduce battery lifespan and efficiency.

Lead-Acid batteries are known for their low self-discharge rate, making them suitable for long-term energy storage. However, they also present certain limitations. Flooded batteries require regular maintenance to replenish water, and they exhibit relatively low specific energy and power. Furthermore, frequent or rapid charging cycles can lead to premature sulfation and shorten the battery's lifespan.

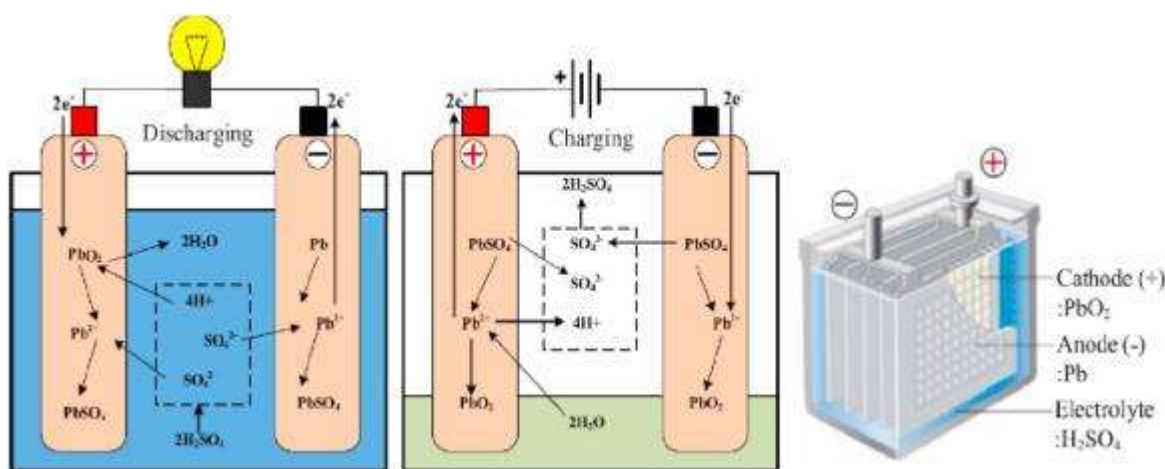


Figure 7.1 A schematic diagram of a Lead-Acid battery cell, illustrating its internal structure and components²²¹

- NiCd battery
 - Main features:
 - production is cheap
 - medium energy density
 - can also be used in devices with high power requirements
 - moderate self-discharge
 - Great memory effect
 - strongly environmentally damaging effect (due to cadmium) – its use is now practically prohibited in Europe.

- Use: Rechargeable batteries for low-power devices (camera, remote control, mouse, RTC, motherboard settings/memory)

Nickel-Cadmium (NiCd) batteries have been used for energy storage since the mid-20th century, demonstrating their long-standing importance. These batteries utilize nickel and cadmium electrodes immersed in an alkaline solution.

During discharge, the positive electrode transforms into nickel hydroxide, while the negative electrode forms cadmium hydroxide. Conversely, during charging, the positive electrode becomes nickel oxyhydroxide, and the negative electrode reverts to metallic cadmium. Potassium hydroxide typically serves as the alkaline electrolyte. NiCd batteries can operate in sealed or flooded configurations depending on the specific application.

These batteries exhibit high charge and discharge rates due to their low internal resistance, enabling rapid power delivery. Key advantages include a long cycle life, often exceeding 3500 cycles, and low maintenance requirements. However, the cycle life is significantly influenced by the depth of discharge, with extended lifespans achievable at shallower discharge depths.

NiCd batteries find applications in various sectors, including industrial uninterruptible power supplies (UPS) and large-scale energy storage systems for renewable energy sources. Their energy efficiency varies depending on the battery construction, with different designs exhibiting varying levels of efficiency.

However, significant drawbacks include high toxicity and the "memory effect," which can impact battery performance. Environmental concerns have led to regulations promoting the recycling of NiCd batteries, potentially impacting their future use.

- NiMH battery
 - Main features:
 - production is cheap
 - cannot be used in devices with high power requirements
 - in conventional chemistry, it has a high energy density, but also a high self-discharge rate ↔ with a newer chemical build, it has a low self-discharge rate, but also a ~25% lower energy density
 - Use: Rechargeable batteries for low-power devices (camera, remote control, mouse, RTC, motherboard settings/memory)
- Lithium ion (Li-ion) battery
 - Main features:
 - very expensive to manufacture
 - very high energy density
 - very low self-discharge
 - in case of explosive breakdown
- Lithium Cobalt Oxide (LiCoO₂) – LCO battery

- Main features:
 - high energy density
 - relatively short service life
 - low thermal stability and limited load capacities
 - must not be charged and discharged at a current greater than C (rated capacity)
- Lithium Iron Phosphate (LiFePO₄) – LFP battery
 - Main features:
 - low internal resistance
 - high load current
 - highly sensitive to temperature
 - charging with a maximum value of around 1 C
 - safe and long-lasting
 - medium energy density
 - increased self-discharge
- Lithium Nickel Manganese (LiNiMnCoO₂) – NMC battery
 - Main features:
 - charging speed can vary between 1-5 C
 - high energy density
 - low cost of production
 - long service life
 - it is characterized either by a high specific energy or by a high specific power (both cannot be at the same time)
- Lithium Manganese Oxide (LiMn₂O₄) – LMO battery
 - Main features:
 - high thermal stability
 - enhanced security
 - limited number of cycles
 - ages even without use (parameters deteriorate over time)
 - low internal cell resistance
 - can be charged with a large C
 - can be loaded with high current (up to 20 – 30 A)
- Lithium Titanate (Li₂TiO₃) – LTO battery
 - Main features:
 - quite expensive to produce
 - its safety is outstanding
 - high cycle life (up to 3000-7000 cycles)
 - can be filled with a high C value

- can be loaded with currents of up to 10 C

The main uses of lithium-based batteries are laptops, phones and electric cars due to the high energy density and load capacity, as well as the high number of cycles.

The Figure . Figure illustrates the energy density of different types of batteries.

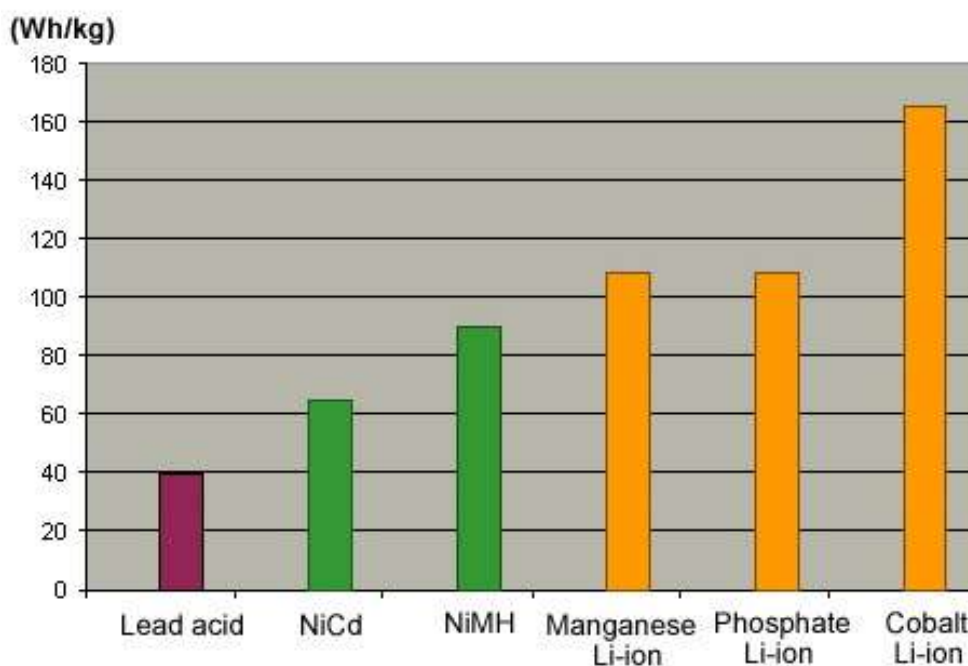


Figure 7.2 Typical specific energy of lead-, nickel-, and lithium-based batteries (batteryuniversity.com, 2022)

In the figure, the stored energy is given in Wh , which is converted into $Joule$ ((0.1) equation).

$$1 Wh = 1 \frac{J}{s} \cdot 3600 s = 3600 J \quad (0.1)$$

Table 7.1 contains typical electrical values of currently common battery types.

Specification	Lead-acid	NiCd	NiMH	Lithium ion		
				Cobalt	Manganese	Phosphate
Specific Energy [Wh/kg]	30-50	45-80	60-120	150-190	100-135	90-120
Specific Density [Wh/dm ³]	60-110	50-150	140-300	300-700	300-700	300-700
Nominal cell voltage [V]	2	1.2	1.2	3.6	3.8	3.3
Charge cutoff voltage [V]	2.4	1.4	1.4	4.2	4.2	3.6
Discharge cutoff voltage	1.75	1	1	2.5-3	2.5-3	2.8
Internal resistance [mΩ]	<100 (12 V pack)	100-200 (6 V pack)	200-300 (6 V pack)	150-300 (7.2 V pack)	25-75 (per cell)	25-50 (per cell)
Peak load current (1C = nominal current)	5C	20C	5C	>3C	>30C	>30C
Best result current (1C = nominal current)	0.2C	1C	0.5C	<1C	<10C	<10C
Life Cycle (80% discharge)	200-300	1000	300-500	500-1000	500-1000	1000-2000
Fast-charge time [h]	8-16	1	2-4	2-4	≤1	≤1
Self discharge [%/month]	5	20	30	<10	<10	<10
In use since	1800s	1950	1990	1991	1996	1999
Toxicity	very high	very high	low	low	low	low

Table 7.1 Typical parameters of different battery types

Figure 7.3 illustrates data on battery types currently in use and under development.

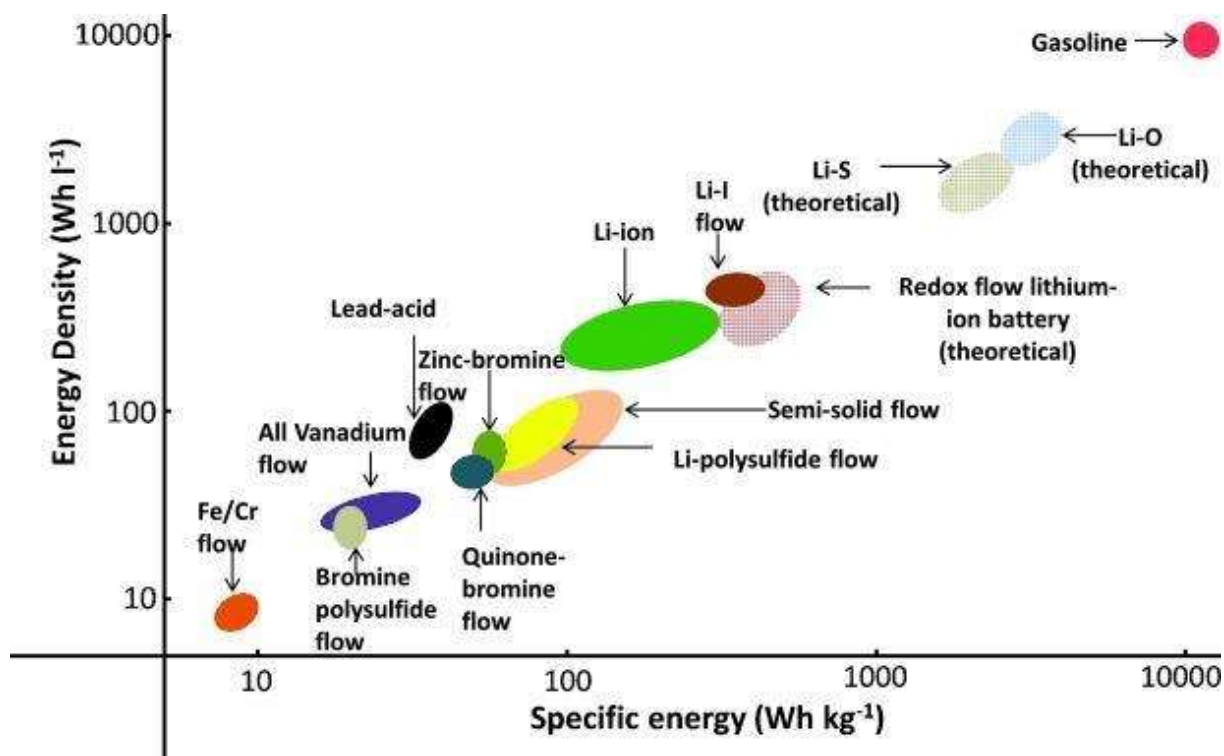


Figure 7.3 Different battery types Energy density $\left[\frac{\text{Wh}}{\text{dm}^3}\right]$ and specific energy $\left[\frac{\text{Wh}}{\text{kg}}\right]$

7.2 Main application of BES

BES systems are critical in various domains, ensuring energy reliability and efficiency:

Battery Energy Storage plays a crucial role in the integration of renewable energy sources like solar and wind. These sources are inherently intermittent, producing energy only under specific conditions. BES ensures that excess energy generated during periods of high production is stored for later use during low production times. This capability bridges the gap between supply and demand, stabilizing energy availability and making renewable energy a more reliable component of the grid. By smoothing out fluctuations, BES enhances grid reliability and enables greater penetration of renewable energy sources.²²²

BES provides essential services for grid stability and performance enhancement. The rapid response capability of modern battery systems allows them to regulate frequency and voltage, ensuring consistent power quality. During peak demand, BES systems discharge energy to alleviate stress on the grid, a process known as peak shaving. Additionally, they act as a buffer during power disruptions, preventing outages and supporting the grid during maintenance or unforeseen challenges.²²³

Energy arbitrage is a key economic application of BES. By storing energy when prices are low—typically during periods of low demand—and discharging it when prices peak, BES systems optimize energy use and reduce operational costs. This application benefits both energy producers and consumers, providing financial savings and improving overall system efficiency.²²⁴

The resilience provided by BES is vital for critical infrastructure. Hospitals, data centers, and industrial facilities require uninterrupted power to maintain operations and prevent data loss or equipment damage. BES systems act as a reliable backup, ensuring seamless power supply during outages. Their ability to provide instantaneous power makes them superior to traditional backup systems, such as diesel generators, in terms of both response time and environmental impact.²²⁵

The electrification of transportation relies heavily on advancements in BES technology. Electric vehicles (EVs) depend on batteries for range, performance, and cost-effectiveness. Innovations in battery chemistry, such as solid-state and fast-charging technologies, are driving the expansion of EV adoption. Furthermore, BES systems support the development of charging infrastructure, enabling faster and more efficient charging solutions for both personal and commercial vehicles. This progress is essential for achieving widespread EV adoption and reducing transportation sector emissions.²²⁶

Distributed Energy Resources (DERs) have emerged as a promising solution to these challenges. DERs, typically smaller-scale than conventional power plants, are often located closer to the point of consumption, enhancing efficiency and reducing transmission losses. Key components of DERs include Renewable Energy (RE) sources and Energy Storage Systems (ESS).

However, the integration of DERs, particularly intermittent RE sources like solar and wind power, presents unique challenges. The variable nature of these sources can lead to fluctuations in power supply and potential grid instability. For instance, solar power generation peaks during midday, while electricity demand often surges in the evening, creating a mismatch between supply and demand.

Energy Storage Systems (ESS) play a crucial role in mitigating these challenges. ESS, encompassing technologies like batteries, pumped hydro, and thermal storage, act as buffers between energy supply and demand. By storing excess energy during periods of low demand or high generation, ESS can be utilized to meet peak demand, smooth out supply fluctuations, and improve grid stability.

Furthermore, ESS can enhance the efficiency and cost-effectiveness of conventional power plants. By maintaining a more consistent level of power generation, ESS can reduce the need for frequent ramping up and down of conventional plants, which can be inefficient and costly.

Beyond grid-level applications, ESS can also provide significant benefits to residential and commercial consumers. By enabling consumers to shift their energy consumption to periods of low demand or utilize stored solar energy during peak demand, ESS can help reduce energy costs and increase energy independence.

In conclusion, the integration of ESS is crucial for the successful and sustainable integration of DERs into the evolving energy landscape. By addressing the challenges of intermittency and variability, ESS can enhance grid reliability, improve energy efficiency, and empower consumers to play a more active role in the energy market.

7.3 Technological barriers, regulatory framework and scalability

The deployment of BES technologies is not without challenges, and these challenges can be categorized into several key areas, including technological barriers, cost, regulatory hurdles, and scalability.

7.3.1 Technological Barriers

The *energy density* of a battery determines how much energy can be stored per unit of weight or volume, a critical factor for applications requiring compact and lightweight solutions, such as electric vehicles (EVs) and portable devices. Lithium-ion batteries have set a high benchmark with their superior energy density. However, emerging chemistries like sodium-ion and zinc-air batteries face challenges in achieving comparable performance. Research focuses on improving the structural and electrochemical properties of these alternatives, but significant advancements are required to close the gap with lithium-based systems.²²⁷

A battery's *cycle life*—the number of charge and discharge cycles it can endure before significant degradation—is a key determinant of its economic viability. Lithium-ion batteries typically offer 3,000 to 5,000 cycles, but alternative chemistries often fall short of this range. Efforts are being directed at enhancing electrode stability and electrolyte formulations to improve durability. Additionally, achieving high round-trip efficiency—the ratio of energy retrieved to energy stored—is critical for operational cost-effectiveness. Many new technologies still exhibit lower efficiencies due to internal resistance and side reactions, necessitating innovations in material science and system design.

²²⁸*Thermal management* is a persistent challenge across all battery technologies, impacting safety, performance, and longevity. Lithium-ion batteries are particularly prone to thermal runaway, a chain reaction triggered by overheating that can lead to catastrophic failure. Emerging

technologies, such as solid-state batteries, aim to mitigate these risks by replacing flammable liquid electrolytes with solid alternatives. Advanced cooling systems and thermal interface materials are also being developed to maintain optimal operating temperatures, ensuring both safety and efficiency. Effective thermal management will be pivotal for large-scale applications like grid storage, where batteries must endure varied environmental conditions and prolonged use.²²⁹

7.3.2 Cost Challenges

Cost remains another significant challenge for BES technologies. Although the cost of lithium-ion batteries has decreased significantly over the past decade, the initial investment required for BES systems is still relatively high. This high capital expenditure (CAPEX) can be a major barrier for many potential users, especially for large-scale applications. For smaller residential or commercial users, the upfront cost may be prohibitive, limiting the adoption of BES systems despite their long-term benefits.

In addition to CAPEX, operational costs (OPEX) also contribute to the economic challenges of BES. These include maintenance costs, such as thermal management systems to prevent overheating and the periodic replacement of degraded components. The need for specialized maintenance adds to the overall expense, particularly for lithium-ion technologies that are more susceptible to thermal runaway. To improve the economic feasibility of BES, it is crucial to develop more cost-effective solutions, both in terms of initial investments and ongoing operational expenses. Emerging technologies, such as solid-state batteries, promise lower OPEX due to their inherent stability, which reduces the need for complex cooling systems and extends their operational lifespan.

7.3.3 Recycling and Disposal

Another critical challenge for BES deployment is the recycling and disposal of batteries. Effective recycling infrastructure is essential to minimize the environmental impact of spent batteries and recover valuable materials such as lithium, cobalt, and nickel. Currently, battery recycling processes are limited in their efficiency and cost-effectiveness. Most existing recycling methods are energy-intensive and can only recover a portion of the valuable materials. This inefficiency not only poses environmental risks but also contributes to the scarcity of critical raw materials.

The development of advanced recycling technologies is crucial for the sustainable growth of BES. Innovations such as hydrometallurgical and direct recycling techniques are being explored to

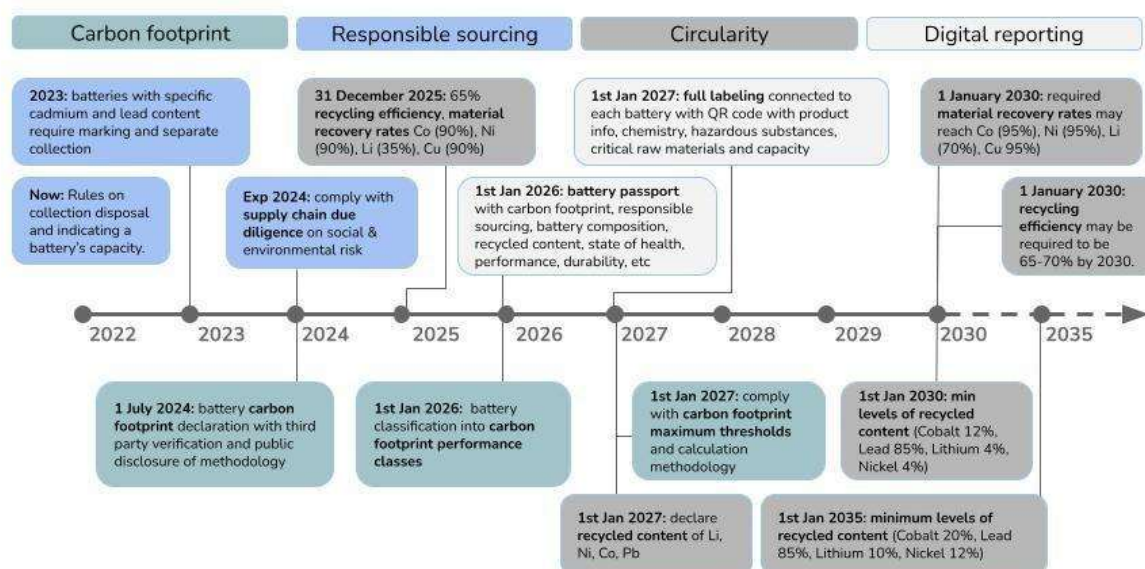
improve the recovery rates of valuable materials and reduce the energy requirements of recycling processes. Additionally, designing batteries with recyclability in mind—such as modular designs that can be easily disassembled—can facilitate more efficient recycling and reduce the overall environmental impact.

7.3.4 Regulatory Framework

The regulatory landscape surrounding Battery Energy Storage (BES) systems is crucial in shaping their development, deployment, and integration into the energy market. This framework encompasses a variety of regulations, incentives, and standards aimed at promoting sustainability, safety, and efficiency in battery technologies. As the demand for energy storage solutions grows, particularly in the context of renewable energy integration, the role of regulatory measures becomes increasingly significant.

One of the most comprehensive regulatory frameworks is the European Union's Battery Regulation²³⁰. This regulation establishes stringent requirements for battery production and lifecycle management, addressing key environmental and ethical concerns associated with battery materials.

The regulation mandates specific targets for recycled content in batteries, aiming to promote a circular economy and reduce reliance on virgin materials. It also requires manufacturers to provide detailed reporting on material sourcing, which enhances transparency and accountability within the supply chain. This is particularly important given the geopolitical risks associated with critical raw materials such as lithium, cobalt, and nickel.

Figure 7.4 Milestones for the EU Battery Regulation²³¹

Moreover, the regulation emphasizes safety standards that must be met by battery manufacturers to prevent hazards like thermal runaway and chemical leaks. These safety requirements are essential for protecting consumers and ensuring that BES systems can operate reliably within the energy grid.²²²

International standards also play a significant role in shaping the regulatory landscape for BES systems. Organizations such as the International Electrotechnical Commission (IEC) establish guidelines for battery performance, safety, and testing protocols that manufacturers must adhere to²³². Compliance with these standards is essential for ensuring product reliability and gaining market acceptance.

Environmental regulations further impact BES systems by enforcing limits on emissions during production processes and mandating proper disposal methods at the end of a battery's lifecycle. For instance, waste management directives require that batteries be recycled or disposed of in an environmentally responsible manner. This focus on sustainability helps minimize environmental impacts associated with hazardous materials found in batteries²³³.

7.3.5 Scalability and Emerging Technologies

Scaling up Battery Energy Storage (BES) systems presents several significant challenges that must be addressed to meet the growing global demand for energy storage solutions. These

challenges encompass resource constraints, manufacturing capacity, cost efficiency, and technological innovations. As the energy landscape evolves, overcoming these scalability hurdles is critical for the successful integration of BES into both existing and future energy systems.

One of the primary challenges in scaling BES systems is the availability of critical raw materials. The production of batteries relies heavily on materials such as lithium, cobalt, nickel, and graphite, which are often subject to supply chain vulnerabilities and geopolitical risks. For instance, over 70% of cobalt is sourced from the Democratic Republic of Congo, where mining practices raise ethical and environmental concerns²³⁴. As demand for batteries increases—driven by electric vehicles (EVs) and renewable energy integration—the pressure on these resources intensifies. This situation necessitates innovative approaches to material sourcing and recycling to ensure a stable supply²³⁵.

To meet the rising demand for BES technologies, manufacturers must significantly expand their production capabilities. Innovations such as gigafactories—large-scale battery manufacturing facilities—are essential for achieving economies of scale and reducing production costs. These facilities enable high-volume production while maintaining quality standards²³⁶. However, building gigafactories requires substantial capital investment and time, posing a barrier for many companies looking to enter or expand within the market.

Additionally, automated production lines are becoming increasingly important in enhancing manufacturing efficiency. Automation can reduce labor costs and improve precision in battery assembly processes, ultimately leading to higher throughput and lower unit costs²²³. However, implementing advanced manufacturing technologies necessitates a skilled workforce and significant investment in training.

7.4 BES Raw material restrictions

Battery Energy Storage (BES) systems rely heavily on a limited set of critical raw materials, each contributing uniquely to the performance of batteries:

- **Lithium:** Essential for achieving high energy density and fast charge-discharge cycles, lithium serves as the backbone of most advanced battery chemistries²³⁷.
- **Cobalt:** Plays a key role in stabilizing the cathode and extending battery life, particularly in high-performance applications, though it raises significant environmental and ethical concerns²³⁸.
- **Nickel:** Enhances energy capacity, enabling batteries to deliver longer operating ranges and support high-demand applications.

- Graphite: Used as the primary material for anodes, it facilitates efficient lithium-ion intercalation.
- Manganese: Adds stability to the cathode structure while improving safety by reducing risks of thermal runaway.

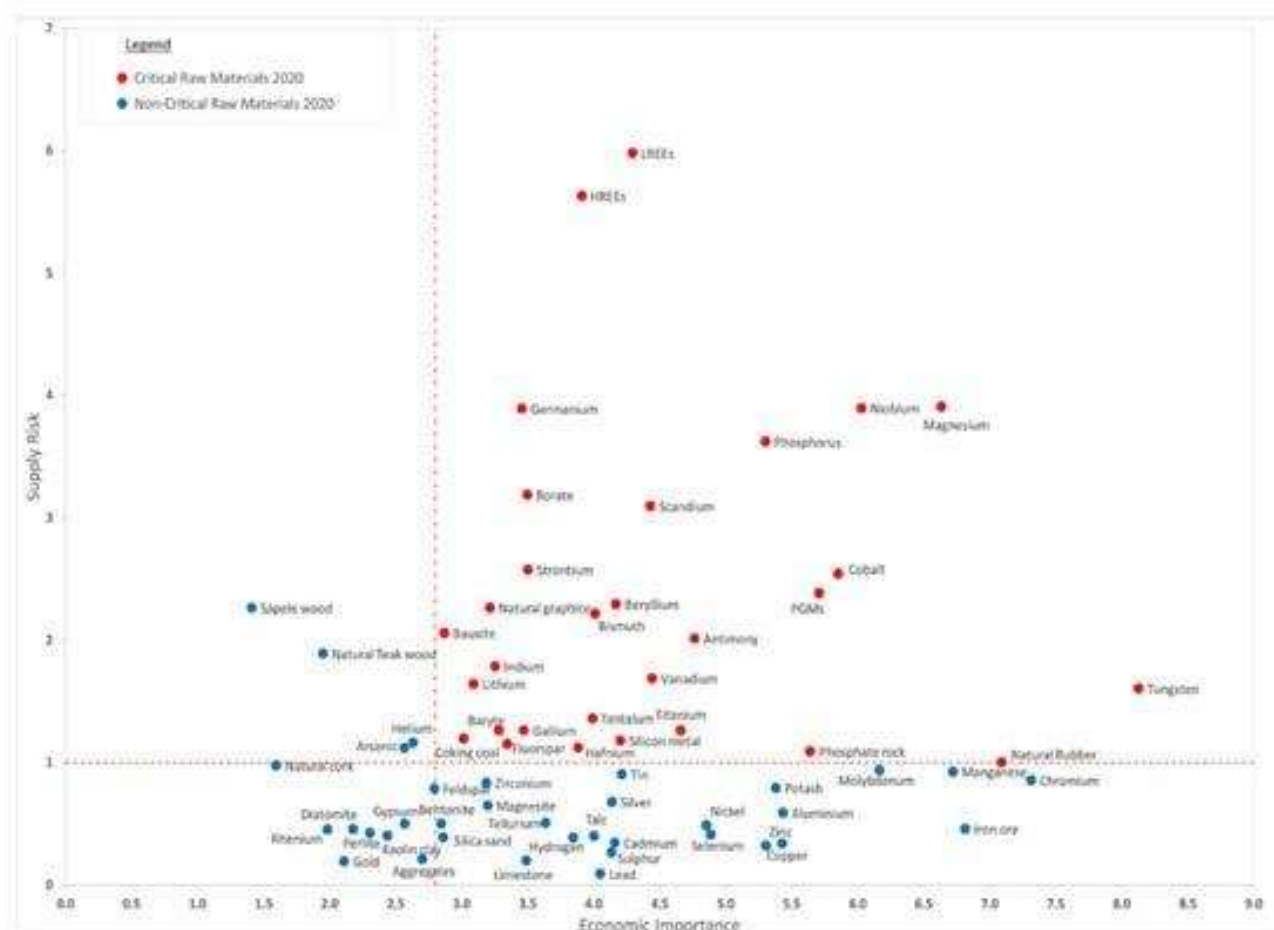


Figure 7.5 Critical Raw Materials (CRMs) chart based on the 2020 CRM list. Study on the EU's list of critical raw materials (2020)

However, the sourcing and processing of these materials present major challenges listed below.

Environmental Impact

Mining activities for critical battery materials such as lithium, cobalt, and nickel have far-reaching environmental consequences. Lithium extraction, particularly in South America's "lithium triangle" (Argentina, Bolivia, and Chile), involves water-intensive processes. These operations often deplete local water supplies, adversely affecting ecosystems and agriculture-dependent communities. For example, the extraction process can consume up to 500,000 gallons of water per ton of lithium, intensifying water scarcity in already arid regions²³⁹.

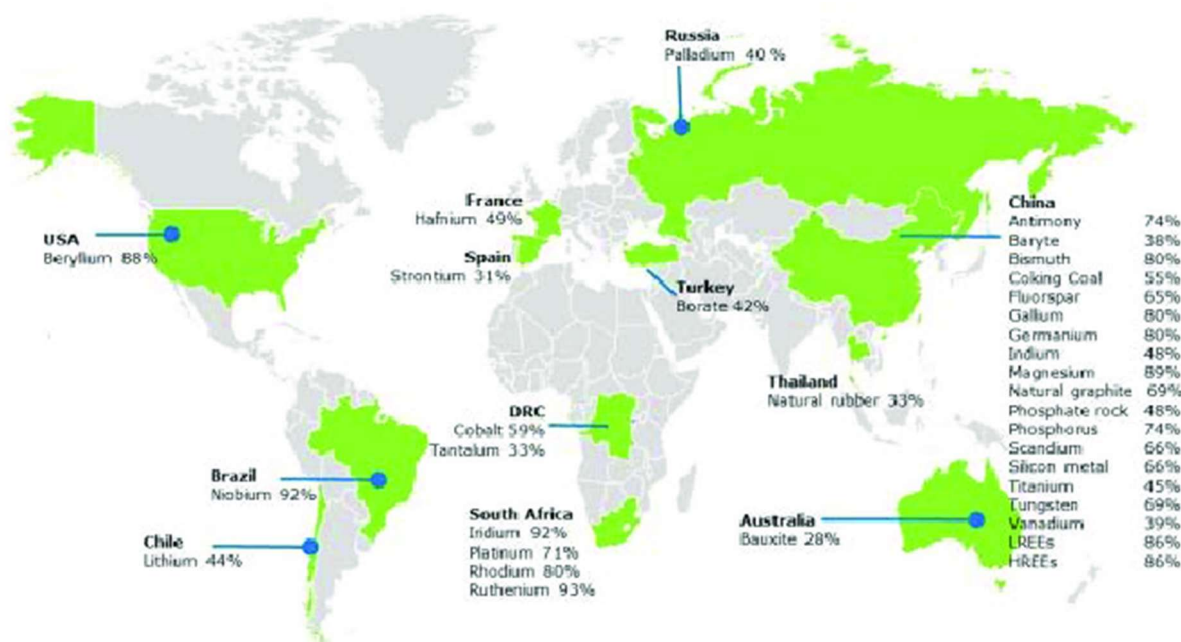


Figure 7.6 Countries accounting for largest share of global supply of CRMs

Cobalt mining, predominantly centered in the Democratic Republic of Congo, is criticized for its environmentally destructive techniques, including unregulated mining that causes soil erosion and contaminates water bodies with heavy metals. Furthermore, the reliance on artisanal mining exacerbates these issues, as these small-scale operations frequently lack environmental safeguards.

Nickel extraction involves high-energy smelting and refining processes that contribute significantly to greenhouse gas emissions. Sulfide ore mining, a common method for nickel extraction, can also lead to acid mine drainage, severely impacting nearby water systems and biodiversity.

The cumulative effects of these practices underline the urgent need for stricter environmental regulations and innovative mining techniques that minimize ecological footprints. For instance, closed-loop water systems in lithium extraction and improved tailings management in cobalt and nickel mining could help mitigate some of these impacts.

Geopolitical and Ethical Concerns

The supply of key materials is geographically concentrated, making global supply chains vulnerable to disruptions. Over 70% of cobalt production comes from the Democratic Republic of Congo, raising concerns about market monopolies and the stability of supply. Moreover, labor

exploitation, including child labor in mining operations, underscores the urgent need for ethical sourcing practices.

7.5 BES Energy Storage costs

The cost of battery energy storage systems (BES) is a critical factor that influences their adoption and widespread deployment. Understanding the different components of these costs, including capital expenditure (CAPEX) and operational expenditure (OPEX), is essential for evaluating the economic viability of BES technologies.

7.5.1 Capital Expenditure (CAPEX)

CAPEX refers to the upfront costs associated with the acquisition and installation of BES systems. For lithium-ion batteries, these costs have decreased significantly over the past decade, largely due to advancements in manufacturing technologies, economies of scale, and increased competition within the market. However, despite these reductions, the initial investment required for BES systems remains relatively high. For large-scale grid applications, the CAPEX can be particularly prohibitive, as it involves not only the cost of battery cells but also additional costs such as power electronics, thermal management systems, and infrastructure upgrades.

CAPEX is also influenced by the choice of battery chemistry. While lithium-ion batteries offer high energy density and long cycle life, they require the use of expensive raw materials like lithium, cobalt, and nickel, which contribute to higher costs. Alternative battery chemistries, such as sodium-ion or flow batteries, are being explored as lower-cost options due to their use of more abundant and less costly materials. These alternatives could reduce CAPEX and make BES more accessible, particularly for applications where high energy density is not a primary requirement.

7.5.2 Operational Expenditure (OPEX)

OPEX refers to the ongoing costs associated with the operation and maintenance of BES systems throughout their lifecycle. Maintenance costs for BES include monitoring the battery's health, managing temperature to prevent overheating, and replacing components that degrade over time. Lithium-ion batteries, for example, require sophisticated thermal management systems to ensure safe and efficient operation, which adds to OPEX. Moreover, the degradation of battery cells over time necessitates periodic replacement, contributing further to operational costs.

Solid-state batteries are emerging as a potential solution to reduce OPEX. Unlike traditional lithium-ion batteries, solid-state batteries do not use liquid electrolytes, which reduces the risk

of leakage and thermal runaway, thus minimizing the need for complex cooling systems. This inherent stability makes solid-state batteries less maintenance-intensive and could lead to significant reductions in OPEX over the long term.

7.5.3 Levelized Cost of Storage (LCOS)

The Levelized Cost of Storage (LCOS) is a key metric used to evaluate the overall cost-effectiveness of BES technologies. LCOS takes into account both CAPEX and OPEX, as well as the expected lifetime and efficiency of the storage system. It provides a comprehensive measure of the cost per unit of energy stored and delivered over the system's operational life. Factors such as round-trip efficiency, cycle life, and depth of discharge all influence LCOS, making it an important tool for comparing different battery technologies.

For lithium-ion batteries, the LCOS has been steadily decreasing due to improvements in efficiency and reductions in CAPEX. However, other technologies, such as flow batteries and compressed air energy storage, may offer lower LCOS for certain applications, particularly those requiring long-duration storage. Flow batteries, for instance, have a lower upfront cost per kWh of storage capacity and longer cycle life, which can lead to a more favorable LCOS for grid-scale applications.

7.5.4 Impact of Economies of Scale

Economies of scale play a significant role in reducing the costs of BES. As production volumes increase, the per-unit cost of batteries tends to decrease due to efficiencies in manufacturing, supply chain optimization, and technological learning. This trend has been particularly evident in the case of lithium-ion batteries, where the rapid growth of the electric vehicle (EV) market has driven down costs for both EV and stationary storage applications. Government incentives, subsidies, and investments in large-scale manufacturing facilities have further accelerated cost reductions, making BES more economically viable.

7.5.5 Financial Incentives and Subsidies

Government policies and subsidies are crucial in making BES technologies economically viable, especially during the early stages of adoption. Incentives such as tax credits, grants, and subsidies can help offset the high CAPEX of BES, making these systems more attractive to consumers and businesses. In some regions, governments also offer financial incentives for

using renewable energy sources in conjunction with BES, further reducing the effective cost of storage. By lowering financial barriers, these incentives can accelerate the adoption of BES technologies and support the transition to a more sustainable energy system.

In conclusion, the cost of BES systems encompasses several components, each of which plays a critical role in determining their overall economic feasibility. Reducing both CAPEX and OPEX through advancements in battery chemistry, economies of scale, and supportive government policies is essential for making BES technologies accessible and affordable. As innovations continue to drive down costs, BES will become an increasingly integral part of the global energy landscape, supporting the growth of renewable energy and enhancing grid stability.

7.6 Existing systems

There are several existing BES technologies currently in use, each with distinct advantages and limitations. Lead-acid batteries are one of the oldest and most widely used forms of battery energy storage. They have been extensively utilized for backup power and off-grid applications due to their reliability and relatively low upfront cost. Despite their long-standing use, lead-acid batteries have significant drawbacks, such as lower energy density and shorter lifespan compared to more advanced battery technologies. These limitations make them less suitable for applications that require compact, high-energy storage solutions. However, their robust performance and cost-effectiveness have ensured their continued relevance, especially in scenarios where space and weight are not primary concerns.

Lithium-ion batteries have emerged as the dominant technology for electric vehicles (EVs) and grid storage, largely due to their high energy density, efficiency, and long cycle life. These characteristics make lithium-ion batteries ideal for both mobile and stationary applications, providing the necessary balance of power, energy capacity, and weight. The success of lithium-ion technology can be attributed to the continuous advancements in materials and manufacturing processes, which have led to improved energy densities, reduced costs, and enhanced safety features. However, the reliance on critical raw materials like lithium, cobalt, and nickel poses sustainability challenges, including supply chain vulnerabilities and environmental concerns. Research efforts are focused on developing alternatives to reduce dependency on these materials while maintaining or improving battery performance.

Emerging chemistries, such as sodium-ion and zinc-air, are gaining increasing attention due to their potential to address the sustainability and cost issues associated with lithium-ion batteries. Sodium-ion batteries, for instance, utilize more abundant and widely available materials, which could significantly lower production costs and improve the security of the supply chain. Although

sodium-ion batteries generally have a lower energy density compared to lithium-ion, ongoing research is working to bridge this gap, making them a promising alternative for large-scale energy storage where weight is less critical. Zinc-air batteries, on the other hand, offer high energy density and the advantage of easy recyclability. Their use of zinc, an abundant and less expensive material, makes them particularly attractive for long-duration energy storage applications. The main challenge for zinc-air technology is improving the rechargeability and efficiency of the cells, but advancements in catalyst and electrolyte development are showing promising results. These emerging technologies are positioned to complement or even replace existing battery chemistries, particularly in applications where cost, sustainability, and material availability are of paramount importance.

Europe witnessed a surge in battery energy storage system (BESS) deployments in 2023. Here are some prominent examples:

- RWE's North Rhine-Westphalia Project (Germany): This large-scale project, totaling 220 MW, aimed to enhance grid stability and support the integration of renewable energy sources. It comprised multiple sites utilizing lithium-ion battery technology²⁴⁰.
- Wärtsilä's Kilmarnock Project (UK): This 300 MW / 600 MWh energy storage system in Scotland demonstrated the growing role of BESS in supporting grid flexibility and reliability in the UK²⁴¹.
- Centrica's 50 MW Battery Storage Plant (UK): This project involved repurposing a former gas-fired power station, showcasing innovative approaches to energy infrastructure utilization.
- Increased Residential and Commercial Deployments: 2023 saw a significant rise in residential and commercial BESS installations across Europe, driven by factors like increasing electricity prices and the desire for energy independence. These systems typically utilize smaller-scale battery systems for applications such as peak shaving and backup power²⁴².

7.6.1 Notable Large-Scale Lithium-Ion Energy Storage Systems

Hornsedale Power Reserve, Australia

The Hornsedale Power Reserve (HPR), owned and operated by Neoen and supplied by Tesla, is one of the world's most prominent lithium-ion battery energy storage systems. Located near Jamestown, South Australia, HPR began operations with a discharge capacity of 100 MW and an energy storage capacity of 129 MWh, which has since been expanded to 150 MW/193.5 MWh.

Sharing its 275 kV network connection point with the 30 MW Hornsdale wind farm, the HPR provides critical grid stabilization by absorbing fluctuations from renewable energy sources and ensuring consistent power delivery.



A significant portion of the system's capacity—70 MW—is reserved for system security services contracted with the South Australian Government. This includes rapid frequency response and other ancillary grid services to enhance energy security. The remaining 30 MW of discharge capacity and 119 MWh of storage are used by Neoen for market participation, demonstrating the economic potential of battery storage in energy trading.

During its second year of operation, detailed studies quantified HPR's impact on the Frequency Control Ancillary Services (FCAS) market, showing substantial cost savings and efficiency improvements. These findings underscore the vital role of advanced lithium-ion energy storage in reducing grid operating costs and facilitating the integration of renewable energy into modern power systems²⁴³.

HPR's market impact during the 2019 calendar year were:

- HPR captured approximately 15% of the Contingency FCAS market volume and 12% of the Regulation FCAS market volume across the mainland NEM regions.
- HPR is modelled to have reduced the total Contingency FCAS cost by approximately \$80M, and the total Regulation FCAS cost by approximately \$36M, for a total NEM cost reduction of approximately \$116M.

- Approximately \$102M of these cost reductions (88%) were during periods when South Australia was interconnected with other NEM regions
- HPR's market value was also particularly evident during a 5-hour South Australia separation event on 16 November 2019, in which it is modelled to have provided a market benefit of approximately \$14M.
- Upon the introduction of HPR into the FCAS markets, average yearly regulation FCAS costs from South Australian generators fell from a high of \$470/MWh to less than \$40/MWh, where they remain today, resulting in considerable savings in South Australian energy costs.

Gateway Energy Storage, California, USA

Gateway Energy Storage, operated by LS Power, is one of the largest lithium-ion battery storage facilities in the United States, with a capacity of 250 MW and an energy storage capability of 250 MWh. The system utilizes advanced lithium-ion battery cells supplied by LG Chem and plays a critical role in enhancing grid reliability and supporting California's renewable energy goals. By storing excess solar energy generated during the day and discharging it during peak demand hours, Gateway helps balance energy supply and demand efficiently.



Located in Otay Mesa, California, near the Mexican border, the facility is strategically positioned adjacent to the Pico and Otay Mesa natural gas-fired power plants, which have a combined capacity of 1 GW. This location underscores its importance as a complementary resource to traditional power generation. Gateway is a benchmark for large-scale energy storage systems, highlighting both the potential and challenges of lithium-ion technology in grid applications.

Energy Storage System (ESS) at Jongno, South Korea

The Jongno ESS project, located in Seoul, South Korea, is a prime example of a large-scale urban lithium-ion storage solution. With a capacity of 150 MW/300 MWh, this system integrates seamlessly into the city's dense infrastructure, demonstrating the adaptability of lithium-ion technology in urban environments. The primary objective of the Jongno ESS is to support South Korea's transition to renewable energy by providing grid stability and peak shaving services.

Additionally, the system highlights advancements in energy management software, leveraging artificial intelligence to optimize battery performance and extend system life. The Jongno project underscores the importance of integrating cutting-edge digital tools with energy storage solutions to maximize efficiency and reliability.

7.6.2 Notable Lead-Acid Storage Systems

Chino Battery Storage Project, California, USA

The Chino Battery Storage Project is a landmark in the history of grid-scale energy storage, utilizing lead-acid battery technology. With a capacity of 10 MW, this system was among the first to demonstrate the feasibility of large-scale battery integration into the grid. Its primary function was to provide peak-shaving services, alleviating stress during high-demand periods and ensuring a reliable energy supply^{244 245}.

Despite being overshadowed by modern lithium-ion technologies, the Chino project highlighted the durability and cost-effectiveness of lead-acid batteries for specific use cases. These batteries, while limited in energy density and lifecycle compared to lithium-ion systems, proved advantageous due to their lower upfront costs and well-understood maintenance requirements. The project also laid the groundwork for subsequent advancements in grid-scale energy storage, influencing design and operational strategies for newer technologies.

7.7 Conclusions: advantages, disadvantages, and recommendations for BES

Battery energy storage systems offer numerous advantages, making them a key technology for modern energy systems. They provide high energy density and efficiency, are highly scalable, and can be used across a wide range of applications, from grid stabilization to backup power. Their rapid response times make them ideal for balancing supply and demand, particularly in systems with a high penetration of renewable energy. However, BES also has its disadvantages, including the dependency on critical raw materials, limited recyclability, and safety concerns, such as the risk of thermal runaway in lithium-ion batteries.

To maximize the potential of BES technologies, several recommendations can be made. Investments in recycling infrastructure are essential to recover valuable materials and reduce

the environmental impact of battery disposal. Research into alternative battery chemistries, such as sodium-ion and solid-state batteries, should be prioritized to address the material and cost challenges associated with lithium-ion technology. Additionally, policymakers should establish supportive regulatory frameworks and incentives that encourage the adoption of BES and facilitate their integration into the energy grid. By addressing these challenges, BES can play a crucial role in the transition to a sustainable and resilient energy future.

7.7.1 Pros and cons

The advantages of BES are numerous, including their versatility across different applications, high energy density, and rapid response times. BES systems are well-suited for both short-term power quality applications and long-duration energy storage, making them an essential tool for modern energy systems. Their ability to stabilize the grid and integrate renewable energy sources makes them a key component in the transition to a low-carbon economy.

However, BES also has its drawbacks. The environmental impact of extracting raw materials, such as lithium and cobalt, is significant, and the limited performance of some alternative chemistries compared to lithium-ion batteries remains a challenge. Additionally, the cost of BES systems, both in terms of initial investment and ongoing maintenance, can be prohibitive, particularly for large-scale applications. Safety concerns, such as the risk of thermal runaway, also need to be addressed to ensure the widespread adoption of BES technologies.

7.7.3 WICE Baseline

Battery Energy Storage plays a pivotal role in the transition to sustainable energy systems. Lithium-ion batteries, as the most prevalent BES technology, perform exceptionally well across several critical parameters:

- **Energy Density:** Lithium-ion batteries lead in energy density compared to most alternatives, such as sodium-ion and zinc-air batteries, making them ideal for applications where space and weight are constrained, like electric vehicles and portable electronics.
- **Technological Maturity:** With decades of development and widespread deployment, lithium-ion batteries exhibit the highest level of technological readiness. This maturity translates to established supply chains, well-understood performance characteristics, and extensive manufacturing infrastructure.
- **Round-Trip Efficiency:** Lithium-ion systems achieve a high round-trip efficiency, typically ranging from 85% to 95%. This efficiency surpasses technologies like hydrogen storage

and compressed air energy storage (CAES), making lithium-ion ideal for applications requiring frequent cycling.

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	50	5
Energy Retention Period	0.1	50	5
Lifetime and Life Cycles	0.1	50	5
Round-Trip Efficiency (RTE)	0.15	50	7.5
Technological Maturity (TRL)	0.2	400	20
Capital Expenditure (CAPEX)	0.1	50	5
Operational Expenditure (OPEX)	0.1	50	5
Environmental Impact	0.1	50	5
Scalability	0.05	50	2.5
Total	1		60

Despite these strengths, lithium-ion batteries face significant challenges:

- **Resource Dependency:** Lithium-ion technology relies heavily on scarce materials like lithium, cobalt, and nickel, leading to supply chain vulnerabilities and environmental concerns. In comparison, alternatives such as vanadium redox flow batteries (VRFBs) and sodium-ion batteries use more abundant and sustainable resources.
- **Lifecycle and Scalability:** While lithium-ion batteries offer moderate lifecycle performance, technologies like VRFBs and flywheel energy storage excel in durability and scalability, especially in grid-scale applications where long lifespans and low operational costs are critical.
- **Thermal Management:** Lithium-ion batteries are prone to thermal runaway, necessitating robust cooling and safety mechanisms. Emerging solutions like solid-state batteries aim to address these safety issues by replacing liquid electrolytes with solid materials.

The optimal application of lithium-ion batteries lies in their flexibility and high performance for consumer electronics, electric vehicles, and medium-scale energy storage. However, to meet the

demands of a sustainable energy future, the energy storage portfolio must expand to include alternatives such as VRFBs, ultracapacitors, and hydrogen storage. These technologies complement lithium-ion systems by addressing its limitations, particularly in terms of material sustainability, lifecycle performance, and scalability.

Through ongoing innovation and strategic integration of diverse BES technologies, a balanced and resilient energy storage ecosystem can be achieved, supporting the global transition to renewable energy systems.

8 Flow cells (VRFB)

Summary of metrics

Parameter	Value/Range
Energy Capacity (kWh)	Several hundred MWh
Power Rating (kW or MW)	1W – 400MW, scalable
Energy Density [Wh/L]	10-30 Wh/kg
Power density [W/kg]	50 W/kg
Energy Retention Period [hour]	6-12 months
Lifetime and Life Cycles [years/cycles]	20 years / 15.000- 20.000 cycles
Discharge Time [hour]	4 - 6 hour
Round-Trip Efficiency (RTE)	65 - 85%
RTE degradation	small
Technological Maturity (TRL)	7
Capital Expenditure (CAPEX)	2021: 350 EUR/kWh (100 MW, 10-hour system)
Operational Expenditure (OPEX)	12 EUR/kWh/year (2021)
Environmental Impact	Moderate (depending on production and recycling processes)
Scalability	High (widely scalable from small to large applications)
Material Sourcing and Sustainability	Moderate (depends on mining and recycling practices)

8.1 Introduction

According to the PhD thesis from University of Porto, 2022²⁴⁶, the redox flow batteries (RFB) are rechargeable batteries that require low maintenance and display a fast response time, a high energy efficiency (up to 85 %), and a long lifetime (up to 20 000). Also, they have the unique feature of decoupling power and energy capacity. The power is set by the battery stack size (e.g., number of electrochemical cells and active area size), and the energy is set by the electrolyte (e.g., total volume and concentration of redox species). The latter is stored in external tanks and pumped from the tanks to the stack and vice-versa. Thus, RFBs can be easily scaled to each application's requirements²⁴⁷. However, the energy density of RFBs is low when compared to, for example, lithium- ion batteries, and a large area is required for installation. RFBs are only suitable for large-scale stationary applications.

History

The concept of RFB was invented in 1954 by Dr. Walther Kangro.²⁴⁸ Two electrolytes – a positive electrolyte, displaying a higher redox potential, and a negative electrolyte, displaying a lower redox potential – are used as energy carriers. The electrolytes are separated by an ion-exchange membrane which, under charging and discharging conditions, allows selected ions to pass and complete redox reactions. However, no experimental demonstration of the RFB concept was carried out until the 1970s, when NASA developed the first RFB. It employed the iron and chromium redox couples in diluted hydrochloric acid. Later in the 1980s, Skyllas-Kazacos and colleagues²⁴⁹ developed the all-vanadium redox flow battery (or simply, vanadium redox flow battery – VRFB). RFBs started being widely researched in 2011, after the Copenhagen Accord was established. Among other goals, the Copenhagen Accord aimed at providing financial support to developing countries for developing new technologies that could help reduce GHG emissions. Significant improvements have been made to RFBs since 2011, leveraging them as the most promising battery technology for large-scale stationary applications. In fact, RFBs are already commercialized, and they currently represent about 4 % of the world's installed power capacity, excluding pumped hydro. Along with performance improvements, many electrolyte chemistries (Figure 8.1) have been researched to find the RFB with the ideal characteristics: safe, recyclable, eco-friendly, cheap, and should display a good reversibility, a good electrolyte stability, a negligible capacity loss, a long cycle life, a high efficiency, and a high power and energy densities.

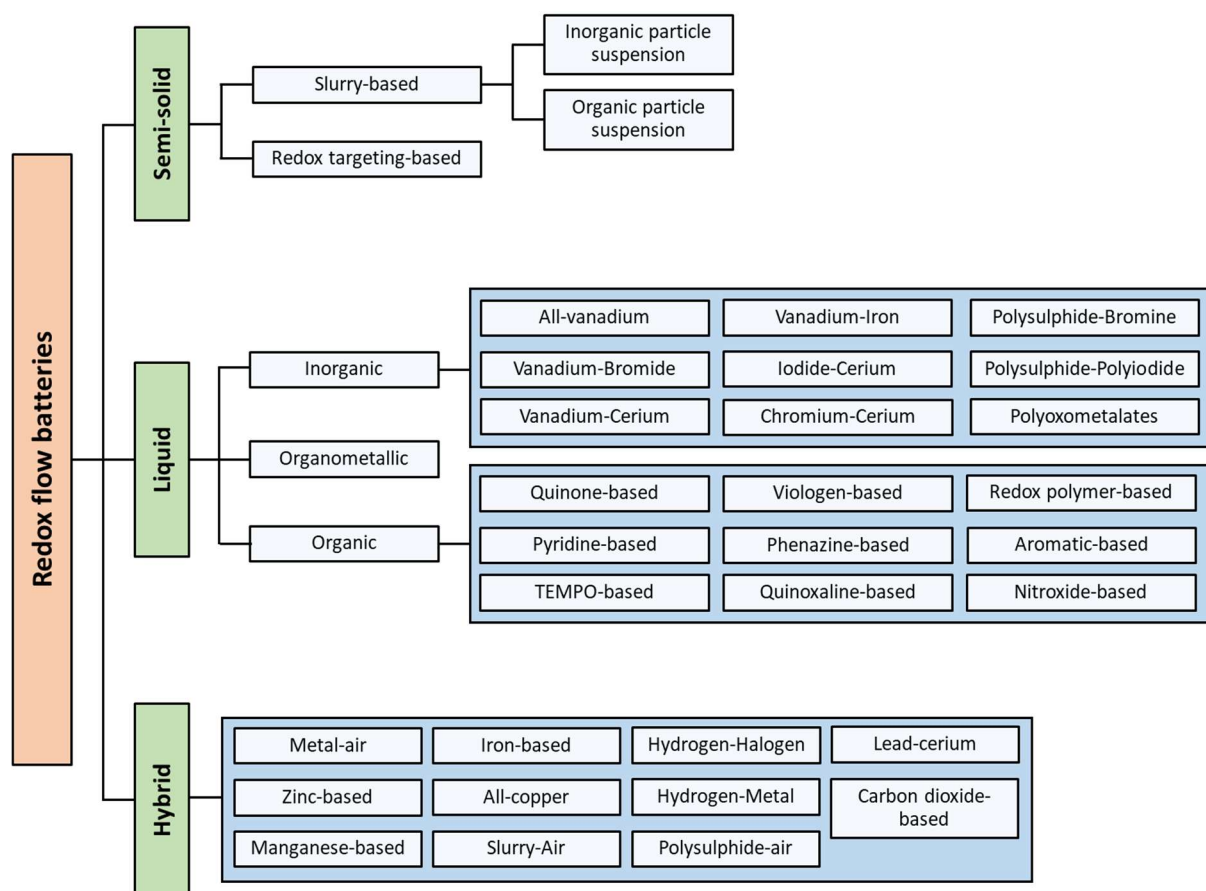


Figure 8.1 – Electrolyte chemistries used in redox flow batteries based on the electrolyte phase (hybrid, liquid, and semi-solid).

The VRFB is the most researched RFB technology since it fulfils several of the previous requirements: it is non-flammable and recyclable, it has a low environmental impact and it displays good reversibility, a long cycle life (>15 000), high efficiency and negligible capacity loss. Also, no precipitation of vanadium salts is observed up to a temperature of 40 °C and the electrolyte cross-contamination can be easily recovered since both storage tanks have the same electrolyte solution. This technology has been implemented in projects from kW up to MW scale and is commercialized by several companies such as VisBlue, Dalian Rongke Power, Invinity Energy Systems, and Enerox. The all-iron RFB has also reached the commercialization stage. It is more eco-friendly and cheaper than the VRFB. However, the electrolyte has poor chemical stability due to pH variations during operation. Other electrolyte chemistries have been receiving great research attention since the VRFB and the all-iron RFB display low power and energy densities. For example, the hydrogen-bromine RFB can be used for applications that require an ESS with a high-power density and the zinc-air RFB is suitable for applications that demand a high energy density. Though, bromine is extremely toxic, hydrogen is flammable and the zinc-air RFB has a low cycle life (<2000) and a low efficiency. Other RFB technologies such as, iron-salt (VoltStorage), zinc-iron (ViZn Energy), zinc-bromine (RedFlow) and hydrogen-manganese (RFC

Power), are also being commercialized. Typically, zinc- based RFBs are cheap and have a high cell potential but display low energy efficiency, and dendrite formation may lead to short-circuit and battery failure. The manganese- hydrogen RFB is also a promising technology that employs cheap and abundant elements. It delivers high power and energy (up to 263 Wh l⁻¹) densities and high energy efficiency at a fraction of the cost of VRFBs. Organic RFBs have also been receiving a great deal of attention since they are more eco-friendly than inorganic RFBs. Currently, Kemiwatt commercializes a quinone-based RFB and JenaBatteries has installed a kW scale pyridine-based RFB. A novel RFB technology employing CO₂ and bromide as redox couples was invented by Gyenge and it is commercialized by Agora Energy. The CO₂ RFB is a recent technology and, thus, displays a very low power density. Though, it holds great promise since it can contribute to lower the concentration of CO₂ in the atmosphere. Recently, a novel microbial RFB was also reported in the literature. Despite the low power and energy (25 – 35 Wh l⁻¹) densities of VRFBs, their advantages overcome the benefits of other RFB technologies. Currently, VRFBs are the most viable RFB technology for large scale stationary applications.

Working principle of VRFB

The VRFB employs vanadium salts dissolved in diluted sulfuric acid as positive and negative electrolytes. Therefore, this technology takes advantage of the four oxidation states of vanadium (V²⁺, V³⁺, V⁴⁺, and V⁵⁺) to store (charge) and release (discharge) energy. As Figure 8.1 shows, the process of charging a VRFB consists in reducing V³⁺ (green solution) to V²⁺ (purple solution) at the negative electrolyte and oxidizing VO²⁺ (blue solution) to VO₂⁺ (yellow solution) at the positive electrolyte. The electrons from the oxidation reaction migrate from the positive side to the negative side through an external circuit. To maintain charge balance, protons (H⁺) cross through the cation exchange membrane (CEM) in the same direction. When an anion exchange membrane (AEM) is used, anions move from the negative electrolyte to the positive electrolyte; this type of membrane contains functional groups that are positively charged. The discharge process is the opposite of the charge process since the electrochemical reactions are reversible.

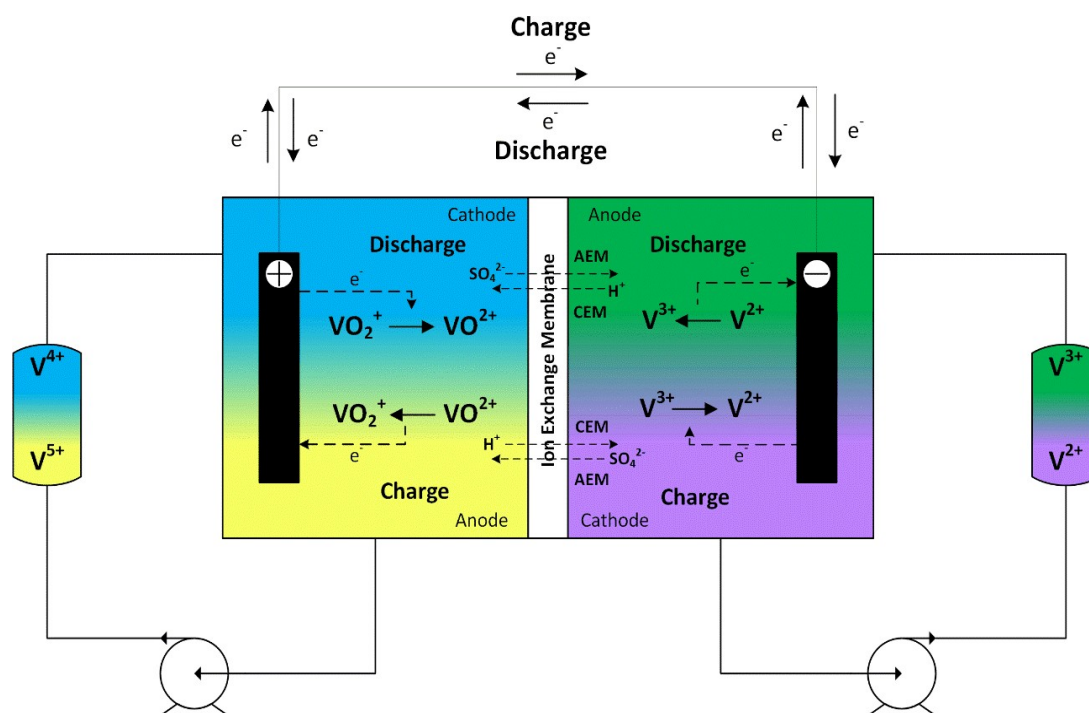


Figure 8.2 – Schematic representation of the charge and discharge processes in a vanadium redox flow battery equipped with a cation exchange membrane (CEM) and an anion exchange membrane (AEM).

The battery is fully charged (SoC = 100 %) when all V^{3+} ions are reduced to V^{2+} and all VO_2^+ ions are oxidized to VO_2^+ and fully discharge (SoC = 0 %) when the opposite is observed.

The electrochemical reactions that take place at the positive (Eq. (2.3)) and negative sides (Eq. (2.4)) are as follows:

Positive sides (2.3):	Negative sides (2.4):
$VO_2^+ + 2H^+ + e^- \text{ charge} \leftarrow VO^{2+} + H_2O$	$V^{2+} \text{ charge} \leftarrow V^{3+} + e^-$
$VO_2^+ + 2H^+ + e^- \text{ discharge} \rightarrow VO^{2+} + H_2O$	$V^{2+} \text{ discharge} \rightarrow V^{3+} + e^-$

and the overall reaction becomes:

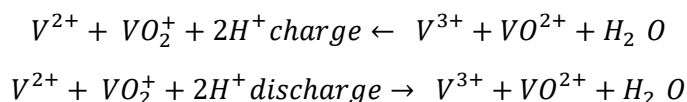




Figure 8.3 – Vanadium Electrolyte For Vanadium Redox Flow Battery VRFB²⁵⁰ (V^{3+} (green solution), V^{2+} (purple solution), VO^{2+} (blue solution), VO_2^+ (yellow solution))

Components and materials

The primary components of a VRFB system are:

- Electrolyte Tanks: These tanks store the vanadium-based electrolyte solutions. One tank contains the positively charged electrolyte (catholyte), and the other holds the negatively charged electrolyte (anolyte).
- Cell Stack: The heart of the VRFB, where the electrochemical reactions occur. It consists of multiple cells, each containing two electrodes (anode and cathode) and separated by an ion-exchange membrane. The electrolyte solutions flow through the cell stack during charging and discharging.
- Pumps and Plumbing: These circulate the electrolytes between the tanks and the cell stack, ensuring continuous operation.
- Power Conversion System: This system converts the electrical energy generated by the electrochemical reactions into a usable form for grid or storage applications.

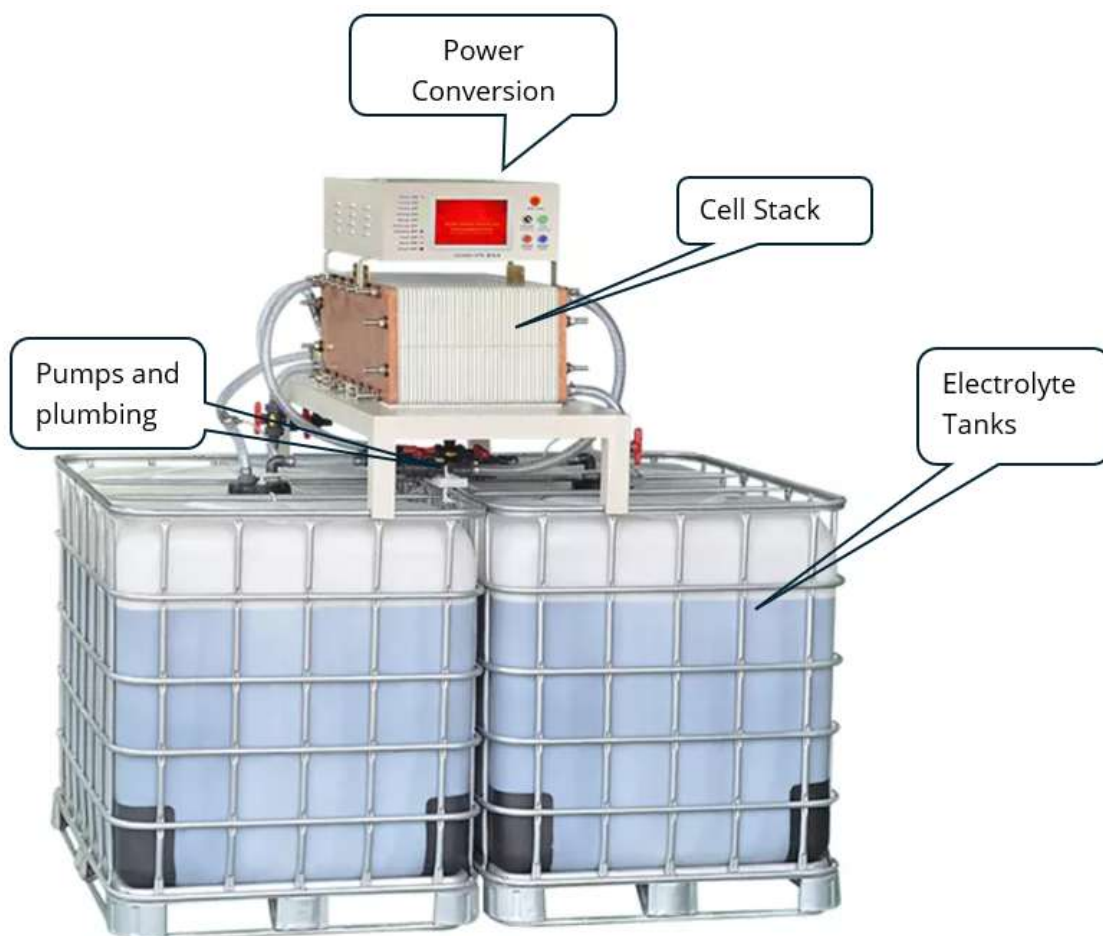


Figure 8.4 - Vanadium redox flow battery system²⁵¹

According to the PhD thesis from University of Porto, 2022²⁴⁶ the storage tanks are used to store the electrolyte solutions, which are pumped through the piping system into the stack, and vice-versa. The stack (Figure 8.4) consists of several electrochemical cells electrically connected in series and hydraulically connected in parallel. It is responsible for converting electricity into chemical energy and chemical energy into electricity and, thus, the performance of a VRFB is established by this component. However, developing a high-performance and leak-free stack is a challenge faced by several commercial companies. A good stack design ensures that both requirements are fulfilled. Additionally, choosing the appropriate internal components (membrane, electrode, gaskets, bipolar plate) and having a rigorous stack assembly procedure can have a significant impact on the performance and lifetime of the stack.

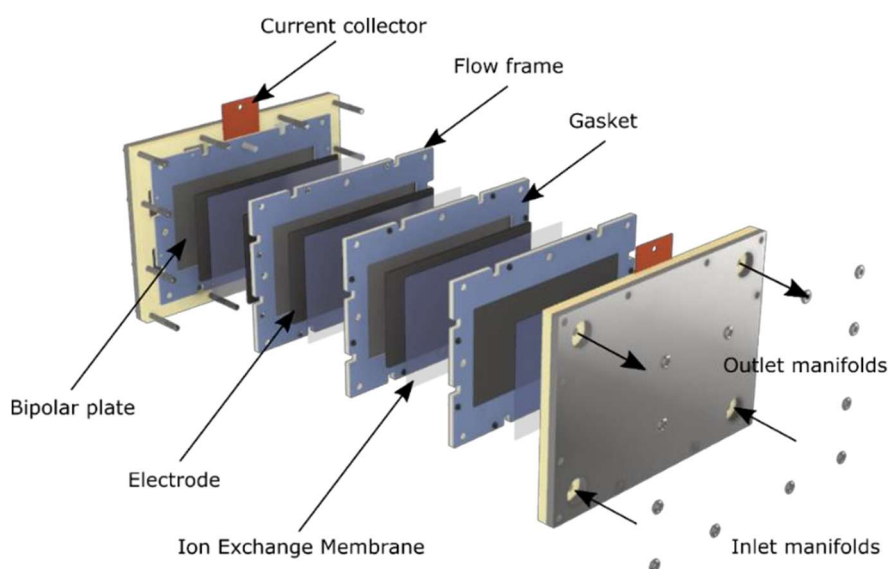


Figure 8.5 – 3D model of a redox flow stack with 4 electrochemical cells.

An electrochemical cell (Figure 8.5) comprehends two half-cells (positive and negative half-cells), divided by an ion exchange membrane. Both half-cells contain a bipolar plate, a flow frame, an electrode, an electrolyte, and gaskets. The difference lies in the redox species present in the electrolyte. The positive half-cell contains the electrolyte with the redox species that display the highest redox potential ($\text{VO}^{2+}/\text{VO}_2^+$), and the negative half-cell comprises the electrolyte with the redox species that provide the lowest redox potential ($\text{V}^{2+}/\text{V}^{3+}$).

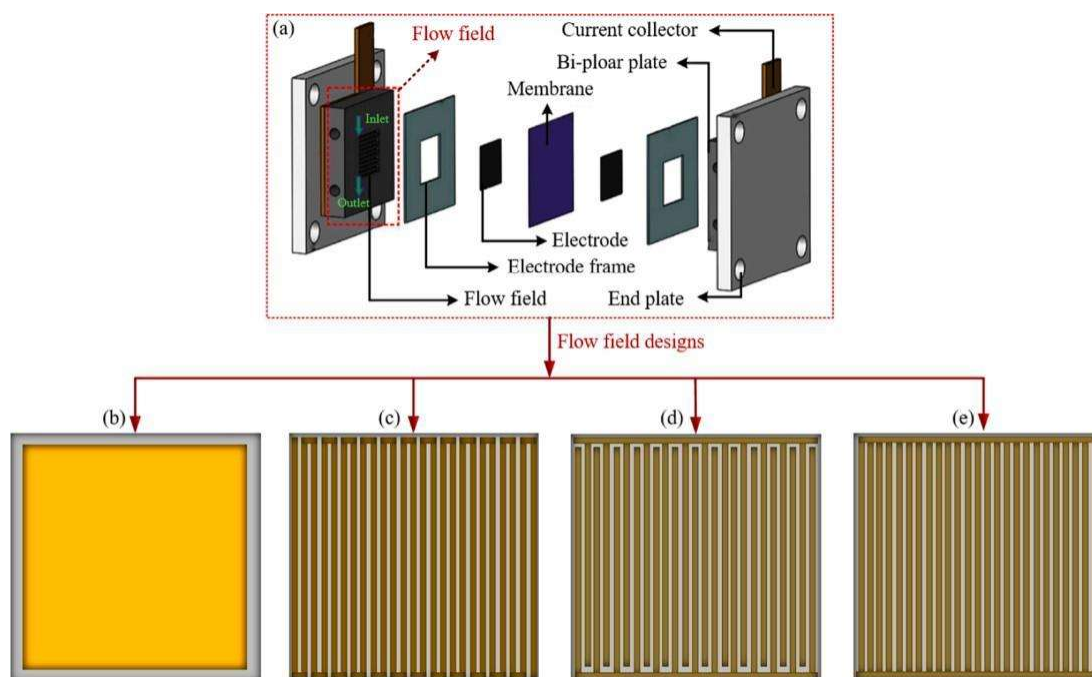


Figure 8.6 – Schematic representation of (a) a single VRFB electrochemical cell comprising (b) no flow field, (c) the serpentine flow field, (d) the interdigitated flow field, and (e) the parallel flow field. Figure from²⁵².

The bipolar plates are used to separate two different electrochemical cells and to allow electrons to transfer between them. Additionally, flow fields may be engraved in the bipolar plates to enhance the electrolyte distribution in the electrodes. A significant amount of flow fields for VRFBs may be found in the literature. RFBs with no flow field are widely reported in the literature. The serpentine, the interdigitated and the parallel flow fields have also been extensively researched. However, the information found in the literature is contradictory and unable to clarify which flow field is best to improve the electrolyte distribution and the performance of VRFBs. On a commercial scale, most VRFBs employ the no flow field configuration since it is cheaper and easier to produce. Graphite-based composites are typically used as materials for bipolar plates since they have a high resistance to acidic solutions and corrosion and good chemical stability, and they are cheap and easy to produce^{253 254}. Copper plates are placed on top of the first and last bipolar plates of the stack to act as current collectors. Flow frames are placed on top of the bipolar plates of each electrochemical cell to provide structural support to the cells. Typically, distribution channels are engraved in the frames to promote a uniform electrolyte distribution in the electrodes and minimize energy losses due to shunt currents. Internal and external electrolyte leakages can be prevented by using gaskets in-between flow frames and in-between flow frames and bipolar plates. The electrodes are used to provide more active sites for electrochemical reactions. They consist of a carbon-based material with high porosity. More specifically, four different materials have been widely used in the literature: graphite felt, carbon felt, carbon paper, and carbon cloth²⁵⁵. Polyacrylonitrile carbon felts are the most suitable electrodes for VRFBs since they have a high surface area, a high electronic conductivity, and good mechanical stability²⁵⁶. Though, they require an activation treatment to improve their wettability and electrochemical activity²⁵⁵. The ion exchange membrane is placed in-between the electrodes to avoid electrolyte mixing and to allow selected ions to pass and complete the redox reactions. Several types of membranes have been tested in VRFB²⁵⁷. Cation exchange membranes (e.g., Nafion®) are currently the most used type of membrane in commercial VRFBs since they display high conductivity and good chemical stability, promoting a better performance and a longer lifetime²⁵⁸. Anion exchange membranes have also been receiving great research attention. They are cheaper and display a better ion selectivity than CEMs but lead to a worse performance, especially when the VRFB is operated at high current densities²⁵⁹.

8.2 Main applications of VRFB

Primary Applications of VRFBs in Large-Scale Energy Storage

1. Grid Energy Storage

VRFBs are extensively used for grid energy storage due to their scalability, long lifespan, and ability to balance power supply and demand. They help in peak shaving, load levelling, and providing backup power²⁶⁰.

2. Renewable Energy Integration

VRFBs support the integration of renewable energy sources like solar and wind by storing excess energy generated during peak production periods and releasing it during low production periods²⁶¹.

3. Microgrid Applications

They are crucial for microgrid applications, providing reliable and stable power in isolated or off-grid systems by mitigating the intermittency of renewable energy sources²⁶².

Contribution of VRFBs to Grid Energy Storage and Renewable Energy Integration

1. Stabilizing Power Supply:

VRFBs help stabilize the power supply by storing surplus energy and discharging it during high demand, thus ensuring a stable and reliable grid operation²⁶⁰.

2. Enhancing Renewable Energy Utilization:

By storing excess energy from renewable sources, VRFBs enhance the utilization of renewable energy, reducing the need for fossil fuel-based power generation²⁶³.

3. Providing Grid Services:

VRFBs provide various grid services such as frequency regulation, voltage support, and spinning reserve, contributing to overall grid stability²⁶⁴.

Industrial Applications Benefiting from VRFBs

1. Data Centers:

VRFBs are used in data centers for uninterrupted power supply (UPS) and backup power, ensuring high operational reliability and reducing downtime²⁶⁵.

2. Manufacturing Plants:

They provide backup power and load levelling, reducing energy costs and enhancing the operational efficiency of manufacturing processes²⁶⁶.

3. Telecommunication Towers:

VRFBs ensure reliable power supply for telecommunication towers, particularly in remote areas, reducing the dependency on diesel generators and lowering operational costs²⁶⁴.

Applications of energy storage technologies in the electricity market

As illustrated in Figure 8.6, bulk energy and ancillary services are used in the electric system to ensure the provision of a combination of flexibility, stability and reliability of the power grid and in response to real-time variances in power supply and demand. Ancillary services often require a fast response time and short discharge duration, achieved through various applications including frequency regulation, voltage support and black start, i.e. the process of restoring power after a blackout (NREL, 2023). Battery technologies used for ancillary services have no rotating parts and can ordinarily respond within fractions of a second. Their operating flexibility allows batteries to take over the role of both spinning and non-spinning reserve.

Application	Description
Bulk Energy Services	
Energy Arbitrage	Energy arbitrage is the time shifting of energy where energy is purchased from the grid at a low price (off-peak), and then sold back into the grid at a higher price (peak) (Zhang et al., 2021).
Load Levelling	Load levelling usually involves storing electricity during off-peak demand to then supplying the electricity during periods of high demand.
Peak Shaving	Peak shaving works by levelling out peaks in electricity use.
Back-Up Power	By operating as an uninterruptable power supply (UPS), ESS can supply (emergency) backup power in case of an electricity grid failure.
Integration	Enhances the efficiency of renewable energy through the integration of technologies such as PSH, CAES and batteries with renewable energy generation (wind and solar).
Seasonal Storage	The purpose of seasonal storage is storing renewable energy during one season (for example summer) and discharges the stored energy in another (for instance winter), depending on the load demand, specifically when solar PV is low.
Customer Energy Management	
Power Quality	Provision of high-power quality and grid improvement.
Ancillary Services	
Spinning Reserve	Spinning reserve is a set of ancillary services in which unused power capacity is activated to respond to system disruptions, such as a sudden loss of generation or a rapid change in demand.
Frequency Regulation	Maintains grid frequency to ensure the balance between electricity supply and demand at all times. For example, when supply exceeds demand, the electric grid frequency increases to balance the power system.
Black Start	Restoring power generation or parts of the power system after a total shutdown, without the need to use external electricity networks.
Voltage Support	Keeping the grid frequency and voltage within strict limits, thereby maintaining the stability of the grid.

Source: Authors based on various sources: Zhang et al., 2021; Bergland, 2017; EPRI, 2021; NREL, 2020.

Figure 8.7 – Energy storage applications in the electricity market²⁶⁷

8.3 Technological barriers, regulatory framework and scalability

Vanadium-based RFBs (V-RFBs) are one of the upcoming energy storage technologies that are being considered for large-scale implementations because of their several advantages such as zero cross-contamination, scalability, flexibility, long life cycle, and non-toxic operating condition²⁶⁸.

Despite VRFBs being a very attractive technology, their market penetration has been hindered by their performance.

8.3.1 Main Technological Barriers Hindering the Widespread Adoption of VRFBs

1. High Initial Costs:

The cost of VRFB components, particularly vanadium electrolyte and membranes, contributes to high initial investment costs, hindering widespread adoption²⁶⁹.

2. Vanadium Cross-Over:

The undesired transport of vanadium ions through the membrane leads to capacity loss and electrolyte imbalance, reducing the efficiency and lifespan of the batteries²⁷⁰.

3. Membrane Durability:

The degradation of membranes over time due to harsh operating conditions impacts the performance and longevity of VRFBs²⁷¹.

Membrane durability is crucial for VRFB performance. The degradation of membranes over time, due to chemical and mechanical stress, leads to decreased efficiency and increased maintenance costs²⁶⁹.

4. Electrolyte Stability:

Stability of the vanadium electrolyte is essential to maintain battery performance. Issues such as precipitation of vanadium species can lead to reduced efficiency and potential system failures²⁷².

Inherent losses

Inherent losses limit the power density and reduce the energy efficiency. These losses, and approaches to minimize them, are briefly addressed below²⁴⁶.

1. Activation Losses

Activation losses occur due to the energy required to overcome the activation barrier of the electrochemical reactions at the electrode-electrolyte interface. They provide information about the reaction kinetics and charge transfer.

These losses result in an overpotential (activation overpotential) and significantly impact the performance of the battery, especially at low to medium current densities.

Reducing activation losses can be achieved by introducing functional groups on the surface of the electrodes (e.g., oxygen, nitrogen, phosphor, boron doping) or depositing metals to create active sites and catalyze reactions. Additionally, using additives in the electrolyte like nanoparticles, nanotubes, and organic additives can enhance reaction kinetics.

2. Ohmic Losses

Ohmic losses arise from the resistance to electron transport through the electrode and bipolar plate, and ion transport through the ion exchange membrane and electrolyte.

These losses generate an overpotential (ohmic overpotential) and lead to a decrease in the potential efficiency of the battery. Poor contact between conductive materials and electrodes with low surface area can significantly increase these losses.

To reduce ohmic losses, one can increase the compression and surface area of the electrodes or use thinner materials. Improving the ionic conductivity of the electrolyte and membrane by using additives or modifying functional groups also helps. Additionally, these losses can be affected by the state of charge (SoC) since electrolyte conductivity increases with SoC.

3. Concentration Polarization

Concentration polarization is related to the mass transfer flux between the surface of the electrode fibers and the electrolyte solution. Due to slow mass transfer and fast reaction kinetics, species concentrations near the electrode fibers differ from those in the bulk electrolyte.

This discrepancy leads to an overpotential (concentration overpotential) and reduces the battery's energy efficiency.

Improving mass transfer to minimize concentration gradients can help reduce these losses. This might involve optimizing flow rates and electrode structures to enhance mixing and distribution of reactants.

4. Shunt Currents

Shunt currents occur due to leakage currents between cells in a stack, driven by potential differences between the cells and the manifold.

These currents lead to energy losses and reduced battery efficiency. They can also cause uneven charging and discharging among the cells.

Minimizing shunt currents can be achieved by optimizing the design of the cell stack and manifolds to balance potential differences and reduce leakage paths.

5. Self-Discharge Reactions

Self-discharge reactions happen due to the crossover of vanadium ions through the membrane, leading to unwanted side reactions.

These reactions reduce the overall efficiency and capacity of the battery by consuming active species.

Enhancing the selectivity of the ion exchange membrane to minimize crossover and optimizing the electrolyte composition to balance ion concentrations can mitigate self-discharge.

6. Gas Evolution

Gas evolution occurs due to the electrolysis of water at high potentials, leading to the production of hydrogen and oxygen gases.

This phenomenon reduces the battery's Coulombic efficiency and can cause pressure build-up and damage to the system.

Controlling the operating voltage within a safe range to avoid water electrolysis and using catalysts to enhance the desired reactions while suppressing gas evolution can help reduce these losses.

8.3.2 Regulatory barriers

While vanadium redox flow batteries (VRFBs) present a promising solution for long-duration energy storage, their widespread adoption in Europe faces several regulatory hurdles.

1. **Classification and Permitting:** The classification of VRFBs under existing regulatory frameworks remains unclear. In some instances, they are treated as chemical plants due to the use of electrolytes, leading to complex and time-consuming permitting processes. This can deter investment and delay project timelines.
2. **Safety Standards:** The lack of harmonized safety standards for VRFBs across Europe poses a challenge. Different countries have varying requirements for the handling, transportation, and operation of these batteries, leading to inconsistencies and potential market fragmentation.
3. **End-of-Life Regulations:** The absence of clear regulations for the disposal and recycling of VRFBs raises environmental concerns. The vanadium electrolyte, while reusable, needs proper handling at the end of the battery's life cycle to minimize environmental impact.
4. **Grid Integration:** Integrating VRFBs into the existing grid infrastructure requires regulatory adjustments. Issues such as grid connection agreements, ancillary service provision, and remuneration mechanisms need to be addressed to ensure the smooth integration and operation of VRFBs in the energy system.

8.3.3 Innovations to Improve Scalability and Cost-Effectiveness of VRFB Systems

1. Advanced Membrane Technologies

Developing membranes with improved selectivity and durability, such as the use of selective layers and advanced materials, can enhance the performance and reduce costs²⁷³.

2. Improved Electrode Materials

Innovations in electrode materials, such as graphene-based electrodes, can increase catalytic activity and reduce kinetic polarization, improving the overall efficiency of VRFBs²⁷⁰.

3. Cost effective and scalable Manufacturing Processes

Advances in manufacturing processes, such as automation and the use of scalable production techniques, can reduce the costs of VRFB components. Techniques like ultrasonic spray coating for creating selective layers on membranes are being developed to enhance scalability and reduce production costs²⁷³.

4. Vanadium Recovery and Recycling

Developing efficient methods for recycling vanadium from industrial waste and spent electrolytes can help ensure a stable supply and reduce material costs. Recycling processes can mitigate the impact of price volatility and supply chain disruptions²⁷⁴.

8.4 Raw material restrictions

8.4.1 Primary Resources Required for VRFBs

Vanadium Redox Flow Batteries (VRFBs) primarily require the following resources^{272 275}:

1. Vanadium Electrolyte

The key active material, which exists in different oxidation states and is crucial for the battery's energy storage capabilities.

2. Electrolyte Solutions

Typically, a mixture of vanadium salts (such as VOSO_4) in sulfuric acid (H_2SO_4) solutions.

3. Polymer Membranes

Used as separators between the two halves of the cell, maintaining ionic conductivity while preventing cross-contamination of vanadium ions.

4. Electrodes

Usually made from carbon-based materials like graphite felt, which provide the surface for electrochemical reactions.

Impact of Vanadium Availability

The availability of vanadium significantly impacts the adoption of VRFBs due to its central role in the battery's operation. Limited availability or supply chain disruptions can lead to higher costs and reduced scalability of VRFB technology.

Just four countries²⁷⁶ share the majority of vanadium's world resources: China with its 47%, followed by Russia at 26%, South Africa at 18%, and, finally, Australia at 9%. Currently, due to strong environmental constraints affecting its production, only few mines of vanadium are in operation in China, Russia, and South Africa. This increases the risk of supply disruption. Opening new mines in Australia will not change the share of resources. China and Russia dominate the market with mainly state-controlled companies²⁷⁷. Considering the significant financial commitment needed to run mines also in the future the market will stay oligopolistic.

The potentially increasing relevance of vanadium for the energy transformation gives the respective governments a strong leverage for acting. Taking into account the risks outlined above, including vanadium in the list of critical metals by the European Commission (EC) was inevitable.

Vanadium²⁷⁸ redox flow battery (VRFB) technology continued to be an increasingly important part of large-scale energy storage as it allows for high-safety, large-scale, environmentally friendly, medium- and long-term energy storage. Installations of VRFB projects continued to increase worldwide as energy companies looked to support renewable energy projects as many countries attempt to lower their carbon emissions. Project Blue and other analysts projected that the VRFB market would account for approximately 17% of vanadium consumption in 2033 compared with only 3% in 2021. The new supply of high-purity vanadium pentoxide needed to support the VRFB market was expected to come from either existing producers or from projects which are, for the vast majority, still in their very early phases of development. Despite the anticipated growth of VRFBs, there will be continued competition from a variety of alternative battery technologies looking to capture a portion of the energy storage market share.

World Mine Production and Reserves: Reserves for Australia, China, and South Africa were revised based on company and Government reports.

	Mine production		Reserves ¹¹ (thousand metric tons)
	2022	2023 ^e	
United States	—	—	45
Australia	—	—	¹² 8,500
Brazil	5,840	6,400	120
China	66,900	68,000	4,400
Russia	^e 20,000	20,000	5,000
South Africa	8,870	9,100	750
World total (rounded)	102,000	100,000	19,000

Figure 8.8: World mine production and reserves (by US government)

As the global battery storage market²⁷⁹ races to secure supplies, VRFB manufacturers are also looking to lock in a strong supply chain. For now, the bulk of vanadium material is owned by China, which could result in a strong reliance on the nation for future large-scale VRFB projects. In 2020, China, Russia, South Africa, and Brazil accounted for roughly 99.8% of global vanadium production. Companies such as Australian Vanadium Limited (AVL) are developing supplies in mineral-rich areas. AVL, with government support, has created the Australian Vanadium Project, which produces and processes VRFB materials in Western Australia that will then be supplied to VRFB manufacturers as either V_2O_5 or vanadium electrolyte.

Vanadium can be challenging to purchase due to its fluctuating price, geopolitical factors, and concentration of supply in a few countries. The risks associated with the supply include:

- Geopolitical Instability: Political issues in key producing countries can disrupt supply.
- Market Demand Fluctuations: Increased demand from the steel industry and other sectors can lead to shortages.
- Environmental and Regulatory Concerns: Stringent mining regulations and environmental policies can affect production levels.

Price Volatility of Vanadium

The price volatility of vanadium affects the economic viability of VRFBs. High and unstable prices can make VRFB systems less competitive compared to other energy storage technologies. This volatility can lead to increased capital costs and uncertainty in long-term financial planning for VRFB projects.

The supply of this vanadium electrolyte is now playing the most important role in the batteries' market growth. Most VRFBs use what is known as 'Gen 1' vanadium electrolyte which is a combination of vanadium pentoxide (V_2O_5), sulphuric acid and water.



Figure 8.9 – Vanadium pentoxide powder²⁸⁰

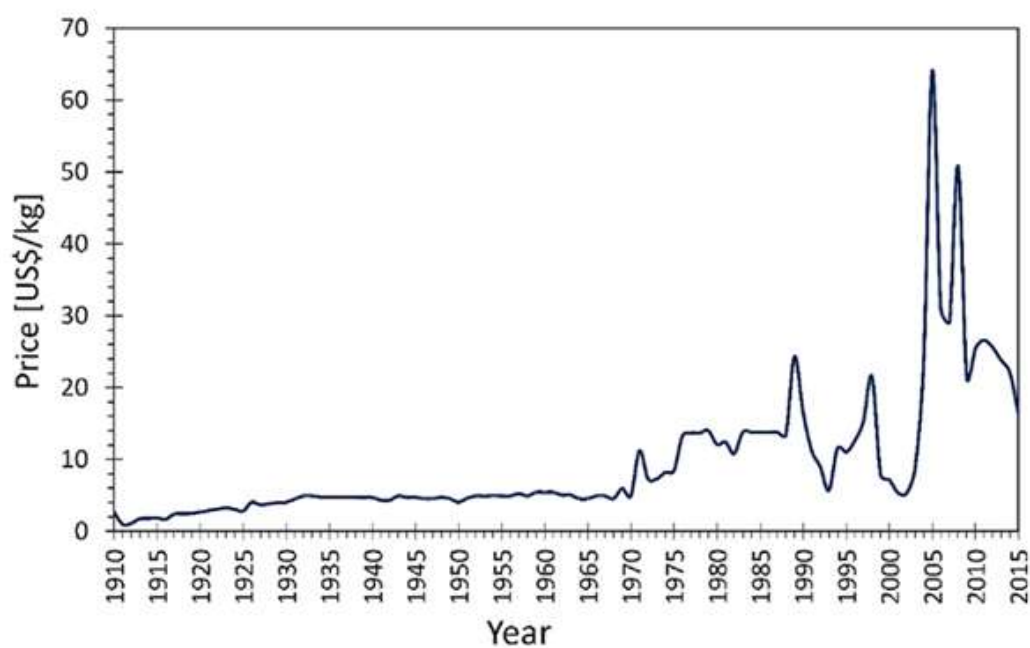
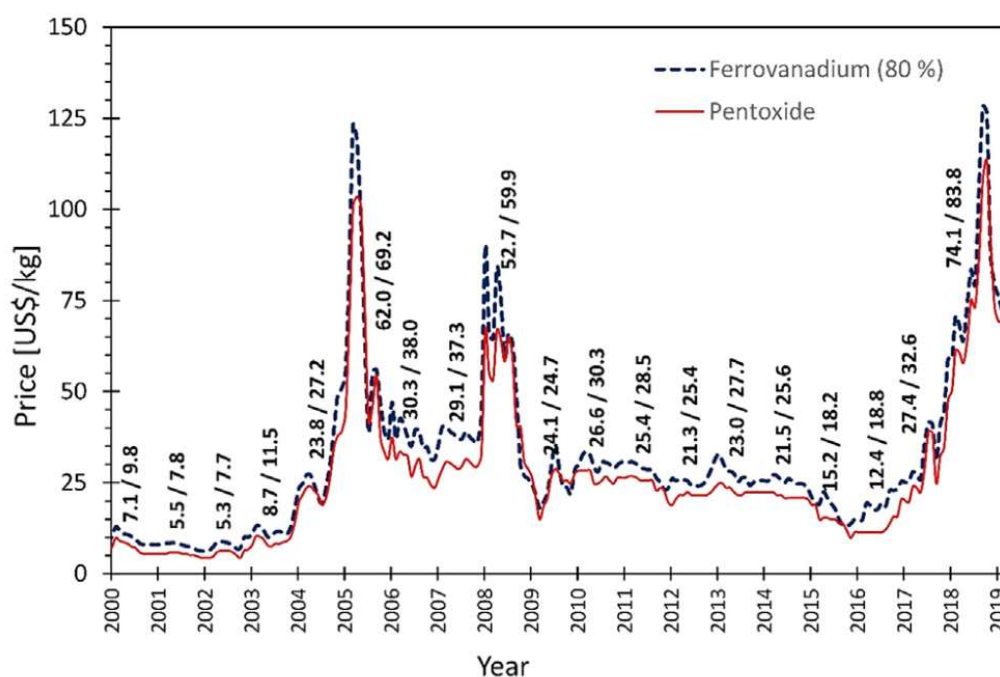
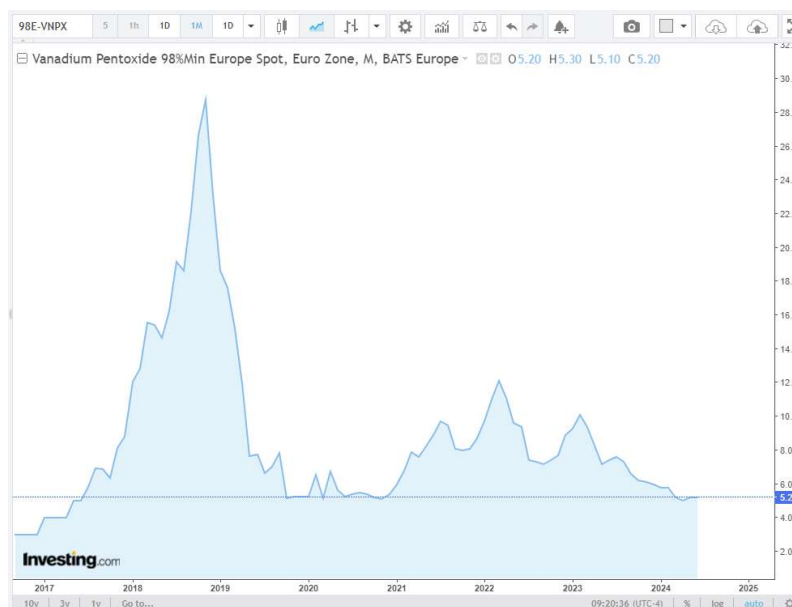


Figure 8.10 – Price of vanadium pentoxide from 1910 to 2015 in the USA²⁷⁴

Figure 8.11 – Price of vanadium pentoxide from 2000 to 2019 in EU²⁷⁴Figure 8.12 – Price volatility of vanadium Pentoxide 98% in EU²⁸¹

The estimated average Chinese vanadium pentoxide price in both 2022 and 2023 was \$9.25 per pound ²⁷⁸.

Strategies to Address Resource Restrictions

Several strategies are being explored to address resource restrictions and ensure a stable supply of vanadium^{282 283}:

1. Recycling and Reuse:

Developing efficient processes to recycle vanadium from spent batteries and industrial waste.

2. Alternative Materials:

Researching alternative electrolyte materials or hybrid systems that reduce dependence on vanadium.

3. Supply Chain Diversification:

Securing multiple sources of vanadium and investing in mining operations in different regions to mitigate supply risks.

4. Innovation in Extraction and Processing:

Improving the methods for extracting and processing vanadium to increase yield and reduce costs.

8.5. VRFB energy storage costs

Main factors contributing to the high initial costs of VRFB energy storage systems are:

1. Cost of Vanadium Electrolyte

The vanadium electrolyte is a significant cost driver due to the high price of vanadium and the complexity of its preparation. Efficient and scalable processes are needed to reduce these costs²⁸⁴.

2. Membrane Costs

High-performance ion-exchange membranes used in VRFBs are expensive due to their sophisticated manufacturing processes and materials²⁸².

3. Electrode Materials

The development and optimization of electrodes, especially those using advanced materials like graphene or nanostructured carbons, add to the overall cost²⁷⁰

Long operational life and low maintenance costs of VRFBs offset initial investment. VRFBs have a long operational life, typically over 10,000 cycles, which spreads the initial investment over many years, reducing the average annual cost²⁸⁵. The stable chemistry of VRFBs leads to low maintenance requirements, as the risk of thermal runaway and degradation is minimal compared to other battery technologies²⁸⁶.

Cost reduction strategies for VRFBs:

1. Improved Membrane Technology

Development of low-cost, high-performance membranes can significantly reduce overall costs. Membranes based on polyvinylpyrrolidone (PVP) and cardo-poly(etherketone) (PEKC) blends are showing promise in reducing costs while maintaining high performance²⁸⁷.

2. Electrode Optimization

Enhancing electrode materials through methods like nitrogen doping or using cost-effective carbon composites can improve performance and reduce costs²⁸⁸.

3. Manufacturing Scalability

Implementing scalable manufacturing processes, such as the NanoJeD method for electrode fabrication, can reduce production costs and improve performance²⁸⁹.

In addition²⁷⁹ to the benefits of the technology, synergies across industries are helping drive the development of flow batteries. Many stakeholders in the vanadium industry see VRFBs as a major source of new demand for the metal that has traditionally been used in steel alloys. This dynamic has resulted in government programs to support the technology's development in China. Several Chinese provinces contain large vanadium reserves that the government is hoping to exploit by encouraging new industries to use the metal. The Chinese government is supporting the development of several large VRFB projects including the 100 MW/500 MWh system with VRB Energy in Hubei Province and the 200 MW/800 MWh system in Dalian with Rongke Power.

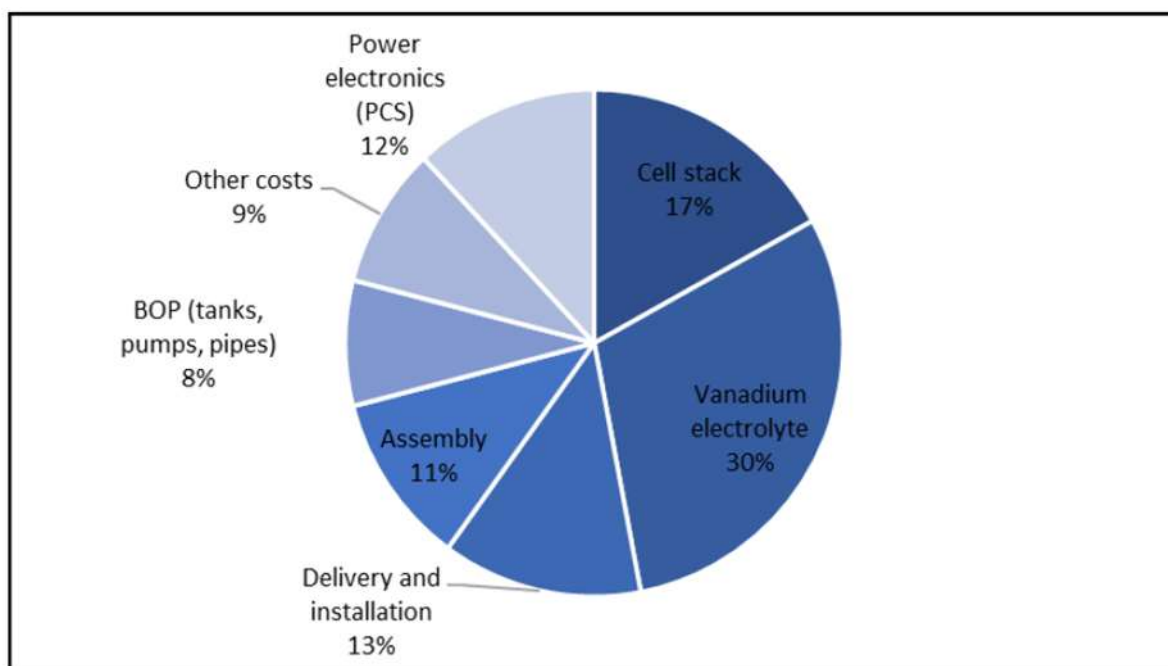
In addition to government-level support for vanadium industries and technologies, several vendors view VRFBs as a complementary business to existing mining activities and have direct or indirect ties to vanadium mining interests. South Africa-based Bushveld Minerals is one of the main vanadium producers in the world. In August 2020, a consortium, which includes Bushveld Minerals, acquired the majority shares in CellCube, a VRFB developer, manufacturer, and distributor. Largo Resources, another one of the major vanadium producers in the world, also has plans to set up its own vertically integrated energy storage company through its subsidiary Largo Clean Resources. Similarly, vendor VRB Energy is majority owned by Ivanhoe Electric, a metal-focused minerals exploration and development company. Australian Vanadium Limited, another vanadium producer, also entered the VRFB market through its formation of subsidiary company VSUN Energy.

The report “2022 Grid Energy Storage Technology Cost and Performance Assessment”²⁶ provides detailed initial and operational and maintenance cost estimates for some energy storage

technologies for the year 2021 and projections for 2030. The information is summarized in the table below.

Table 8.1: Initial and M&O cost for different types of Energy Storage

Type	Initial cost	M & O cost
Pumped Storage Hydro (PSH)	2021: 240 EUR/kWh (100 MW, 10-hour system) 2030: 130 EUR/kWh (100 MW, 24-hour system)	Fixed O&M costs for 10-hour systems: 12 EUR/kW-year (2021)
Lithium-ion Batteries LFP (Lithium Iron Phosphate)	2021: 320 EUR/kWh (100 MW, 10-hour system) 2030: 265 EUR/kWh (100 MW, 4-hour system)	
Lithium-ion Batteries NMC (Nickel Manganese Cobalt)	2021: 370 EUR/kWh (100 MW, 10-hour system) 2030: 305 EUR/kWh (100 MW, 4-hour system)	
Vanadium Redox Flow Batteries (VRFB)	2021: 350 EUR/kWh (100 MW, 10-hour system)	Fixed O&M costs: 12 EUR/kW-year (2021)
Compressed-Air Energy Storage (CAES)	2021: 270 EUR/kWh (100 MW, 4-hour system) 2030: 110 EUR/kWh (100 MW, 10-hour system)	Fixed O&M costs: 6 EUR/kW-year (2021)



Source: Bushveld Energy 2018.

Figure 8.13 – Price volatility Average cost breakdown of 250kW/ four hour VRFB system, AC installed ²⁶⁷

Figure 4: The LCOS for VRFB
modelled over a 40 year lifecycle US\$111/kWh

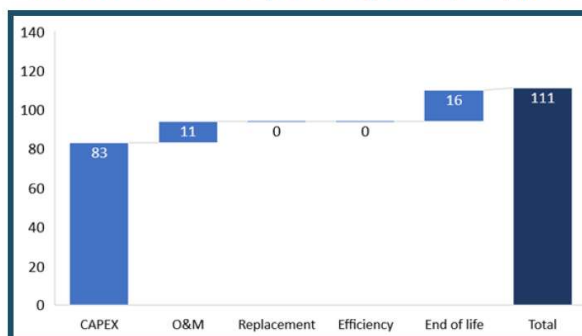
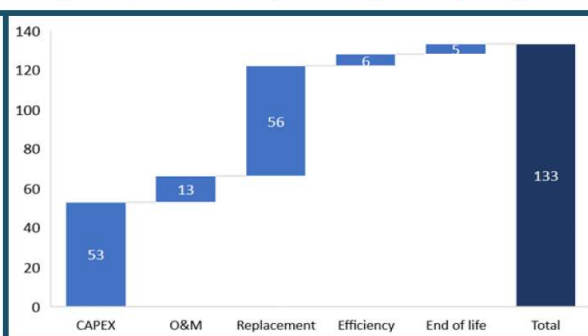


Figure 5: The LCOS LIB (LFP)
modelled over a 40 year lifecycle US\$133/kWh



Source: Infinity Energy Systems, 2023

Figure 8.14 Levelized cost of storage (LCOS) for VRFB and lithium battery ²⁶⁷

Despite the increasing research on the LCOS, there is no unified understanding of the calculation method of energy storage costs. While some studies have ignored economic parameters such as replacement or charging costs, others have excluded technical parameters such as operational and maintenance costs and the self-discharge rate. Also, different studies use different discount rates.

While the [Infinity Energy data](#) shows a positive outcome for VRFBs over a 40-year timeframe, which is not an unusual timeframe in the power sector, it is important to approach committing

to a 40-year agreement carefully due to various factors and assumptions that impact a project's lifespan. Moreover, the dynamic nature of storage and battery technologies could present challenges for investors to commit to such a prolonged agreement.

The LCOS for both systems indicates a value of US\$111/kWh for the VRFB and US\$133/kWh for the LIB (see Figure 8.14).

8.6 VRFB Development perspective and environmental impact

VRFBs differ from traditional batteries in several key aspects:

1. Separation of Power and Energy Storage:

In VRFBs, the energy storage capacity is determined by the size of the electrolyte tanks, while the power output is determined by the size of the cell stack. This decoupling allows for independent scaling of power and energy, which is not possible in traditional batteries like lithium-ion or lead-acid, where power and energy are inherently linked.

2. Liquid Electrolytes:

VRFBs use liquid electrolytes that are stored in external tanks and circulated through a cell stack during operation. Traditional batteries typically use solid or gel electrolytes contained within the battery cells.

3. Long Cycle Life:

VRFBs can undergo tens of thousands of charge-discharge cycles with minimal degradation, significantly outlasting many traditional batteries.

4 Safety:

The aqueous electrolyte solutions used in VRFBs are non-flammable and less prone to thermal runaway compared to the electrolytes in lithium-ion batteries, enhancing safety.

Development perspective

Figure 8.15²⁹⁰ shows in semi-log coordinates the numbers of patent families (solid lines) and of journal articles (dotted lines), related to lithium batteries (Li-ion and Li-metal combined, shown in red), leadacid batteries (LABs, shown in black), redox flow batteries (RFBs, shown in blue) and fuel cells (FCs, shown in green) by year. Several interesting conclusions can be drawn from this figure.

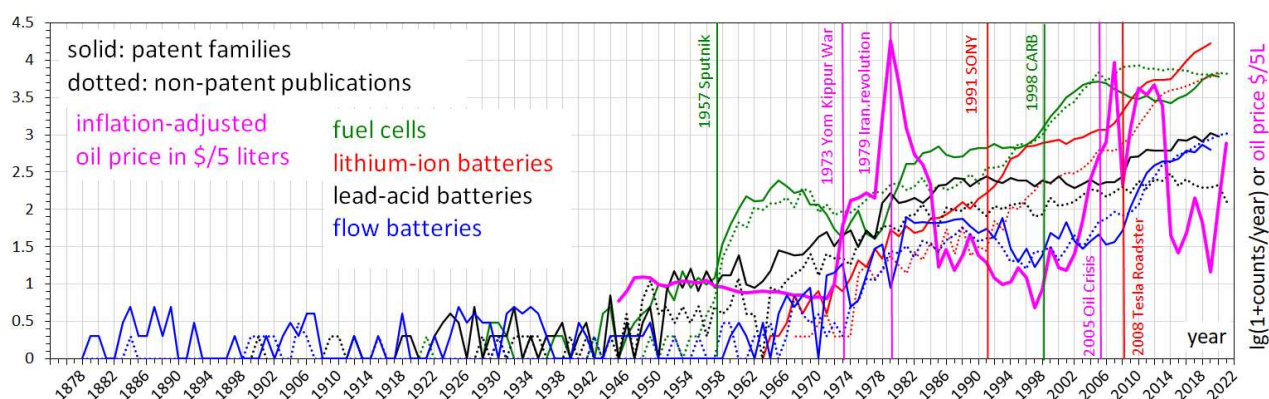


Figure 8.15 Log number of publications about electrochemical powersources - Journal of The Electrochemical Society

Vanadium Redox Flow Batteries (VRFBs) have evolved significantly over recent years, focusing on enhancing efficiency and reducing costs. Here are some key developments:

1. Electrode Innovations

Recent advancements in electrode materials, such as the use of carbon-based electrodes and modifications with metal oxides, have significantly improved the performance of VRFBs. The incorporation of materials like MXene enhances electrode performance, offering a cost-effective solution for high-power VRFB applications.²⁶⁵

The use of biomass-derived carbon materials as electrocatalysts has also been explored to improve electrochemical activity and reduce costs²⁸³

2. Membrane development

Innovative composite membranes, such as Nafion/lignin composites, have been developed to offer high conductivity and low vanadium ion permeability, enhancing the overall efficiency and reducing the cost of VRFBs²⁹¹

The introduction of hybrid membranes with enhanced proton transport channels has significantly improved the ion selectivity and conductivity of VRFBs, leading to better performance and longer cycle life²⁹².

3. Energy management systems

Advanced battery management systems (BMS) tailored for VRFBs have been designed to optimize performance and extend battery life. These systems integrate online monitoring and protection mechanisms to ensure optimal battery operation²⁹³.

4. Electrolyte optimization

Early VRFBs faced challenges with low energy density and instability of vanadium electrolytes. Advances in electrolyte chemistry have led to high-purity vanadium electrolytes that are more stable and have higher energy densities, improving overall battery efficiency.

Researchers have introduced various chemical additives to the vanadium electrolytes to suppress side reactions and enhance stability. These additives help maintain the electrolyte's performance over extended cycles. Advanced electrocatalysts, such as tungsten oxide structures and fullerene nanocomposites, have been developed to enhance the electrochemical reactions in VRFBs, improving power density and energy efficiency²⁹⁴.

Maintaining the pH of the electrolyte within an optimal range has been shown to improve the efficiency and lifespan of VRFBs. This involves using buffers or other methods to control the pH and prevent detrimental reactions.²⁹⁵

The development of novel flow fields, such as spiral flow fields, has improved the uniformity of electrolyte flow and reduced local concentration polarization, enhancing the overall efficiency of VRFBs²⁹⁶

4. System Design

Innovations in system design, including more efficient flow field designs and optimized pump systems, have reduced energy losses and operational costs. Integration of smart monitoring and control systems has also helped in optimizing performance and extending battery life.

5. Manufacturing Processes

Advances in manufacturing techniques have reduced production costs. Automation and standardization in the production of VRFB components have contributed to economies of scale and reduced costs.

6. Temperature Management

Improved thermal management techniques have been developed to maintain optimal operating temperatures for the electrolytes, preventing degradation and enhancing efficiency. These techniques include advanced cooling systems and optimized flow field designs.

These technological improvements have collectively enhanced the efficiency and cost-effectiveness of VRFBs, making them more competitive with other energy storage technologies.

Environment perspective

VRFBs offer several environmental advantages over conventional batteries, making them a more sustainable option for large-scale energy storage:

1. Recyclability:

VRFBs have a higher recyclability ratio compared to lithium-ion batteries. Recycling strategies can significantly reduce the environmental impacts by lowering the demand for virgin materials and minimizing waste²⁹⁷.

2. Toxicity:

Vanadium (V) is one of the toxic elements with the most extensive distribution in nature. Despite the vast use of V in heavy industries, its presence in the environment can be harmful to living organisms. Soil can be polluted by V released from both natural and anthropogenic sources. (APIS, 2001)²⁹⁸

Next to the neurological effects vanadium can cause breathing disorders, paralysis and negative effects on the liver and kidneys. Laboratory tests with test animals have shown that vanadium can cause harm to the reproductive system of male animals, and that it accumulates in the female placenta. ([Lenntech, 2024](#))

However, VRFB systems do not produce toxic by-products during their operation. They also have a lower risk of fire and explosion compared to lithium-ion batteries, enhancing their safety profile²⁸⁵.

3. Lower Greenhouse Gas Emissions:

The use of VRFBs in energy storage can contribute to a reduction in greenhouse gas emissions by enabling more efficient use of renewable energy sources and reducing the reliance on fossil fuels²⁹⁹.

VRFBs have a lower environmental footprint due to their long cycle life and stable performance. They can endure tens of thousands of charge-discharge cycles with minimal degradation, leading to less frequent replacements and lower overall material consumption.

8.7. Conclusions: advantages, disadvantages and recommendations for VRFB

8.7.1 Pros and cons

Main Advantages of VRFBs Compared to Other Energy Storage Technologies

1. Long Lifespan and High Cycle Stability:

VRFB technology has a high cycle life, with many vendors predicting ranges of 15,000-20,000 full cycles with 100% depth of discharge (DoD) availability. VRFBs can also switch between charge and discharge states without a rest period and without capacity degradation, resulting in increased operational availability²⁷⁹. VRFBs can achieve over 10,000 cycles without significant degradation, making them ideal for long-term energy storage applications³⁰⁰.

2. Scalability:

The power and energy capacity of VRFBs can be independently scaled, providing flexibility in system design and application³⁰¹

3. Safety and Environmental Friendliness:

VRFBs are inherently safe, with no risk of thermal runaway, and they use non-toxic, environmentally friendly materials²⁶².

4. No Cross-Contamination:

The use of the same electrolyte in both half-cells prevents cross-contamination and simplifies maintenance²⁸⁵.

Key Disadvantages and Challenges Facing VRFBs

1. High Initial Costs:

The cost of vanadium and the manufacturing processes for components like membranes and electrodes contribute to high initial investment costs³⁰⁰

2. Low Energy Density:

VRFBs have a lower energy density compared to other battery technologies, limiting their use in applications where space and weight are critical²⁶².

3. Complex System Design:

The system complexity, including the need for pumps, flow management, and balancing, can complicate the design and increase operational costs²⁶⁶.

4. Risk of electrolyte leakage

Although the technology presents minimal fire risk, in addition to vanadium, the electrolyte compounds primarily consist of water along with additives such as sulfuric acid or hydrochloric acid, which are corrosive and toxic in nature. The risk of electrolyte leakage or spillage as well as fumes venting from a VRFB system presents a safety risk that must be properly managed²⁷⁹.

Table 1. Technical metrics overview of battery technologies

	Conventional Lead-Acid Battery	Lithium-Ion Battery (Iron Phosphate)	Flow Battery (Vanadium)
Power density	150 W/kg	245-430 W/kg	50 W/kg
Energy density	25-35 Wh/kg	100-265 Wh/kg	10-30 Wh/kg
Efficiency	45-85%	85-95%	65-85%
Depth of Discharge (DoD)	50%	85-95%	100%
Self-discharge	0.1-0.3%	0.1-5%	Small
Voltage, V	2.1	3.6	1.2-1.6
Thermal runaway	Yes	Yes	No
Lifespan	3-5 years	5-10 years	20-25 years
Cycle life*	1000	2000-4000	>10000

Figure 8.16 - Technical metrics overview of battery technologies²⁶⁷

Table 2-1. VRFB Solutions Strength, Weakness, Opportunity, and Threat Analysis

Strengths	Weaknesses
• Relative high efficiency compared with some other long-duration technologies • Safe, nonflammable electrolyte • Long lifecycle • Virtually unlimited cycles • 100% DoD • End of life reusability/recyclability • Salvage value at end of project life	• Lower energy density compared with Li-ion leading to larger and heavier systems • Vanadium electrolyte can account for 30%-50% of the total system cost, higher relative to other chemistries • Less mature supply chain than other battery technologies
Opportunities	Threats
• VRFBs can out-compete Li-ion batteries for long-duration applications, which are increasing in demand • Much of the future VRFB demand could be met by existing vanadium suppliers who have historically supplied it for steel alloy • Long-term offtakes with low cost producers allow for long-term price stability	• In the past, vanadium has faced fluctuating price volatility. If this continues, it could delay future growth for VRFBs • Production pace of VRFBs not propelled through EV applications

(Source: Guidehouse Insights)

Figure 8.17 SWOT analysis for VRFB²⁷⁹

Recommendations to Overcome Challenges and Fully Realize the Potential of VRFBs

1. Cost Reduction Strategies

Alternative Materials

Developing alternative materials for electrolytes, membranes, and electrodes that are cheaper and more abundant can reduce costs²⁸⁸.

Recycling and Reuse

Implementing recycling processes for vanadium and other components can lower the overall material costs²⁸⁵.

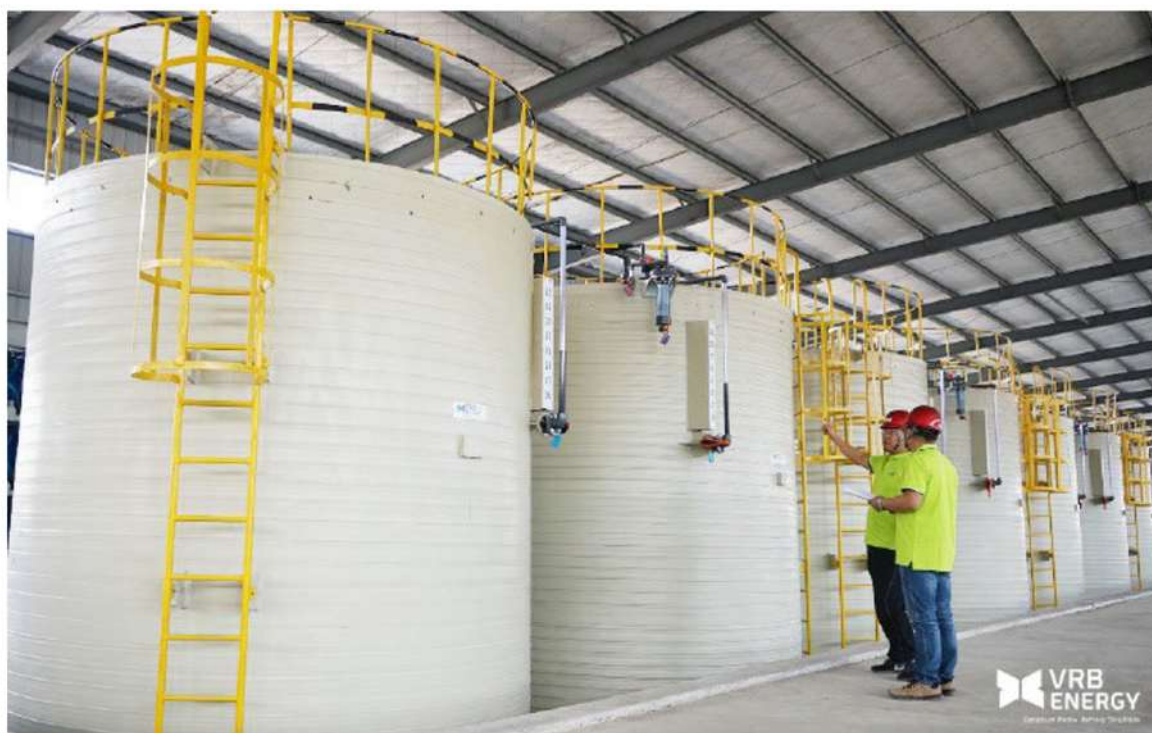
2. Enhancing Energy Density

Advanced Electrode Materials:

Using advanced materials like graphene and nanostructured carbons can improve electrode performance and increase energy density³⁰².

Advanced Electrolyte Materials:

VRFB energy and power densities are relatively low, requiring heavier and physically large systems. The environment where the system is to be installed must be able to house the required electrolyte tanks and pumping systems, which can be large depending on the desired energy storage capacity. Figure 8.18 shows the size of the electrolyte tanks used for a 3 MW/12 MWh VRFB demonstration project from VRB Energy in Hubei²⁷⁹.



(Source: VRB Energy)

Figure 8.18 – Electrolyte Tanks for a 3 MW/ 12 MWh VRFB

Optimized Flow Fields:

Designing optimized flow fields to enhance mass transfer and reduce polarization can improve battery efficiency and performance²⁹⁶.

3. Improving System Design:

Simplified System Integration:

Simplifying the system design and integrating advanced battery management systems (BMS) can reduce complexity and operational costs²⁹³.

Scalable Manufacturing:

Developing scalable manufacturing processes to produce components in larger quantities can lower production costs and improve economic feasibility³⁰³.

Market Barriers

VRFBs are continuing to gain traction for various storage applications due to their durability and advantages providing long-duration energy storage. Although momentum has grown, obstacles remain for the technology to overcome, primarily around capital cost and market demand.

Despite the advantages and overall potential of the technology, VRFBs have not been used often in short-duration (i.e., less 4 hours) applications. The short-duration energy storage applications that are in high demand in today's market have been dominated by Li-ion batteries because of their drastic drop in capital cost over the past two decades. The lower power and energy densities of VRFBs compared with alternative battery storage technologies means VRFB systems must be physically larger and heavier than Li-ion battery systems of comparable specifications. VRFBs require large electrolyte tanks and pumping systems meaning they are primarily suited for stationary applications where such systems can be accommodated. Li-ion batteries have proven to be versatile in numerous applications, being used in both grid-scale and distributed energy storage applications, EVs, and consumer electronics. As a result, VRFBs have not enjoyed the same widespread project portfolio, market growth, or media attention. Consequently, many flow battery vendors that started in the past 5-10 years have been unable to compete in the battery storage marketplace. Bankruptcies at hopeful flow battery vendors have ensued, including Imergy, EnerVault, and EnStorage.

The lower round-trip efficiency of VRFBs compared with Li-ion battery systems can affect revenue for applications such as arbitrage that rely on high margins between the price of energy being discharged and the cost of energy for charging. Flow batteries average between 70%-85% round-trip efficiency, compared with 90%-95% average for Li-ion batteries, potentially affecting the economics of projects based around bulk shifting of energy. To alleviate this, some flow battery companies are designing the stack to automatically drain the electrolyte when it is not being used in an effort to reduce unnecessary chemical reactions. Additionally, the long cycle lifetimes and deep discharge capabilities of VRFBs enable more revenue to be earned over the operational lifetime of a single VRFB helping to offset the lower round-trip efficiency.

However, the most significant challenge not just for VRFBs but for flow batteries in general has been the limited number of successfully deployed systems in operation partially due to the low demand for applications in which VRFBs offer more advantageous economics. In 2021, flow batteries made up only 3% of the battery market. And although there are a few established VRFB manufacturers, there are many that are still either early stage or startups. These early stage companies are unable to offer the same type of performance guarantees that come with Li-ion batteries from the widespread network of global suppliers. This has limited demand from highly risk averse utilities and project developers looking to secure long-term business deals with manufacturers²⁷⁹.

8.7.2 VRFB Case Studies and Recent Projects

Although flow batteries have had a gradual pace of implementation, future projects are taking advantage of economies of scale and are expected to lead the way for increased market share.

A 50 MW/200 MWh flow battery is also in progress in Australia. The Pangea Storage Project plans to invest \$200 million and use technology provided by CellCube. The company promises a 25-year guarantee on its battery system with no degradation. These projects are evidence of the growing interest in flow batteries globally. Another large deployment by Sumitomo that is 15 MW/60 MWh is also a notable project and mentioned later in this paper as a highlighted case study.

One of these large projects is planned deployment for Dalian, China, where an 800 MWh plant is scheduled to come online in 2022. The vendor to this project, Rongke Power/UniEnergy, also has plans for a manufacturing plant for additional flow batteries²⁷⁹.

The 100MW/400MWh Redox Flow Battery Storage Demonstration Project was connected to the 220kV Chunan Line and Chuwan Line in Dalian on 24 May, 2022. The capacity of the first-phase project cost is about 1.9 billion yuan (\$280 million) or 4.75 yuan/Wh (\$0,75). It will have a total capacity of 200MW/800MWh and a total investment of about 3.8 billion yuan (\$517 million) when completed³⁰⁴.



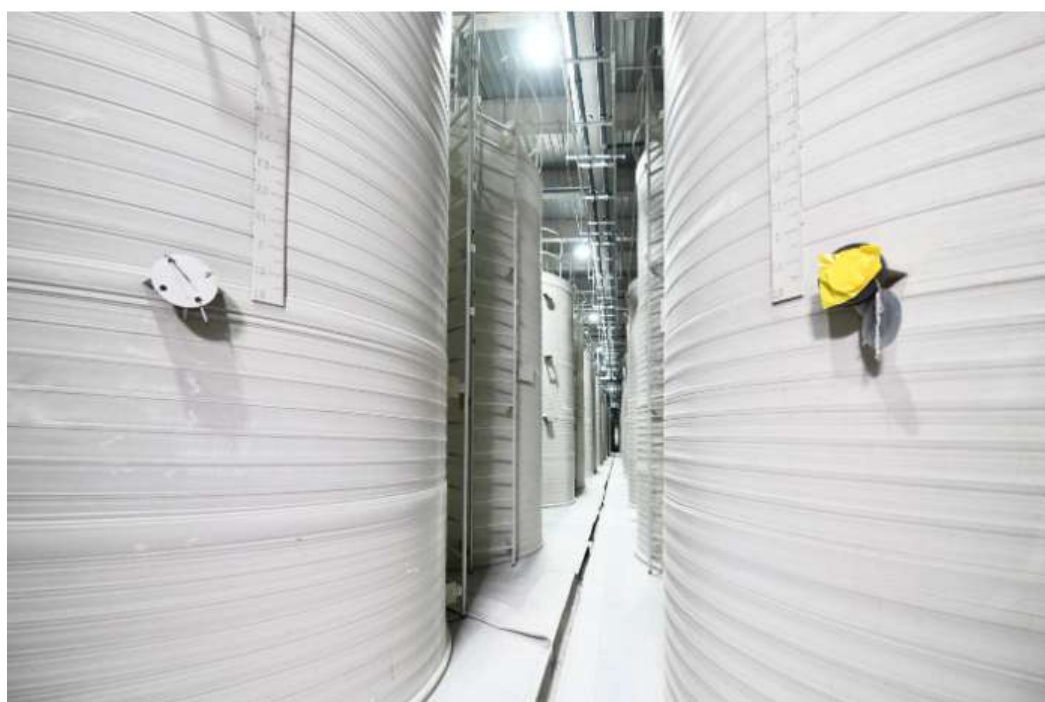
Figure 8.19 – Dalian Flow Battery Energy Storage Peak-shaving Power Station³⁰⁵



Figure 8.20 – Power module ³⁰⁵



Figure 8.21 – System debugging ³⁰⁵

Figure 8.22 Electrolyte tanks³⁰⁵

Sumitomo Electric – Grid-Scale VRFBs in Japan²⁷⁹

Sumitomo Electric installed a 15 MW/60 MWh VRFB at the Minami-Hayakita substation owned by Hokkaido Electric Power Company in the town of Abira on the island of Hokkaido, Japan. The installation in 2015 was part of a demonstration project, supported by Japan's Ministry of Economy, Trade, and Industry, to determine how to best incorporate large-scale variable, renewable energy sources such as wind and solar into the electric grid.

The battery was installed inside a dedicated two-story building because of the cold weather climate in the region and consists of 520 cell stacks and 5,200 cubic meters of electrolyte. It is one of the world's largest redox flow batteries in operation. The system underwent capacity testing at the time it was commissioned and in total the 13 banks showed a discharge capacity of roughly 75 MWh, higher than the 60 MWh that was specified.

Because of the success of the demonstration project over 3 years, Sumitomo Electric was selected again as the installer for another large VRFB system on the island of Hokkaido, Japan.

Invinity – VRFB in Energy Superhub Oxford

The Energy Superhub²⁷⁹ (ESO) project, led by Pivot Power, a part of EDF Renewables, combines energy storage technology with EV charging, low carbon heating, and smart energy management systems to reduce carbon emissions. Once fully operational, the government-backed project aims to save 10,000 metric tons of CO₂ each year, rising to 25,000 metric tons each year by 2032.

The ESO is the site of the UK's largest flow battery, a VRFB manufactured by Invinity Energy Systems, with a power output of 2 MW and an energy capacity of 5 MWh, enough to serve the daily electricity needs of roughly 600 UK households. The VRFB, which was fully energized in December 2021, is combined with a 50 MW Wärtsilä Li-ion system to form a single hybrid energy storage asset, the largest vanadium flow and Li-ion hybrid system ever deployed. Through a Joint Venture with Bushveld Minerals, Invinity formed a special purpose vehicle called Vanadium Electrolyte Rental Limited (VERL) to lease the electrolyte used in the VRFB at the Superhub to the project developer, Pivot Power. By leasing the electrolyte for 10 years from VERL, Pivot Power lowered the upfront cost associated with getting the system deployed.

The hybrid battery³⁰⁶ system is the UK's first and largest grid-scale battery storage system connected directly to the transmission network allowing it to deliver large volumes of power to public and commercial EV charging locations across the city of Oxford without straining local electricity networks. The VRFB is the first resource activated when the system is called upon so that wear and tear on the Li-ion battery can be reduced. The Li-ion system is only called into service when the required response exceeds the capability of the VRFB thereby minimizing the required number of charge and discharge cycles for the Li-ion battery. Because Li-ion batteries experience significant degradation with each discharge cycle, a hybrid configuration making use of a VRFB extends the operational life of the asset. A hybrid ESS like this is a promising configuration as more variable, renewable energy sources are brought online this decade and longer, more frequent discharge cycles are required.



Figure 4.1: The hybrid battery

Figure 8.23 - The hybrid battery consists of two core assets, a 50 MW (peak power) / 50 MWh (energy) lithium-ion battery and a 2 MW (power) / 5 MWh (energy) vanadium redox flow battery.



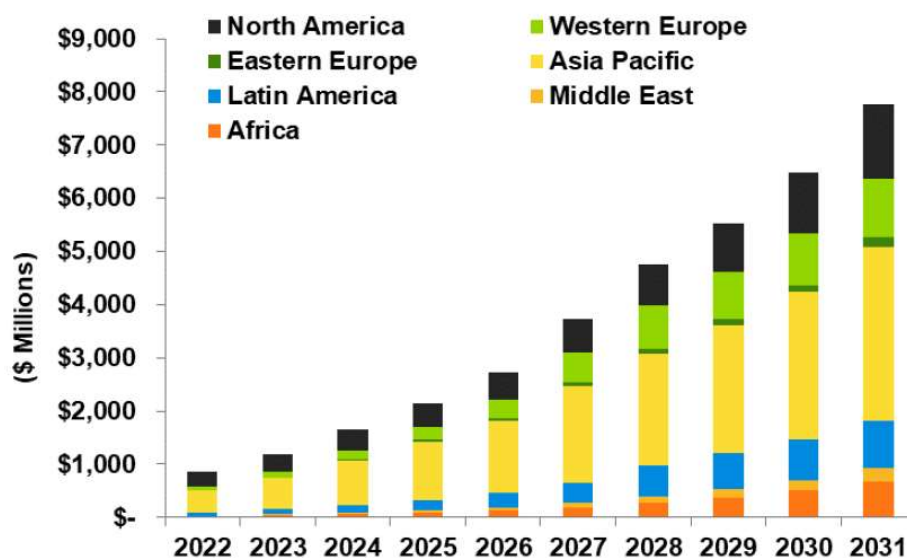
Source: Gunjan et al., 2022

Figure 8.24 – Operational VRFB project globally²⁶⁷

Market Forecasts

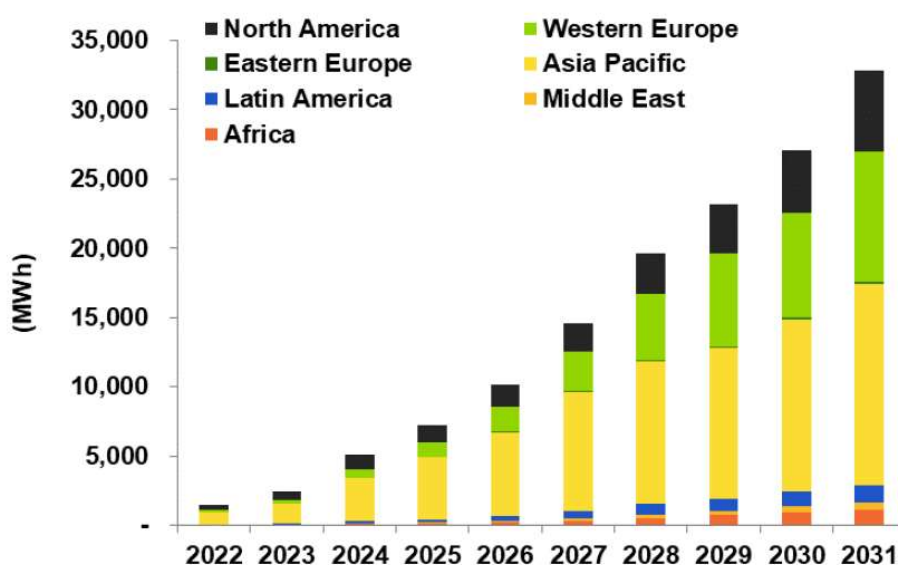
Guidehouse Insights' industry analysts²⁷⁹ use a variety of research sources in preparing white papers. To create and model energy storage forecasts, a variety of factors and assumptions are prepared to understand and accurately assess the market of interest. For VRFBs, inputs are entered to analyze total addressable market, the competitiveness of energy storage against alternatives, the split of VRFB technology, duration, and CAPEX investment. Likewise, revenue is calculated using a bottom-up approach based on average prices for battery system components across the stationary energy storage and EV markets. The system sizes are based on industry averages. The following forecasts were independently developed by Guidehouse Insights.

Leading the VRFB market in revenue is Asia Pacific, North America, and Western Europe, respectively. These three regions also lead the flow battery market in general and are leaders for energy storage deployments globally. Asia Pacific leads significantly, with a compound annual growth rate (CAGR) of 25.7% for revenue and 37.4% for energy capacity. By 2031, it is estimated that Asia Pacific will reach around 14.5 GWh of annual VRFB energy capacity. North America is expected to reach 5.8 GWh and Western Europe is anticipated to reach 9.3 GWh.



(Source: Guidehouse Insights)

Figure 8.25 Annual Installed VRFB Utility-Scale and Commercial and Industrial Deployment Revenue by Region, All Application Segments, World Markets: 2022-2031



(Source: Guidehouse Insights)

Figure 8.26 Annual Installed VRFB Utility-Scale and Commercial and Industrial Battery Deployment Energy Capacity by Region, All Application Segments, World Markets: 2022-2031

8.7.3 Will it change everything score

VRFB storage systems represent a promising alternative to traditional lithium-ion batteries, offering a distinct set of advantages and challenges. To assess their potential to revolutionize

the energy storage landscape, we will calculate their "Will it Change Everything Score" based on a weighted combination of key factors. This score will provide a comprehensive evaluation of VRFB storage systems' disruptive potential, considering not only their technical capabilities but also their environmental impact, scalability, and market viability compared to the current dominant technology, lithium-ion batteries.

Table 8.2: Types of Energy Storage and Their Properties³⁰⁷

Type of energy storage	Capacity	Usage time	Efficiency level (%)	Lifetime	Cost
Lithium based batteries	0,001-0,1 MW	min-h	85-99	5-15 years, 500 to 1.500 charge cycles	High cost of raw materials
Pumped hydro energy storage	up to 5000 MW	1-24 h	65-85	40-60 years	high initial, low operational
Gravity energy storage	large, scalable (kW – GW)	1-24 h	70-90	40-60 years	high initial, low operational
CO ₂ -based energy storage	large, scalable	1-24 h	40-60	20-30 years	high initial, lower long-term
Solid state energy storage	high energy density	min-h	high due to low internal resistance	10-15 years, up to 10.000 cycles	high manufacturing cost
Hydrogen power production	scalable (kW-GW)	s-months	60-80	5.000-40.000 hours	high production and infrastructure costs
Compressed air technology	depends on storage capacity, suitable for large-scale storage	1-24 h	45 (diabatic), 70 (adiabatic)	20-40 years	high initial, lower operational
Liquid air energy storage	Scalable, (kW – GW)	1-24 h	50-70	30-60 years	high initial
Flow batteries (vanadium redox batteries)	scalable	s-10 h	75-85	15-25 years, 10.000-20.000 cycles	high initial
Supercapacitors	0,01-1 MW, rapid charge/ discharge	ms-s	90-95	10-20 years, 1 million charge and discharge cycles	higher cost per unit of energy
Superconducting magnetic energy storage	0,001-10 MW	s	90	20-30 years	higher cost per unit of energy

Type of energy storage	Capacity	Usage time	Efficiency level (%)	Lifetime	Cost
Flywheel energy storage	0,002-20 MW, high power, short duration	s-min	85-95	15-25 years	high initial

Scoring VRFB Storage Systems

1. **Energy Density** VRFB storage systems generally have lower energy density compared to lithium-ion batteries due to the large volumes required for substantial energy storage.
 - Score: 30
2. **Energy Retention Period** VRFB storage systems can store energy for long periods without significant losses, making them suitable for long-term energy storage. Their storage duration is almost unlimited, therefore a maximum score is well justified
 - **Score:** 100
3. **Lifetime and Life Cycles** VRFB storage systems can offer an exceptionally high number of cycles with minimal degradation.
 - **Score:** 100
4. **Round-Trip Efficiency (RTE)** VRFB storage systems typically have a round-trip efficiency of around 65-85%, which is lower than lithium-ion batteries.
 - Score: 40
5. **Technological Maturity (TRL)** VRFB storage systems have different TRL levels. In conclusion, VRFB is less established than lithium-ion batteries and have fewer market actors.
 - Score: 40
6. **Capital Expenditure (CAPEX)** VRFB storage systems often have much higher initial costs than Lition batteries.
 - Score: 35
7. **Operational Expenditure (OPEX)** VRFB storage systems have relatively low operational costs, primarily due to minimal maintenance requirements.
 - Score: 80
8. **Environmental Impact** VRFB storage systems are environmentally friendly due to the use of common materials and minimal reliance on toxic substances. They also have a lower risk of accidents, reducing the chance of environmental contamination.
 - Score: 90
9. **Scalability** VRFB storage systems offer better scalability than lithium batteries: In a VRFB, energy storage capacity (electrolyte volume) and power output (size of the electrochemical stack) are separate. To increase capacity, one can simply add more electrolyte tanks, while increasing power requires scaling the stack. This modular

approach allows for easy scalability tailored to the exact needs of a project, whether it's increasing capacity, power, or both. In lithium-ion systems, energy and power are interlinked; to increase storage, more battery cells are required, which also increases power output. This makes scalability less flexible and typically costlier at larger scales.

- Score: 55

Weighted Scores Calculation

Parameter	Weight	Score	Weighted score
Energy Density	0.1	30	3
Energy Retention Period	0.1	100	10
Lifetime and Life Cycles	0.1	100	10
Round-Trip Efficiency (RTE)	0.15	40	6
Technological Maturity (TRL)	0.2	40	8
Capital Expenditure (CAPEX)	0.1	35	3.5
Operational Expenditure (OPEX)	0.1	80	8
Environmental Impact	0.1	90	9
Scalability	0.05	55	2.75
Total	1		60.25

Conclusion

The "Will it Change Everything Score" for gravity storage systems is 60.25, indicating a potential to impact the energy storage landscape significantly. While they may not match the energy density and efficiency of lithium-ion batteries, their advantages in terms of long-term storage, environmental impact, and low operational costs make them a viable and sustainable alternative, especially in applications requiring large-scale, long-duration energy storage. Further development and optimization could enhance their competitiveness and broader adoption.

Impact potential of technology



Figure 8.27

9. Superconducting Magnetic Energy Storage (SMES)

Summary of Metrics

Parameter	Technology: Superconducting Magnetic Energy Storage
	Value/Range
Energy density per unit of volume [Wh/kg]	0,5 - 5 Wh/kg
Power range [MW]	100 kW to 10 MW
Time of Permanent Energy Storage [hour]	unlimited
Life time [years/cycles]	30 years
Discharge Time [minutes]	milliseconds to seconds
RTE (Round-Trip Efficiency) [%]	90-95
RTE degradation	0
Technology Maturity / Technological Readiness Level (TRL):	8
System size Energy Capacity	up to Mwhs
CAPEX per kW of Power Capacity [EUR/kW]	Depends on E/P ratio 300 €/kWh (E/P=4) to 2000 €/kWh (E/P=0.25)
CAPEX per kWh of Energy [EUR/kWh]	2 - 3% of investment
OPEX per kWh of Energy [EUR/kW/year]	There's no available data
OPEX per kWh of Energy [EUR/kWh/year]	There's no available data

Sources: Tixador, 2008³¹², EERA, 2019³⁰⁹,

9.1 Introduction

In the dynamic landscape of energy storage technologies, Superconducting Magnetic Energy Storage (SMES) emerges as a compelling contender. Distinguished by its exceptional efficiency, rapid response times, and prolonged lifespan, SMES systems capitalize on the unique properties of superconductors to store energy in the form of a magnetic field.

Superconducting magnetic energy storage (SMES) is a French invention. The energy is stored via an electric current existing in a coil made of a superconducting wire. Once the coil is short circuited (closed), the current flows forever since there is no loss and produces a magnetic field as in MRI coils³⁰⁸. The energy is hence stored in the coil in a magnetic and electric form and can be recovered in a very short amount of time.

At the core of SMES technology lies the phenomenon of superconductivity. Certain materials, when cooled below a critical temperature, exhibit zero electrical resistance. This remarkable property allows for the persistent flow of electrical current within a superconducting coil, effectively trapping energy within a magnetic field. The absence of electrical resistance translates

to minimal energy losses during storage and discharge cycles, making SMES systems exceptionally efficient.

Despite its promising attributes, SMES technology faces challenges that necessitate further research and development. The requirement for cryogenic cooling to maintain superconducting conditions poses a significant technical and economic hurdle. Additionally, the relatively high capital costs associated with superconducting materials and cryogenic systems can impede widespread adoption. However, ongoing advancements in material science and cryogenic technologies hold the potential to mitigate these challenges and unlock the full potential of SMES.

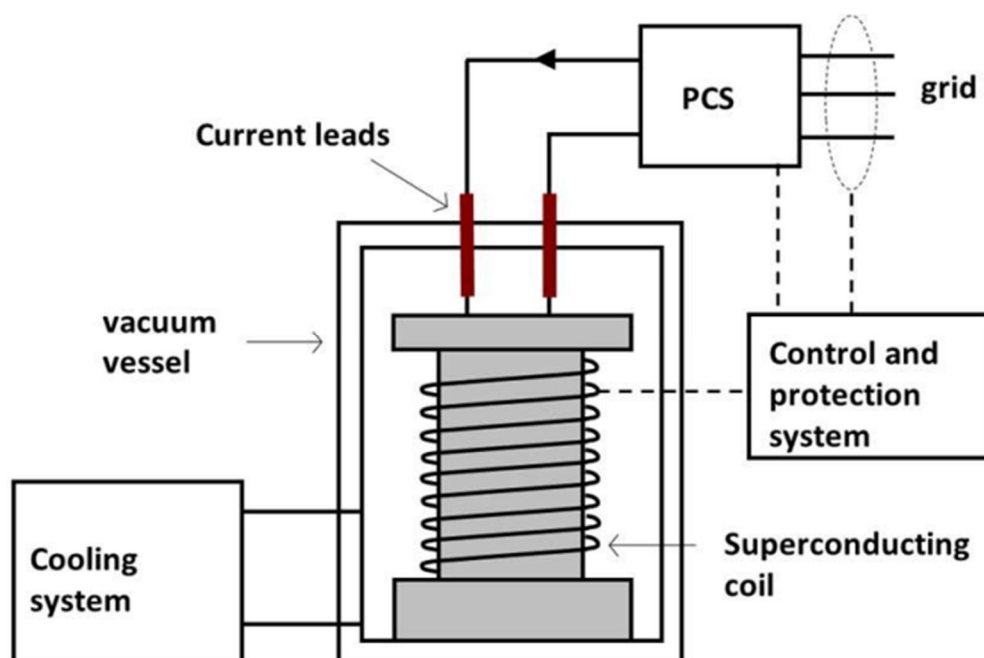


Figure 9.1. Schematic representation of a SMES system, including the Power Conditioning System (PCS), cryogenics and control and protection system, besides the superconducting coil³⁰⁹

A basic schematic of a SMES system. A SMES system is primarily composed of three essential components: a cryogenic refrigerator, a superconducting coil made from low-temperature superconductors (LTS) or high-temperature superconductors (HTS), and a supply of liquid helium or nitrogen for cooling purposes.

In this setup, the superconducting coil is housed within a cryostat and kept at extremely low temperatures by the cryogenic refrigerator. The coil stores energy in the magnetic field generated when electric current flows through it. Helium, often used in liquid form, plays a key role in maintaining the superconducting state of the coil by cooling it to cryogenic temperatures. The pump ensures circulation of the helium within the system, maintaining the desired temperature conditions.

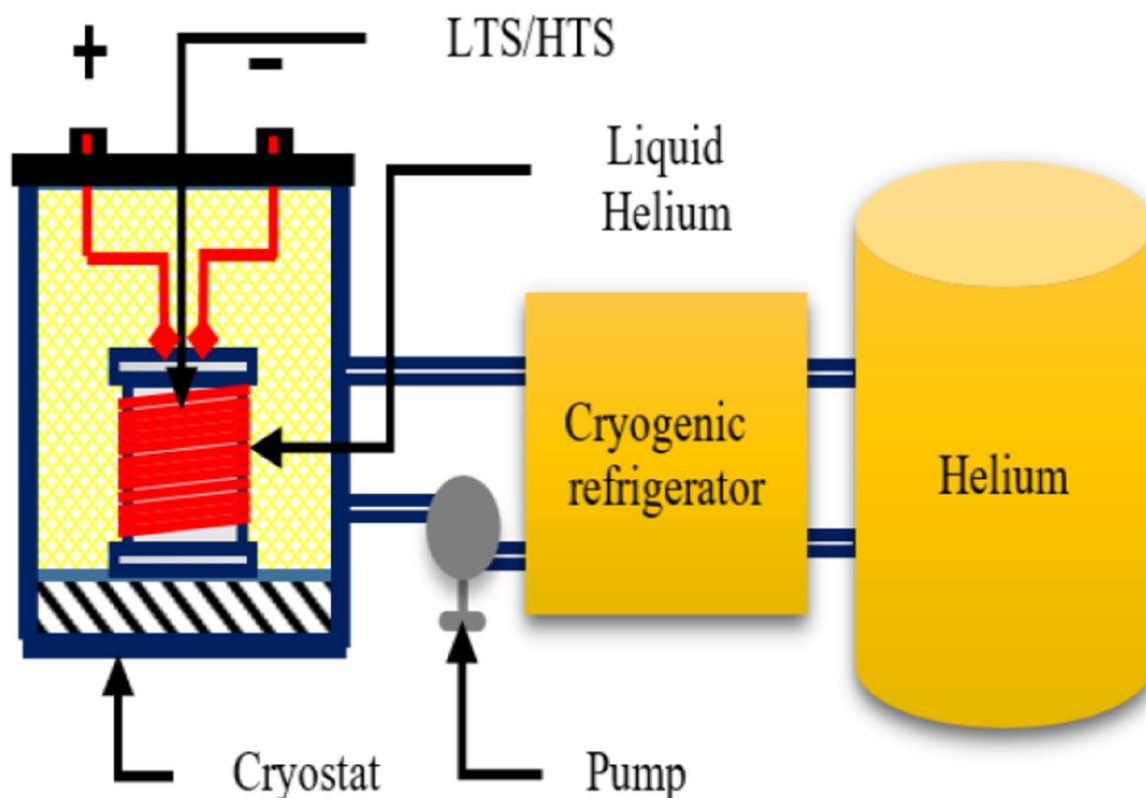


Figure 9.2: SMES is primarily made up of three components: a cryogenic refrigerator, a low- and high-temperature superconducting coil magnet, and helium/nitrogen liquid - (Khaleel, et al., 2023)³¹⁰

Physics

Principles of Magnetic Energy Storage

A superconductor is defined by many physical quantities. These are the most important ones:

a.) The critical temperature T_c

It corresponds to the temperature below which the material becomes superconducting. We can use degrees Celsius but physicists prefer degrees Kelvin ($^{\circ}\text{C} = \text{K} - 273.15$).

b.) The critical current I_c

It corresponds to the maximum current that can go through a superconductor. If the current exceeds this value, the material becomes a normal metal again and starts resisting and heating like any other metal. More often, physicists use the term “current density” (J), that is the current divided by the cross section of the electric wire. For instance, in a cuprate, the current density is more than 10 000 amperes per cm^2 .

c.) The critical field B_c

It corresponds to the maximum magnetic field that can be applied to a superconductor. Above the critical field B_c , the material becomes a normal metal again. For instance, in mercury, this field is 0.04 Tesla (about 1000 times the earth magnetic field). For some superconductors, we have to define two critical fields, B_{c1} and B_{c2} , because of the presence of vortices. For example, in a cuprate, B_{c1} is about 0.01 Tesla, but B_{c2} can be as high as 60 teslas, which is more than a million times higher than the Earth's magnetic field. (B_{c1} : Lower critical field where magnetic flux first penetrates the superconductor B_{c2} : Upper critical field where superconductivity is completely destroyed.)

d.) The penetration length λ ("lambda")

When a magnetic field is applied to a superconductor, it is expelled and can only penetrate a short depth of the surface of the sample, measured as the penetration length. It is usually very small, from 10 to 100 nanometres (1 nanometre = 1 billionth of a metre).

f.) The coherence length ξ ("xi")

It corresponds to the distance to which a Cooper pair spreads, or to the necessary distance for a superconducting wave to develop. It also corresponds to the size of the heart of the vortex. It can vary highly depending on the superconducting material, going from a micrometre in superconductors such as aluminium to only a few nanometres in cuprates.

g.) The gap

The superconductor is characterised by its wave function formed from the Cooper pairs. This wavefunction has an energy called "gap": it corresponds to the minimum energy needed to break one of the Cooper pairs. In conventional superconductors, the higher the T_c , the greater the gap, and the latter is the same in all directions (isotropic). In unconventional superconductors such as cuprates or heavy fermions. The gap can be "anisotropic" and can present symmetries with very different shapes.

These parameters define the operational limits and are crucial for the design and functionality of SMES systems.

The operation of SMES is rooted in fundamental principles of electromagnetism and superconductivity. At its heart, an SMES system stores energy in the magnetic field generated by a direct current flowing through a superconducting coil.

The energy (E) stored in the magnetic field of an inductor is given by:

$$E = \frac{1}{2}LI^2$$

where:

- **L** is the inductance³¹¹ of the coil which is a measure of its ability to store energy in a magnetic field. (in henrys, H),
- **I** is the current flowing through the coil (in amperes, A).

This equation illustrates that the stored energy increases with the square of the current, highlighting the efficiency of using high currents in superconducting coils.

Operation of SMES Systems

Charging and Discharging Cycles

- **Charging:** Electrical energy is introduced into the superconducting coil, generating a magnetic field where the energy is stored.
- **Discharging:** The stored energy is released back into the electrical grid by reducing the current in the coil, converting magnetic energy back to electrical energy.

The voltage across a superconducting coil is described by:

$$V = L \frac{dI}{dt}$$

- **V:** This represents the voltage across the superconducting coil in the SMES system.
- **dI/dt:** This signifies the rate of change of current flowing through the coil with respect to time. In other words, it indicates how quickly the current is increasing or decreasing.
- **L:** This represents the inductance of the superconducting coil in the SMES system, which shows how well the coil can store magnetic energy and resist changes in current.

This equation shows that the voltage across the inductor is proportional to how quickly the current is changing. If the current changes rapidly, the voltage across the inductor will be higher.

In a superconducting coil, the current can persist indefinitely without an external power source due to zero resistance.

Cryogenic Cooling

Maintaining superconductivity requires cooling the coil below its critical temperature, often achieved using cryogenic liquids like liquid helium or nitrogen. This cooling infrastructure is essential but adds complexity and cost. A temperature rise above the critical point in an SMES system is a serious event with potentially severe consequences - when the temperature exceeds the critical point, the material's resistance suddenly increases, leading to rapid Joule heating ($P = I^2R$) which further raises the temperature in a dangerous feedback loop. This thermal runaway can result in rapid energy discharge, structural damage to the coil, vaporization of the cryogenic

coolant, and potential pressure vessel rupture if the helium or nitrogen rapidly expands. Therefore, maintaining the cryogenic cooling system's integrity and having robust safety protocols are paramount in ensuring the safe and reliable operation of SMES technology..

Magnetic Field Strength and Structural Integrity

High magnetic fields generate significant mechanical forces within the coil, necessitating robust structural support to prevent deformation or failure. Designing the coil to withstand these forces is critical for safe and reliable operation.

Storing AC power from an external power source requires an SMES system to first convert all AC power to DC power. Interestingly, the conversion of power is the only portion of an SMES that is not perfectly efficient, accounting for all total system loss.

The main characteristics of the SMES are a strong power density (specific energy is 1-10 W-h/kg (4-40 kJ/kg and specific power of SMES is ~10,000–100,000 kW/kg), but a moderate energy density (less than 40 kJ/L), a very high (infinite) number of charge/discharge cycles and an energy conversion efficiency exceeding 95%, with self-discharge rate of 0 (Wayback Machine Tixador, 2008)³¹².

The SMES system is more an impulsive current source than an energy storage device. SMES is hence an excellent solution for non-interruptible power supply systems or some FACTS (Flexible AC Transmission System), which are static equipment to enhance electric networks.

Superconducting coils

"Magnets produce magnetic fields that can be strong but that strongly weaken when moving away. In order to get a strong field on a big volume, electromagnets are required, i.e. a metal wire coil in which an electric current flows. The current that flows in a circle, creates a magnetic field perpendicular to the section of the coil and in all its volume.

To get a strong field, a high electric current is required. But when there is a current, there is resistance, and where there is resistance, there is heating, because of the Joule effect. Due to heating, the coil could melt if the losses (alternatively thermal energy output) are too great. To avoid this problem, we can either cool the wire with water (very expensive and not very convenient) or use a superconducting wire, because the latter has zero resistance and hence does not heat. Magnetic fields of several teslas (1 tesla is equal to about 10 000 times the earth magnetic field) can be obtained; using coils with several thousands turns of superconducting wires plunged in liquid helium. These wires are often made from niobium and titanium alloys (NbTi) or niobium and tin (Nb₃Sn). These coils are often called "superconducting magnets" by misuse of language.

These strong magnetic fields are used for MRIs in hospitals, for Nuclear Magnetic Resonance (NMR) in chemistry and in physics, in physics laboratories to study the effect of fields on solids,

in particle accelerators to make particles turn, to store electricity, to make the plasma used in ITER³¹³ (International Thermonuclear Experimental Reactor) for the fusion project levitate, but also on board the Maglev train to make it levitate.

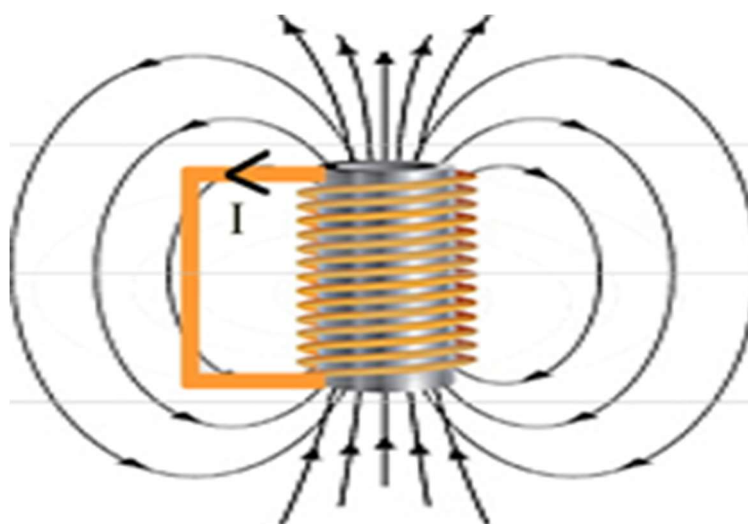


Figure 9.3 Magnetic energy storage in a short-circuited (closed) superconducting coil.

Resistance in a Superconductor

“In a superconductor, below a temperature called the “critical temperature”, the electric resistance very suddenly falls to zero. At zero resistance, the material conducts current perfectly. This is incomprehensible because the flaws and vibrations of the atoms should cause resistance in the material when the electrons flow through it. However, in a superconductor, the electric resistance is equal to zero although the flaws and vibrations still exist.

. Due to zero resistance, an electric current can circulate forever in a superconducting ring even when the battery has been unplugged! This is how magnetic fields are created in MRIs. It might seem odd that a battery could create a low voltage electric current at the terminals of a superconducting network, since the voltage should be equal to zero because of the absence of electric resistance. What happens is that the electric tension created by the battery is divided into the other parts of the network, i.e. the metallic wires that link the battery to the superconductor and to the interior of the battery (internal resistance).

The measurements taken over the course of several years show that the current never decreases. Even though the current is perpetual, it is not a violation of the thermodynamic laws (which forbids perpetual motion machines), because in this case no energy is created. The electric and magnetic energy is merely stored in the ring.

Explanation : the electrons form a new original quantum collective state that is not sensitive to collisions anymore. The electrons are not slowed and the electric resistance has disappeared.

Figure 9.4 depicts the major components of SMES, the charging process, and the discharging process. SMES, in particular, offers a high and rapid self-discharge due to its self-cooling over cryogenic liquid.

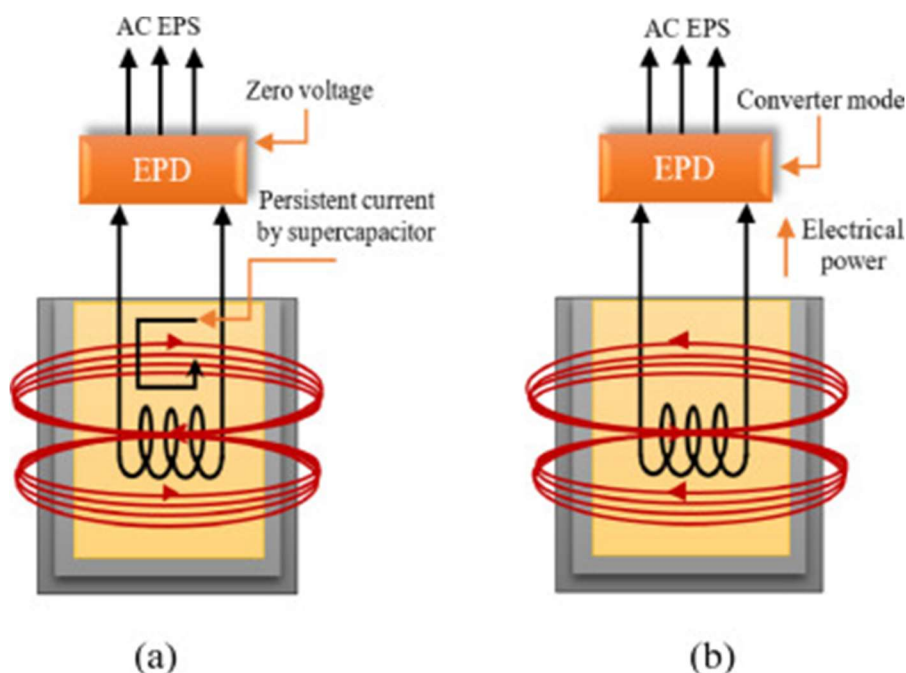


Figure 9.4 Source: Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems. September 2023." (Khaleel, et al., 2023)³¹⁰

History

The journey begins with the discovery of superconductivity by Dutch physicist **Heike Kamerlingh Onnes** at the University of Leiden. He observed that mercury exhibited zero electrical resistance when cooled below 4.2 Kelvin (-268.95°C). This groundbreaking finding earned him the Nobel Prize in Physics in 1913 and laid the foundation for future applications of superconductivity, including SMES.

The concept of using a superconducting coil to store energy was first proposed by Professor B. W. McConnell at the University of Wisconsin–Madison in the late 1960s. Recognizing the potential of zero-resistance superconductors to store large amounts of energy with minimal losses, McConnell's idea was a significant leap toward practical energy storage solutions.

In 1970; the motivation was to level the load in the French electricity network. The energies required (thousand of MWh) led nevertheless to huge magnets (1 km in diameter) with a lot of realisation difficulties. Furthermore, SMES is not the best solution in this case due to **its rather low energy density. Pumped hydroelectric and compressed air units offer higher performances.** With energies of some to tens of MJ, SMES can be used in the electricity networks

as a **Flexible AC Transmission System (FACTS)**. A FACTS is a static device installed in the electric grid in order to enhance its operation in terms of controllability and power transfer capability. It is generally a power-electronics-based device.

The U.S. Department of Energy began funding research into SMES during the 1970s, focusing on its potential to enhance grid stability and efficiency. At LANL, Dr. James W. F. Fountain and later Dr. Ferdinand M. Dahlgren led projects to develop small-scale SMES prototypes. These early efforts demonstrated the feasibility of SMES technology and its ability to provide rapid energy discharge, essential for power grid applications.

1973 Experimental demonstration: Professor Harold A. Peterson (University of Wisconsin-Madison, USA) conducted experiments that provided one of the first practical demonstrations of SMES. His work showcased the technology's potential in utility applications, particularly in managing power system stability and responding to sudden demand changes.

In the 1980s, the Los Alamos National Laboratory collaborated with the Bonneville Power Administration (Pacific Northwest, USA) to explore SMES for grid stabilization. The team focused on developing SMES units capable of injecting large amounts of power into the grid within milliseconds, addressing issues like power oscillations and blackouts. The 30 MJ, 10 MW superconducting energy storage system was devised to interact in the Western U.S. Power System as an alternate means to damp unstable oscillations at 0.35Hz on the Pacific HVAC Intertie.³¹⁴ This SMES operated in real grid conditions for about one year, with over 1200 hours of energy transfers. This represented more than 10⁶ cycles for the magnet. The main operating problems concerned the power converter and above all the refrigerator. No problems occurred with the superconducting magnet and the cryostat. In addition to the refrigerator problems, alternative solutions were found to damp the oscillations and the SMES operation was stopped. This experience was the first successful and conclusive demonstration of a large SMES operation in a real power grid.

The feedback from past experience in the United States and Japan is very positive. However, few SMES systems have been sold because of the high initial cost and the competition of more developed technologies. Even though high temperature materials³¹⁵ cannot reduce the total cost, they make SMES systems more attractive because they enhance the mass performances of superconducting magnets and reduce the cost of cryogenics (investment and functioning).

Current research trends

In recent years, Superconducting Magnetic Energy Storage (SMES) technology has made significant strides through various innovative projects worldwide. In the early 2000s, the United States advanced SMES practicality by developing second-generation high-temperature superconducting (HTS) tapes, which operate at higher temperatures and reduce cooling costs. This innovation enhanced the feasibility of SMES systems for broader applications. In 2004, the

Korea Electrotechnology Research Institute (KERI) in South Korea installed a 3 megajoule (MJ) SMES system aimed at improving industrial power quality. This system successfully demonstrated how SMES could mitigate voltage sags and interruptions, highlighting its potential in stabilizing power supply for sensitive industrial processes.³¹⁶

Building on global interest, China launched a national SMES program in 2008 through the Chinese Academy of Sciences, focusing on grid applications and renewable energy integration. This initiative led to the development of prototype SMES units designed to enhance grid stability amid increasing renewable energy penetration. Between 2010 and 2013, the European Union funded the EUROSMEs project, where multiple countries collaborated to explore SMES for grid stabilization and support of wind and solar power. In 2012, Japan's Chubu University developed a 10 MJ HTS SMES system, one of the largest at that time, aiming to demonstrate large-scale energy storage capabilities for grid applications. Further advancements include Germany's efforts in 2015 at the Karlsruhe Institute of Technology to utilize SMES for stabilizing wind power output, and the United States' exploration in 2017 of integrating SMES into microgrids at the Massachusetts Institute of Technology. These projects collectively underscore the global momentum in leveraging SMES technology to enhance grid reliability and accommodate the growing share of renewable energy sources.

9.1.1 Summary

In summary several **SMESs have proved their operational capabilities for short-term (seconds) power at MW scale**. They are commercially available and the field test experience is very large in the US and Japan. Nevertheless, the number of SMES sold remains very low and does not increase much. The major reason is the high initial cost while in competition with more mature technologies. Moreover SMES addresses niche applications having high active power – short time demands. (Tixador, 2008)³¹²

9.2 Main applications of SMES

Superconducting Magnetic Energy Storage (SMES) systems are being increasingly integrated into various sectors of the electrical grid due to their unique properties of high efficiency, rapid response, and unlimited charging cycles. The following are the primary applications of SMES systems based on current studies³¹⁰:

1. **Power Quality Improvement** SMES is frequently deployed to address Power Quality (PQ) issues in the electrical grid. By instantly injecting both active and reactive power, SMES helps maintain high-quality power flow, especially during transient disturbances. This rapid response can mitigate problems such as voltage sags, swells, and harmonic distortions, ensuring the stability of voltage levels during various disturbances. Its ability

to store and release large amounts of energy instantaneously makes it ideal for handling PQ challenges in dynamic systems.

2. **Frequency Management and Voltage Stability** SMES is extensively used for frequency management within the electrical grid. It provides immediate reactive power during periods of load fluctuation, ensuring frequency stability. Additionally, it supports voltage stability by quickly absorbing or injecting reactive power into the system. This feature is especially important in grids with high penetration of renewable energy sources (RES), where voltage and frequency can fluctuate unpredictably .
3. **Integration with Renewable Energy Sources (RES)** The intermittent nature of renewable energy sources like wind and solar presents significant challenges for grid stability. SMES is increasingly integrated with these renewable energy systems to smoothen power output fluctuations. By serving as an energy buffer, SMES helps balance the mismatch between power generation and consumption, improving the overall efficiency and reliability of RES . Its quick response time and high power density make it an effective tool for managing the inherent variability of renewable energy production.
4. **Grid Stabilisation and Support for Hybrid Energy Storage Systems (HESS)** SMES plays a critical role in stabilising the electrical grid, particularly in combination with other energy storage technologies such as batteries, flywheels, and supercapacitors. This hybrid approach, known as Hybrid Energy Storage Systems (HESS), allows for a more robust and flexible energy management solution. In such configurations, SMES provides immediate, high-power bursts of energy, while the other systems manage longer-term storage needs
5. **Uninterruptible Power Supplies (UPS)** One of the traditional applications of SMES is in Uninterruptible Power Supply (UPS) systems. Due to its fast energy discharge capability, SMES can bridge the gap between a power outage and the activation of backup generators. This makes it particularly useful in critical infrastructure sectors, such as hospitals, data centres, and industrial facilities where even brief interruptions in power can lead to significant disruptions .

One of the first systems was installed in 1993 for an ammonia production furnace. Another 1.4 MVA/2.4 MJ SMES was installed at the Brookhaven National Laboratory (USA) to offer high quality power for a synchrotron source. It provides power during voltage sags or momentary interruptions to avoid beam loss. Owens Corning's extrusion and production lines in North Carolina have been protected by SMES from voltage sags. Likewise, in South Africa, a SMES has protected a paper machine against 72 dips in 11 months. In Japan several SMESs have been built. One objective is the protection of sensitive load against voltage dips. In 2003 a 5 MW – 7 MJ SMES was fabricated using NbTi solenoid in a 4 pole configuration. It has compensated voltage dips in a liquid crystal manufacturing factory. Another SMES system with a rating of 10 MVA was built in 2005. A national Japanese program is carried out on SMES for load fluctuation compensations.

They have initiated the development of high-Tc SMES and tested a 1 MVA SMES using a Bi-2212 PIT wire, but operating at 4 K . (Tixador, 2008)³¹²

6. Another SMES class are **pulse power sources** for dedicated applications having very high power demand over a short time. Examples of such applications are electromagnetic launchers and magnetic forming. One such current development is described in Section V. Pulse power SMES sources using toroidal coil magnets have been also studied in Russia. . (Tixador, 2008)³¹²
7. **Flexible Alternating Current Transmission Systems (FACTS)** SMES is employed in FACTS to enhance the controllability and increase the power transfer capability of transmission systems. It improves the flexibility of grid operations by supporting voltage regulation, power flow control, and system reliability. Through its ability to provide immediate reactive power, SMES helps FACTS devices respond quickly to changing load demands and maintain stability during grid disturbances .

Table 9.1 below characterises three different SMESs intended for different power and energy ranges. Only the smallest was constructed and operated.

	SMES plant	SMES/ETM	5 MVA SMES
Energy	5250 MWh (18.9 TJ))	20.4 MWh (73 GJ)	7.3 MJ
Power	1000 MW	400 MW	5 MW
Magnet	- diameter	1000 m	129 m
	- height	19 m	7.5 m
Current	200 kA	200 kA	2657 A
Superconductor	NbTi	NbTi	NbTi
Operating temperature	1.8 K	1.8 K	4 K
Status	Only design	Abandoned	Used for voltage dips

Table 9.1: SMES characteristics Source: Tixador, 2008 ³¹²

SMES in power grid based on optimization problems

The image from the Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems³²⁶ study illustrates a comprehensive diagram of a hybrid energy storage and generation system integrated into a three-phase (3-φ) electrical grid. The system showcases several advanced energy technologies, including a Flywheel, Fuel Cell, and Superconducting Magnetic Energy Storage (SMES) system, connected to the grid through various power conversion stages such as DC-AC inverters and transformers. Additionally, it incorporates conventional renewable energy sources, including Wind Turbines, Photovoltaic (PV) solar panels, and Battery Energy Storage Systems (BESS), all contributing to the grid's energy stability. The diagram demonstrates how different energy sources, both storage and generation, are transformed and integrated into the grid through alternating current-direct current (AC-DC) conversions, ensuring efficient power flow and stability for modern electrical systems. The image

highlights the strategic role of SMES and other technologies in enhancing the grid's flexibility and performance, particularly when integrated with renewable energy sources.

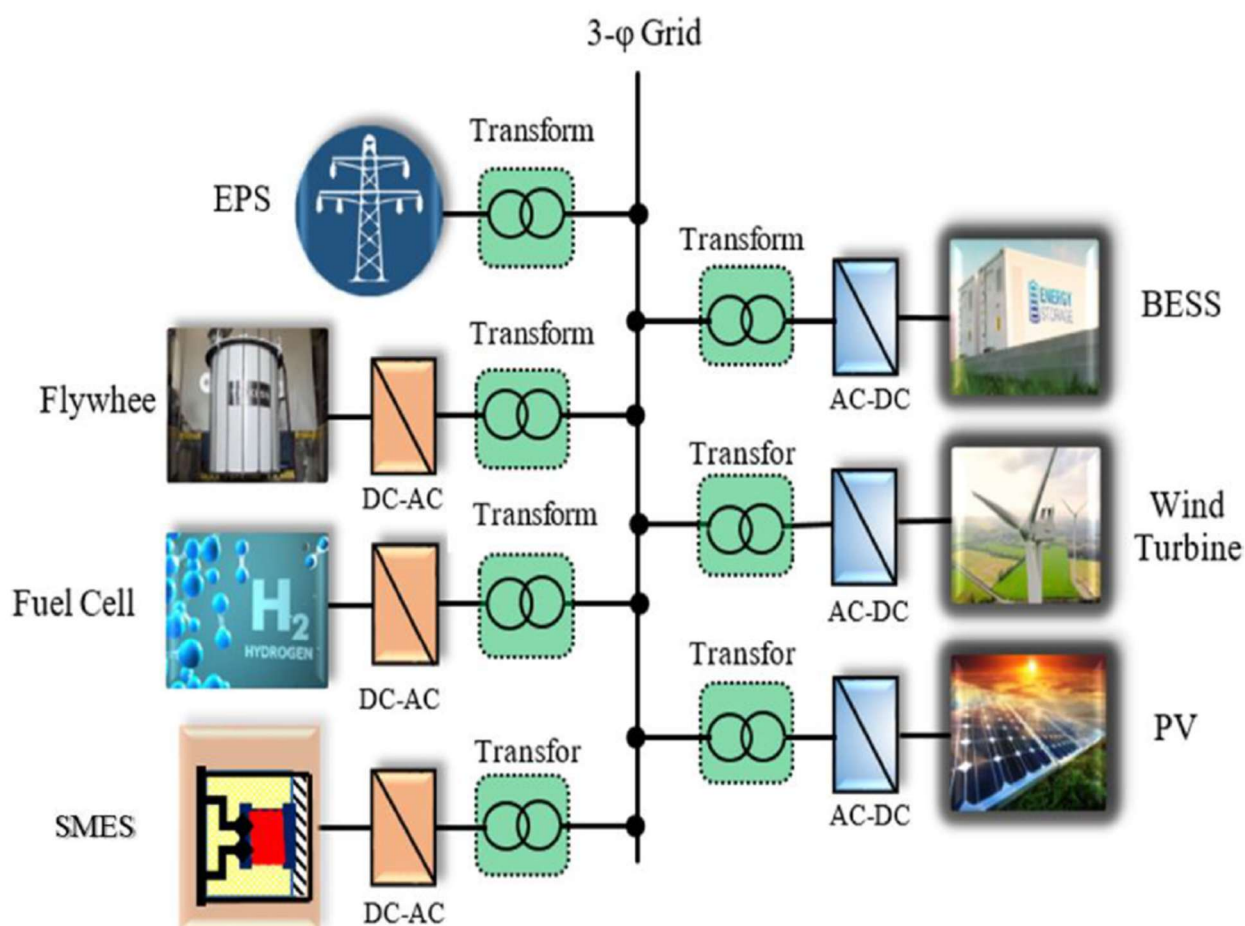


Figure 9.5 A sample diagram for the hybrid system Source: Khaleel, et al, 2023³¹⁰

9.3 Technological barriers, regulatory framework and scalability

“There are just a few studies that have examined the SMES in the power grid in terms of its structures, technical control issues, power grid optimization issues, and contemporary power protection issues. Thus, the configurations of SMES and energy power system integration, SMES identification and characteristics, benefits of contemporary technologies connected to enhance energy power system owing to power quality disturbances, technical issues in the energy power system integrated SMES, and SMES optimization for hybrid energy storage system (HESS) and contemporary power protection system challenges. (Khaleel, et al., 2023)³¹⁰

9.3.1 Main technological barriers

As described in Chapter 9.1, **Cryogenic Cooling** is a major technical and energetic hurdle to tackle during the operation of SMES, as maintaining cryogenic temperatures requires significant energy input that impacts the overall system efficiency.

Superconducting coils in SMES systems require continuous cooling below their critical temperature to maintain their superconducting properties. This is typically accomplished through the use of cryogenic fluids such as liquid helium or nitrogen. While essential for operation, this cooling system introduces additional complexity and expenses to the overall infrastructure.

A critical concern in SMES operation is the potential for temperature excursions above the superconducting threshold. Such events can have serious implications and may lead to significant system failures. Consequently, the integrity of the cryogenic cooling apparatus is of utmost importance. Equally crucial is the implementation of comprehensive safety measures to ensure the dependable and secure functioning of SMES technology.

The emphasis on maintaining precise temperature control and the necessity for robust safety protocols underscores the technological challenges and operational considerations inherent in SMES systems.

The required temperature for cryogenic cooling of superconducting magnets typically depends on the type of superconducting material used:

1. **Low-Temperature Superconductors (LTS)** Common LTS materials include **Niobium-Titanium (NbTi)** and **Niobium-Tin (Nb₃Sn)**. Their critical temperatures (below which they become superconducting) are:
 - NbTi: approximately **9.2 K (-263.95°C)**
 - Nb₃Sn: approximately **18 K (-255.15°C)** Despite these critical temperatures, they are typically cooled to **4.2 K (-268.95°C)** using **liquid helium** as the cooling agent to ensure stable operation.
2. **High-Temperature Superconductors (HTS)** High-temperature superconductors like **Yttrium Barium Copper Oxide (YBCO)** have higher critical temperatures, typically around **93 K (-180.15°C)**. These superconductors can often be cooled using **liquid nitrogen**, which boils at 77 K (-196°C) and is less expensive and easier to handle compared to liquid helium.

For SMES (Superconducting Magnetic Energy Storage) systems, especially the more common low-temperature superconducting variants using materials like NbTi, cooling to around **4 K (-268.95°C)** is necessary to maintain the superconducting state and ensure optimal performance.

If the temperature in an SMES system rises above the critical temperature and reaches room temperature, several critical consequences occur:

1. Loss of Superconductivity:
 - The most immediate effect is the loss of superconductivity in the coil's material. The material transitions from a state of zero electrical resistance to a normal conducting state with finite resistance.
2. Rapid Energy Dissipation:
 - The persistent current flowing in the superconducting coil encounters resistance once superconductivity is lost.
 - This resistance causes the electrical energy stored in the magnetic field to rapidly dissipate as heat within the coil.
 - The amount of heat generated can be substantial, potentially leading to a significant temperature rise in the coil and surrounding components.
3. Potential Damage and Safety Concerns:
 - The excessive heat generated can cause thermal stress and damage to the coil, insulation, and other parts of the SMES system.
 - In extreme cases, the rapid heating could lead to a fire or even an explosion if adequate safety measures are not in place.
4. Loss of Stored Energy:
 - The stored energy in the magnetic field is essentially lost as it is converted into heat. The SMES system becomes inoperable until it is cooled back down to its superconducting state.
5. System Shutdown:
 - To prevent catastrophic damage, the SMES system would likely have safety mechanisms that trigger an emergency shutdown if the temperature rises above a certain threshold.
 - This shutdown would isolate the SMES system from the power grid and initiate cooling procedures to bring the temperature back down.

The **cost of manufacturing superconducting coils** from high-temperature superconductors (HTS) like YBCO or BSCCO remains prohibitively expensive. These materials are difficult to produce and require intricate processing, making large-scale deployment costly.³¹⁰

Magnetic Field Limitations: The magnetic field generated by the superconducting coil in SMES systems can affect nearby equipment and requires significant shielding. This adds complexity and cost to the installation and design.

Energy Density Constraints: While SMES systems excel at rapid energy discharge, their energy density (the amount of energy stored per unit volume) is lower (0,5 – 5 Wh/kg)³¹⁷ compared to other storage technologies, such as batteries. This limits their application where long-term, large-scale energy storage is needed.

9.3.2 Regulatory barriers

Environmental and Safety Regulations The high magnetic fields generated by SMES systems may face scrutiny under **EU electromagnetic compatibility (EMC) regulations**³¹⁸. These fields could interfere with nearby equipment and infrastructure, requiring additional compliance measures. Additionally, the use of cryogenic liquids (e.g., liquid helium) may require adherence to **EU environmental regulations**, potentially increasing the regulatory burden.

Cryogenic Safety Regulations: SMES relies on superconducting coils cooled to extremely low temperatures using cryogenic liquids like liquid helium or liquid nitrogen. Regulations governing the handling, storage, and transportation of cryogenic substances in pressure equipment³¹⁹ would apply. This includes adherence to safety standards to prevent leaks, explosions, or asphyxiation hazards.

9.3.3 Scalability

The SMES systems are limited in their scalability. Aside from unscalable upfront costs, SMES systems have high maintenance requirements, and storage capacity cannot be easily increased. In contrast, lithium-ion battery storage systems can easily be connected, while combining SMES devices requires scaling the cryogenic cooling infrastructure in kind. To achieve commercially useful levels of storage, around 1 GWh (3.6 TJ) a SMES installation would need a loop of around 160 km. A problem is also the infrastructure required for an installation. Until room temperature superconductors are found, the 160 km loop of wire would have to be contained within a vacuum flask of helium/liquid nitrogen. This in turn would require stable support, most commonly envisioned by burying the installation. (Khaleel, et al., 2023)³¹⁰

9.4 Resource restrictions

The effectiveness and scalability of SMES technology largely depend on the availability and supply chain of the raw materials required. This chapter examines the raw material constraints associated with SMES, focusing on scarce and common materials, geopolitical risks, supply chain length, material availability, and the role of recycled materials.

9.4.1 Key Materials Used in SMES Systems

SMES is primarily made up of three components: a low- and high-temperature superconducting coil magnet, a cryogenic refrigerator, and helium/nitrogen liquid.

Superconducting Materials

- **Niobium-Titanium (NbTi):** A widely used low-temperature superconductor operating at around 4 Kelvin. NbTi is essential for constructing superconducting coils in SMES systems. The critical temperature (below which they become superconducting) is around 4.2 K (-269°C). This is usually achieved using liquid helium as the cooling agent.

Niobium-Tin (Nb_3Sn): Offers higher critical magnetic fields and temperatures than NbTi but is more brittle and challenging to manufacture. Nb_3Sn has a slightly higher critical temperature of about 18 K.

Approximately 90% of global niobium production comes from Brazil³²⁰, making the supply chain vulnerable to regional political and economic instability

- **High-Temperature Superconductors (HTS):** Materials like Yttrium Barium Copper Oxide (YBCO) and Bismuth Strontium Calcium Copper Oxide (BSCCO) operate at higher temperatures (up to 77 Kelvin), reducing cooling requirements.

China produced most of the world's supply of yttrium from its weathered clay ionadsorption ore deposits in the southern Provinces—primarily Fujian, Guangdong, and Jiangxi—and from a lesser number of deposits in Guangxi and Hunan. Yttrium also was produced from similar clay deposits in Burma.³²¹

Structural and Conductive Materials

Steel, copper aluminium materials has been discussed in previous chapters.

Cooling Agents

- **Liquid Helium:** Required for cooling low-temperature superconductors like NbTi and Nb_3Sn . Helium is a limited resource. Helium is a non-renewable resource found in recoverable quantities in only a few locations around the world, many of which are being depleted. Once helium is released in the atmosphere, it will continue rising until it escapes into space, making it the only truly unrecoverable element. Its shortate can become a problem. (Bureau of Land management, 2000)³²²
- **Liquid Nitrogen:** Used with high-temperature superconductors, offering cost and handling advantages over liquid helium.

Bismuth and Strontium

- **Limited Producers:** Bismuth is primarily produced as a byproduct of lead and tungsten mining, with China being a significant supplier.
- **Supply Risks:** Any fluctuations in the mining of primary metals can affect the availability of bismuth and strontium for SMES applications.

9.5 SMES energy storage costs

Despite its undeniable success, there are still a number of significant obstacles for SMES systems to overcome, with the cost and performance of the economy being one of them.

Several SMES systems are designed using the state of art superconductors and have taken into account their electromagnetic properties. The magnets of the SMES systems are designed using a global optimization algorithm. Both solenoid and toroid configurations are designed and

compared. The capacities of SMES systems are designed on different scales including kJ-, MJ- and GJ-class for different applications. Finally the costs are calculated based on the commercial price of superconductors. The result indicates that the solenoid configuration is suitable for kJ-scale SMES, while the toroid configuration is suitable for GJ-scale SMES. (Zhu, et al., 2013)³²³

This point of view claims that the economic and technological comparison of energy storage systems offers significant benefits in terms of efficiency, power capital cost (PCC), energy capital cost (ECC), and life cycles. Costs for power conversion systems and storage energy units are shown in Table 9.2. as a range for ECC by EUR/kWh and PCC by EUR/kW, respectively. The efficiency, economic cost, and life cycles of energy storage system technology are other aspects that affect its viability. Equation is defined in this context as the Equivalent Annual Cost (EAC) formulation, which combines investment economic cost and system life cycles.

$$EAC = \frac{ESS_{cost} * discount\ rate}{1 - \frac{1}{1 + discount\ rate}}$$

Equation

Costs, efficiency and life-cycle characterization of Supercapacitor in comparison with other energy storage methods.

Energy Storage System	Efficiency	PCC (power capital cost)	ECC (energy capital cost)	Life-cycles
SMES	95–98%	175-430 EUR/kW	879-63,323 EUR/kWh	> 20 years
Flywheel	90–95%	219-307 EUR/kWh	879-12,312 EUR/kWh	> 10 years
Lead-acid	75–90%	263-527 EUR/kWh	175-351 EUR/kWh	5–10 years
Supercapacitor (SC)	85–95%	175-351 EUR/kWh	439-879 EUR/kWh	> 20 years
Li-ion	85–95%	61-3518 EUR/kWh	183-3,341 EUR/kWh	5–15 years
NaS batteries	75–90%	879-2,638 EUR/kWh	263-439 EUR/kWh	5–15 years

Table 9.2 Source: (Khaleel, et al., 2023)³¹⁰

9.6 SMES development perspective and environmental impact

“The use of superconducting magnetic energy storage (SMES) is becoming more and more significant in energy power systems, including power plants, transmission and distribution grids, and demand loads. Delivering power to demand loads is, in general, the main goal of energy power systems. It must take into consideration operational capacity-building for energy power systems in order to continually maintain power quality stable of customer loads. Additionally, the energy must be accessible in case an unexpected condition arises on the energy power

system. This viewpoint places SMES where continuous innovation in storage energy is a requirement for the energy power system. Utilising SMES also offers the extra benefit of rapid reactions and unlimited charging and discharging cycles for electrical power systems. Additionally, it lowers expenses, increases stability significantly, and boosts the energy power system's economic output and efficiency. SMES assumes special significance as one of the most crucial energy storage system technologies for these aspects. Despite this, rising energy usage severely restricts energy power system growth. Concerns about electrical energy losses are growing as a result of industrial and consumer demand loads, feeder voltage resistance and the safety of the system's complete equipment. Additionally, the SMES technology can instantaneously inject both active and reactive power into the EPS to create a high-quality power flow in the system. SMES can also achieve better electrical efficiency (95–98%). While highlighting that the fundamental driving force should be based on the idea of storing excess energy during off-peak hours for use at a later time. As an example, the energy storage system can respond by supplying electricity if the power plan is unable to handle a sudden increase in power generation during peak hours. And it appears that, with all of this technological convergence, the main purpose of SMES processes is to address issues of this nature in accordance with agreed-upon IEEE standards. But it's possible that the SMES' main function will be required.” (Khaleel, et al., 2023)³¹⁰

There is a necessity for more studies primarily focusing on SMES in terms of structures, technical control issues, power grid optimization issues, and contemporary power protection issues.

9.6.1 SMES environmental impact

Most of the environmental concerns associated with present-day energy storage devices do not exist with SMES: it does not use or produce harmful chemicals, no dams or other radical changes to the landscape are required, and it is silent in its operation. (Blanchard, 1989)³²⁴

However, “consideration of the environmental impact of SMES systems includes possible biological effects on humans as well as on other vertebrates, plants and bacteria; effects on the operation of essential life support systems such as cardiac pacemakers; and effects on such equipment as watches, microprocessors, automobile and aircraft ignition systems and magnetic credit cards. Present knowledge of the biological effects of steady (DC) high and low intensity magnetic fields is reviewed, including synergetic effects of such fields in the presence of 60 Hz electric and magnetic fields; effects on cell growth, DNA synthesis, endocrine system rhythms, Ca^{++} efflux, bacterial motion and bird migration are considered briefly. If the environment outside the fenced-in SMES area is to be accessible to persons with cardiac pacemakers the safe field level will have to be below 1.7 mT. Selecting an arbitrary safety factor of 1.7 giving a field of 1.0 mT one obtains an exclusion radius of 2.0 km for a presently considered 5500 MWh solenoidal storage system and 255 m for a proposed 20 MWh device.” (Polk, Boom, 1986)³²⁵

Common superconducting materials include mercury, vanadium, and niobium-titanium.

Mercury is mined as mercuric sulphide (cinnabar ore). Mercury is most harmful when you breathe in the vapours that are released when a container is open or a spill occurs. Mercury emitted into the air eventually settles into water or onto land where it can be washed into water. Once deposited, certain microorganisms can change it into methylmercury, a highly toxic form that builds up in fish, shellfish and animals that eat fish. ([EPA, 2024](#))

Vanadium (V) is one of the toxic elements with the most extensive distribution in nature. Despite the vast use of V in heavy industries, its presence in the environment can be harmful to living organisms. Soil can be polluted by V released from both natural and anthropogenic sources. (APIS, 2001)²⁹⁸

Next to the neurological effects vanadium can cause breathing disorders, paralysis and negative effects on the liver and kidneys. Laboratory tests with test animals have shown that vanadium can cause harm to the reproductive system of male animals, and that it accumulates in the female placenta. ([Lenntech, 2024](#))

Environmentally, the main issues related to [niobium](#) and [tantalum](#) mining are **land disruptions, the volume of waste materials and their disposal, and the radioactivity of some tailings and waste materials that contain thorium and uranium**. ([USGS, 2017](#)) Niobium, when inhaled, is retained mainly in the lungs, and secondarily in bones. It **interferes with calcium as an activator of enzyme systems**. ([Lenntech, 2024](#))

However, they are others alloys (such as Nb-Ti and Nb-Ge), and intermetallic compounds³²⁶ (such as Nb₃Sn, Nb₃Al, and MgB₂); 2) ceramic compounds, including Chevrel compounds (e.g., PbMo₆S₈ and SnMo₆S₈) (Chevrel et al., 1971)³²⁷, copper-based oxides³²⁸ (Rogalla and Kes, 2012)³²⁹, ruthenium-based oxides (Maeno et al., 1994)³³⁰, and iron-based pnictides and chalcogenides³³¹ (Hosono et al., 2015)³³²; 3) organic materials (e.g., K₃C₆₀, Cs₃C₆₀, and Ba₄C₆₀) (Rosseinsky et al., 1993)³³³; Palstra et al., 1995³³⁴; Baenitz et al., 1995)³³⁵; 4) semiconductor, semi-metal, and insulators (e.g., SiC, diamond, and graphite) (Ekimov et al., 2004)³³⁶; Muranaka et al., 2008³³⁷; Cao et al., 2018³³⁸) that can be found in SMES.

9.7. Conclusions: advantages, disadvantages and recommendations for SMES

9.7.1 Advantages and disadvantages

Pros

“The defining feature of SMES systems is their **unbeatable efficiency**. Minimal energy is wasted in the process of storing energy. SMES systems have an end-to-end efficiency **nearing 100% (not considering cryogenic cooling energy)**, while lithium-ion batteries range from 80% to 90%, and

pumped hydroelectric storage sees a system efficiency range from 70% to 85%. In applications where energy may be intermittent or sparse, such as a rural microgrid or a large satellite, energy conservation may be paramount, and maximising storage efficiency may be necessary, even if it costs more upfront.

Moreover, SMES systems exhibit **rapid response times for both charging and discharging**, making them ideal candidates for applications requiring swift and precise power delivery and stabilisation. For example, semiconductor manufacturing or medical facilities greatly benefit from SMES systems as their equipment can generate large power surges that can easily be serviced by an SMES system, even compared to high-performance Li-Ion battery systems.”

Longevity and Low Maintenance: With no rotating parts aside from vacuum and refrigeration systems, SMES systems offer long operational lifespans and easy maintenance with reduced pollution levels.

It can be deployed in places where other technologies such as pumped hydro or compressed air are not feasible. (Ahmed, 2015) ³³⁹

SMES does not use or produce harmful chemicals, no dams or other radical changes to the landscape are required, and it is silent in its operation.

Cons

SMES systems have **very high upfront costs** compared to other energy storage solutions (See Table 9.2). Superconducting materials are expensive to manufacture and require a cryogenic cooling system to achieve and maintain a superconducting state of the coil material.

SMES technology is in **need of a large amount of power to keep the coil at low temperature**, combined by the high overall cost for the employment of such a unit. Superconductors such as yttrium barium copper oxide (YBCO) and bismuth strontium calcium copper oxide (BSCCO) are created via intricate synthesis techniques using high-purity raw materials, making them far more costly to manufacture than everyday wire. Additionally, YBCO and BSCCO have critical points at 93K (-292.3F) and 110K (-261F) at atmospheric pressure, meaning they are only superconductive when kept at extremely low temperatures and require complex cryogenic systems to create such environments.

SMES systems are **limited in their scalability**. Aside from unscalable upfront costs, SMES systems have high maintenance requirements, and **storage capacity cannot be easily increased**. In contrast, lithium-ion battery storage systems can easily be connected, while combining SMES devices requires scaling the cryogenic cooling infrastructure in kind.

AC-DC conversion: storing AC power from an external power source requires an SMES system to first convert all AC power to DC power. Interestingly, the conversion of power is the only portion of an SMES that is not perfectly efficient, accounting for all total system loss.

To achieve commercially useful levels of storage, around 1GW.h (3.6 TJ) a SMES installation would need a loop of around 160 km.

A problem is also the **infrastructure required for an installation**. Until room temperature superconductors are found, the 160 km loop of wire would have to be contained within a vacuum flask of helium/liquid nitrogen. This in turn would require stable support, most commonly envisioned by burying the installation. (Shackell, 2024)³⁴⁰

In terms of the environmental impact they can have a negative impact on vertebrates and cause negative environmental impact due to the resourcing of raw materials needed for SMES. (Ahmed, 2015)³³⁹

9.7.2 SMES market and deployed systems

Superconducting Magnetic Energy Storage Market Size was valued at USD 0.07 Billion in 2022. The Superconducting Magnetic Energy Storage Market industry is projected to grow from USD 0.08 Billion in 2023 to USD 0.20 Billion by 2032, exhibiting a compound annual growth rate (CAGR) of 12.50% during the forecast period (2023 - 2032)³⁴¹.

Some known deployed systems worldwide:

1. Japan: LTS SMES Units

- **Power:** 10 MW each
- **Purpose:** Bridging instantaneous voltage dips for critical industrial customers.
- **Details:** Three Low-Temperature Superconducting (LTS) SMES units were commissioned in 2011 and are used to provide stability against voltage sags and improve power quality. These units serve in industrial regions prone to voltage fluctuations³⁰⁹

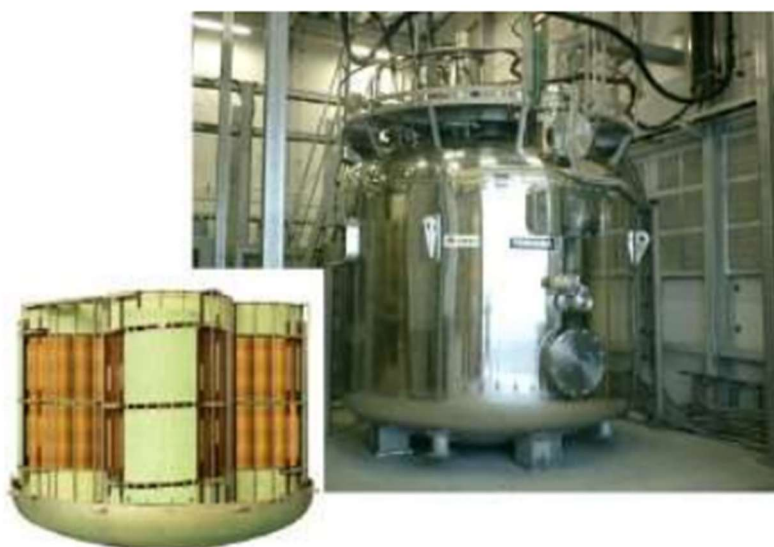


Figure 9.6 10 MVA/1 s SMES at Kameyama field test, in Japan. Image from [Nagaya et al. 2012](#)

2. France: DGA-CNRS-Nexans High-Tc SMES

- **Energy:** 800 kJ
- **Purpose:** Research and development for high-temperature applications.
- **Details:** Developed by the DGA (Direction Générale de l'Armement), CNRS (Centre National de la Recherche Scientifique), and Nexans, this High-Tc SMES focuses on improving power density and stability. It serves as a prototype to evaluate the potential of high-temperature superconductors in grid applications

3. USA: BPA SMES System (Bonneville Power Administration)

- **Energy:** 30 MJ
- **Purpose:** Load leveling and dynamic stability.
- **Details:** The BPA 30 MJ SMES system was installed to enhance the dynamic stability of the power grid in Oregon, USA. It has been particularly successful in load leveling and stabilising frequency during transient events.

In conducting our Energy Outlook study, we encountered limitations in identifying operational SMES energy storage systems suitable for site visits. This challenge may be attributed to the specialized niche applications of SMES technology, often tailored to specific industrial processes, grid ancillary services, or research environments. Additionally, the complexity and cost factors associated with SMES deployment could contribute to the limited availability of operational sites for broader observation and analysis.

9.7.3 Recommendations and WICE index

By shedding light on the challenges, potential solutions, and opportunities associated with SMES integration, this review paves the way for advancements in energy storage technologies and their seamless integration into modern power networks. The identified future scope includes:

- **Reliability and Safety Considerations:** Given the criticality of power systems, future research should continue to explore the reliability and safety aspects of SMES integration. This includes studying failure modes, developing fault-tolerant designs, and implementing robust protection mechanisms to ensure the reliable and safe operation of energy power systems equipped with SMES.
- **Economic Analysis and Market Integration:** Further investigation is needed to evaluate the economic feasibility and market integration of SMES in the EPS. Future studies can analyse the cost-effectiveness of SMES technology, assess its impact on electricity markets, and develop business models that incentivize the deployment of SMES systems.
- **Large-Scale Deployment and Field Testing:** Future research can focus on large-scale deployment and field testing of SMES systems in real-world power grids. This would

provide valuable insights into the practical challenges, performance validation, and operational considerations associated with integrating SMES into existing infrastructure.

By addressing these future research directions, the scientific community can advance the understanding and practical implementation of SMES technology in the energy power system. This will contribute to the development of more reliable, efficient, and sustainable power systems, ultimately facilitating the transition to a clean energy future.

While SMES offers an incredibly unique advantage over other energy storage applications and is truly state-of-the-art technology, SMES is unlikely to be widely adopted in most energy storage applications in the near future. Currently, superconducting materials are limited in their capabilities and supply. Current technologies require cryogenic temperatures to exhibit superconductivity and bulk, grid-capable superconductor production has not yet been achieved.

However, physicists are working to discover new, high-temperature superconductor materials that may one day allow for room-temperature superconductivity. If this is achieved, and the material could be mass-produced, the efficiency and performance of SMES will likely propel market adoption ahead of other technologies. Advancements in superconducting materials, cryogenic technologies, and cost reduction strategies could dramatically enhance the competitiveness of SMES systems, but today, they are restricted to research and niche energy infrastructures. (Khaleel, 2023)³¹⁰

Recommendations given by European Energy Research Alliance (EERA) in 2019³⁰⁹ on potential, barriers and challenges, the recommendations are the following:

- Improve critical material properties of HTS and MgB₂ tapes. This includes higher in-field current densities, lower AC and ramping losses, optimised wire architectures, longer lengths of high quality, high amperage conductors and cost reduction.
- Improve the modelling tools for a better design, optimising the costs and reliability of the SMES systems from the mechanical, thermal and electromagnetic point of view.
- Develop SMES related system technology with a focus on new concepts in magnet design, standardised components for cooling systems, cryostats and low loss current leads.
- Develop low-temperature heat rejection cryocoolers for working between 120-30 K with cooling power in the range of 100's of W, able to work with cryogenics at 120 or 77 K as high temperature, thus allowing the use of LCH₄, LN₂ or LO₂ as a first cooling step.
- Develop robust and self-stabilised HTS SMES magnets including high-performance electrical insulation with low-cost manufacturing and winding methods. Modular approaches and methods for up-scaling must be considered.
- Demonstrate HTS SMES system performance in attractive applications with long term field tests. From this, promising business cases need to be further developed and first niche markets need to be addressed.

- Explore the opportunities of hybrid SMES systems at different TRL levels depending on the maturity of the hybrid system, ranging from system studies up to first demonstrations.

Superconducting Magnetic Energy Storage (SMES) systems offer a unique set of advantages, particularly their instantaneous response time and high efficiency, compared to traditional lithium-ion batteries. However, SMES also faces significant challenges, especially in terms of cost and scalability. To assess SMES's potential to reshape the energy storage market, we will calculate its "Will it Change Everything Score" based on a weighted evaluation of nine key factors. This score compares SMES to the current dominant technology, lithium-ion batteries, and highlights its disruptive potential.

1. Energy Density

SMES systems typically have significantly lower energy density compared to lithium-ion batteries. While SMES excels at rapid power delivery, the amount of energy it can store per unit volume is very limited. This makes it suitable for short-duration applications rather than long-term energy storage.

Score: 10

2. Energy Retention Period

While SMES systems can store energy with virtually no direct losses from the superconducting coil itself, maintaining the required cryogenic cooling introduces a steady energy drain. Over time, the energy required to keep the system at superconducting temperatures reduces the net amount of stored energy. This cooling requirement is a continuous overhead that diminishes the overall retention capabilities, especially for long-term storage. As a result, while SMES is efficient in short durations, its ability to retain energy over extended periods is less ideal than initially considered:

Short-term storage: For short durations (minutes to hours), SMES systems can have higher overall efficiency than lithium-ion batteries, despite the cooling losses. This is because they have very high round-trip efficiency (close to 100%) during charge and discharge cycles.

Long-term storage: For longer durations (days to weeks), lithium-ion batteries generally outperform SMES in terms of energy retention. The continuous energy consumption for cryogenic cooling in SMES systems outweighs the self-discharge losses of batteries over extended periods.

Considering the losses during periods where SMES are not charged, we give a much lower score for these systems than the baseline Lithium batteries.

Score: 30

3. Lifetime and Life Cycles

While the superconducting coil in an SMES system itself has a long lifespan with no chemical degradation and can handle virtually unlimited charge-discharge cycles, other parts of the system are subject to wear. The cryogenic cooling system, in particular, degrades over time due to the continuous mechanical and thermal stress, necessitating regular maintenance or replacement of parts like compressors and insulation. Moreover, components such as power electronics (for converting between AC and DC) and magnetic shielding also experience gradual degradation. These factors reduce the overall lifetime and reliability of the SMES system when compared to just the superconducting coil's performance. As a result, while SMES still outperforms batteries in terms of cycle life, the system's total lifetime is not entirely maintenance-free.

Score: 80

4. Round-Trip Efficiency (RTE)

SMES systems are known for their extremely high round-trip efficiency (RTE) at the level of the superconducting coil itself, with efficiencies typically cited in the range of 95-98%. This is due to the negligible resistive losses in the superconducting state. However, when accounting for the energy required to operate the cryogenic cooling system, the overall efficiency of the entire system decreases. The energy required to maintain the low temperatures necessary for superconductivity (typically around 4 K for low-temperature superconductors) is continuous and substantial. As a result, while SMES still outperforms many other energy storage technologies in terms of efficiency, the net RTE of the full system—including cooling—is lower than the ideal coil-only efficiency.

Score: 50

5. Technological Maturity (TRL)

SMES technology is relatively mature in niche applications such as power quality improvement and grid stability, with a TRL of around 8 for these specific uses. However, its high cost and technical challenges have prevented broader commercial adoption, keeping its overall maturity lower than lithium-ion batteries.

Score: 70

6. Capital Expenditure (CAPEX)

The high cost of superconducting materials and the need for cryogenic cooling systems make SMES significantly more expensive to build compared to lithium-ion batteries. This high upfront cost is a major barrier to its widespread adoption.

Score: 10

7. Operational Expenditure (OPEX)

SMES systems have relatively low operational costs once installed, as the main expense is maintaining the cryogenic system. The lack of moving parts and chemical wear results in minimal maintenance requirements over time.

Score: 60

8. Environmental Impact

SMES is environmentally friendly, as it does not involve toxic materials or chemical reactions. However, there are concerns regarding the sourcing of rare superconducting materials and the disposal of cryogenic fluids like liquid helium, which can be environmentally costly.

Score: 60

9. Scalability

While SMES is highly effective in small-scale, high-power applications, its scalability is limited by the high infrastructure and material costs. Scaling up for grid-level energy storage remains a significant challenge.

Score: 40

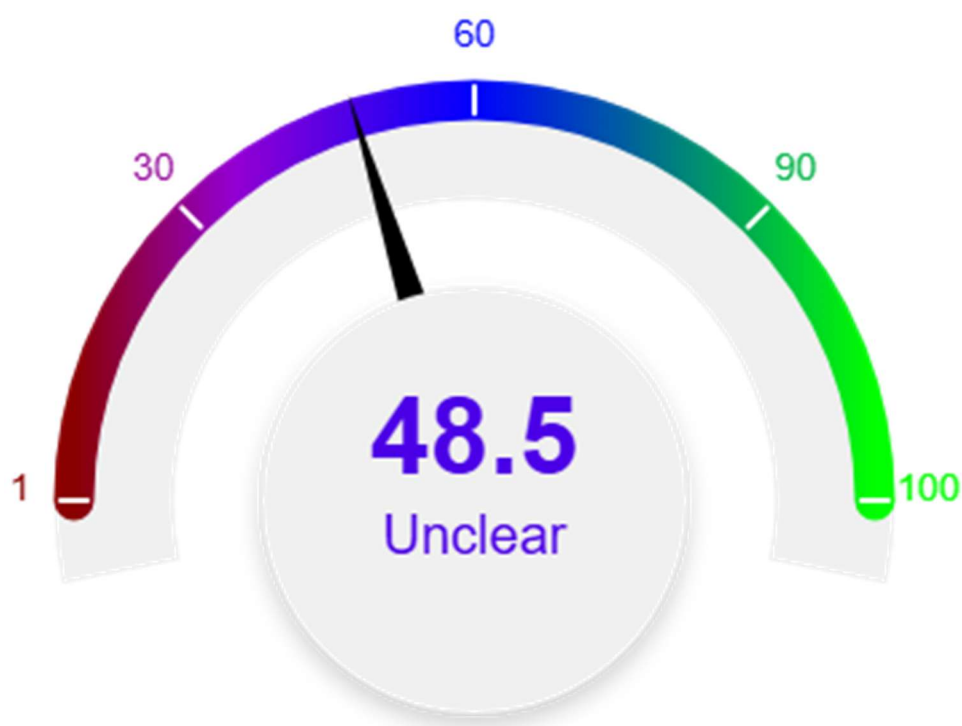
Weighted Scores Calculation

Using the weights provided, we calculate the weighted scores for each parameter:

Parameter	Weight	Score	Weighted score
Energy Density	0.1	10	1
Energy Retention Period	0.1	30	3
Lifetime and Life Cycles	0.1	80	8
Round-Trip Efficiency (RTE)	0.15	50	7.5
Technological Maturity (TRL)	0.2	70	14
Capital Expenditure (CAPEX)	0.1	10	1
Operational Expenditure (OPEX)	0.1	60	6
Environmental Impact	0.1	60	6
Scalability	0.05	40	2
Total	1		48.5

This 48.5 WICE score indicates that while SMES excels in certain critical areas like efficiency and long-term durability, its high costs and limited scalability pose significant barriers to its widespread adoption in the energy storage market.

Impact potential of technology



10. Ultracapacitors (UC)

Summary of Metrics

Parameter	Technology: Ultracapacitors/Supercapacitors
	Value/Range
Energy density per unit of volume [Wh/kg]	8 - 20 Wh/l / 35Wh/kg
Power range [MW]	up to 100MW
Time of Permanent Energy Storage [hour]	Less than 1 hour (typically a few minutes, not suitable for long-term storage)
Life time [years/cycles]	10-15 years / Up to 1 million cycles
Discharge Time [minutes]	1-15 minutes
RTE (Round-Trip Efficiency) [%]	92%-95%
RTE degradation	0.14% / year
Technology Maturity / Technological Readiness Level (TRL):	Supercapacitor Technology: TRL 9 – Implementation Hybrid Storage: TRL 6 – Demonstration
System size Energy Capacity (kWh)	1 kWh to 50 kWh (depending on use case; UC/SC are often modular)
CAPEX per kW of Power Capacity [EUR/kW]	€4,607 and €9,214 €/kWh
CAPEX per kWh of Energy [EUR/kWh]	
LCOS per kWh of Energy [EUR/kWh/year]	0.31 – 0.38€/kWh

Source: An Evaluation of Energy Storage Cost and Performance Characteristics¹¹¹, [Technology Strategy Assessment – U.S. Department of Energy](#), Frost & Sullivan (2020).³⁴⁶

“If I were to make a prediction, I’d think there’s a good chance that it is not batteries, but super-capacitors.” - Elon Musk about the future of electric vehicles³⁴²

10.1 Introduction

While Musk continues to be an innovative force in many fields - particularly with Tesla's success in electric vehicles powered by lithium-ion batteries - his earlier comments on supercapacitors seems a bit out of place. Or is it? We are trying to answer this question in the next chapter.

Ultracapacitors, also known as supercapacitors, are advanced energy storage devices that offer unique benefits compared to traditional batteries. Unlike batteries, which rely on chemical reactions to store energy, ultracapacitors store energy through **electrostatic charge**. This results in a **much faster charging and discharging** process, making them highly suitable for applications where quick bursts of energy are required, such as regenerative braking in electric vehicles or balancing grid power fluctuations. They have a **long lifespan**, often outlasting batteries by tens of thousands of cycles, and **perform well in extreme temperatures**, further enhancing their reliability.

However, ultracapacitors also have limitations that make them distinct from batteries. Their **energy density is significantly lower**, meaning they cannot store as much energy in the same amount of space as a typical lithium-ion battery. This makes them **less ideal for long-duration** energy storage, where batteries excel. Despite this, ultracapacitors are increasingly being integrated into hybrid energy systems, working alongside batteries to deliver both rapid power and longer-term storage. Their growing role in energy storage solutions reflects a broader trend toward diversifying energy technologies to meet specific needs efficiently.

Physics

The physics behind this energy storage can be understood by examining the simple structure of an ultracapacitor. It consists of **two electrodes**, typically made of high-surface-area materials like activated carbon, separated by a thin **insulator called a dielectric**. When a voltage is applied across the electrodes, positive and negative ions from the electrolyte accumulate on the respective electrode surfaces, forming the **electric double-layer**.

Schematic illustration of a Supercapacitor / Ultracapacitor

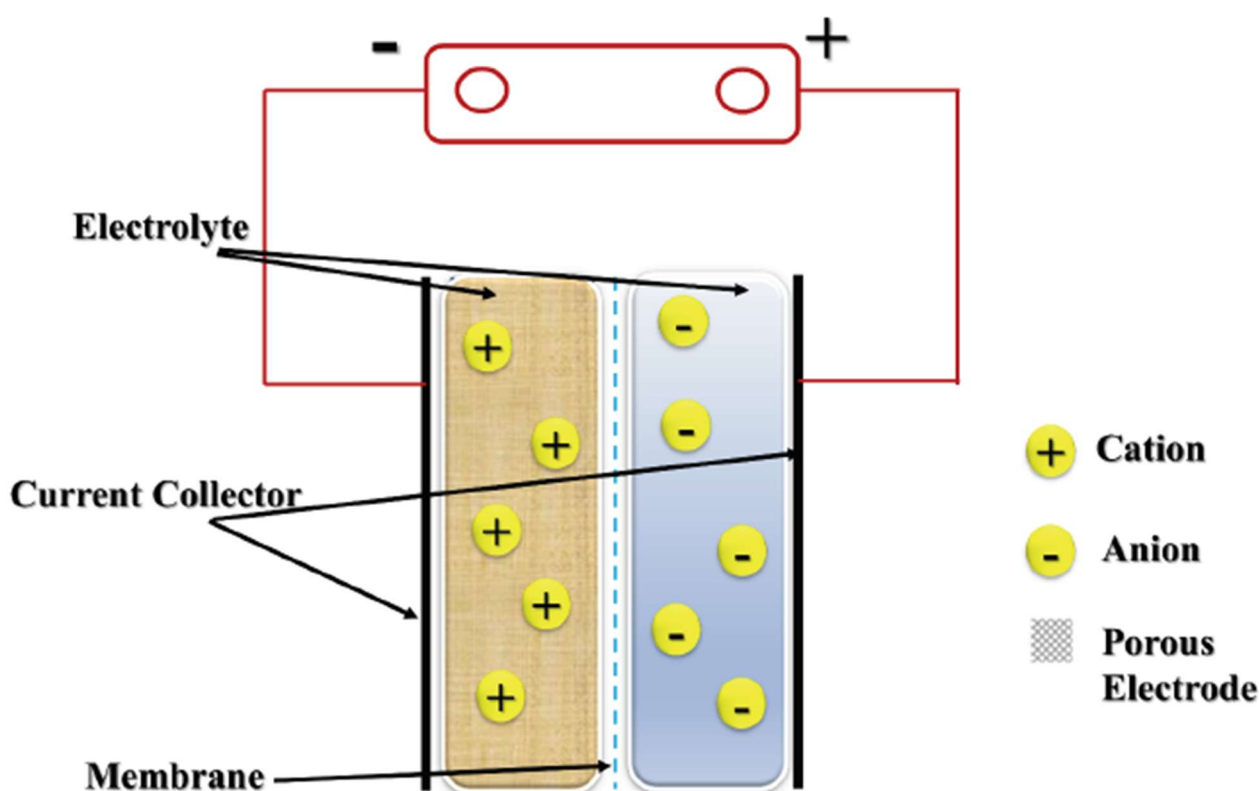


Figure 10.1 Schematic illustration of a Supercapacitor; [Source](#)

The capacitance of an ultracapacitor is directly proportional to the **surface area** of the electrodes and inversely proportional to the **distance** between them. **The larger the surface area and the thinner the dielectric, the higher the capacitance.** This is why ultracapacitors often use porous materials with extremely high surface areas for their electrodes.

The energy stored in an ultracapacitor can be calculated using the following formula:

$$E = \frac{1}{2} * CV^2$$

where:

- E is the stored energy in joules
- C is the capacitance in farads
- V is the voltage across the capacitor in volts

This formula shows that the energy stored in an ultracapacitor is proportional to the capacitance and the square of the voltage. Therefore, increasing either the capacitance or the voltage will increase the stored energy. However, ultracapacitors typically have lower voltage limits compared to batteries, which is a trade-off for their higher capacitance and faster charge/discharge rates.

Ultracapacitors exhibit a nearly linear discharge characteristic within their operating range, meaning that the voltage across the capacitor decreases linearly with the amount of charge withdrawn (though the stored energy follows a square relationship with voltage). This contrasts with batteries, which tend to have a flatter discharge curve with a more rapid voltage drop near the end of their capacity. (Häggström, 2018)³⁴³

Unlike ordinary capacitors, ultracapacitors do not use the conventional solid dielectric, but rather, they use electrostatic double-layer capacitance and electrochemical pseudocapacitance (Bueno, 2019)³⁴⁴, both of which contribute to the total capacitance of the capacitor.

Classification of Ultracapacitors / Supercapacitors

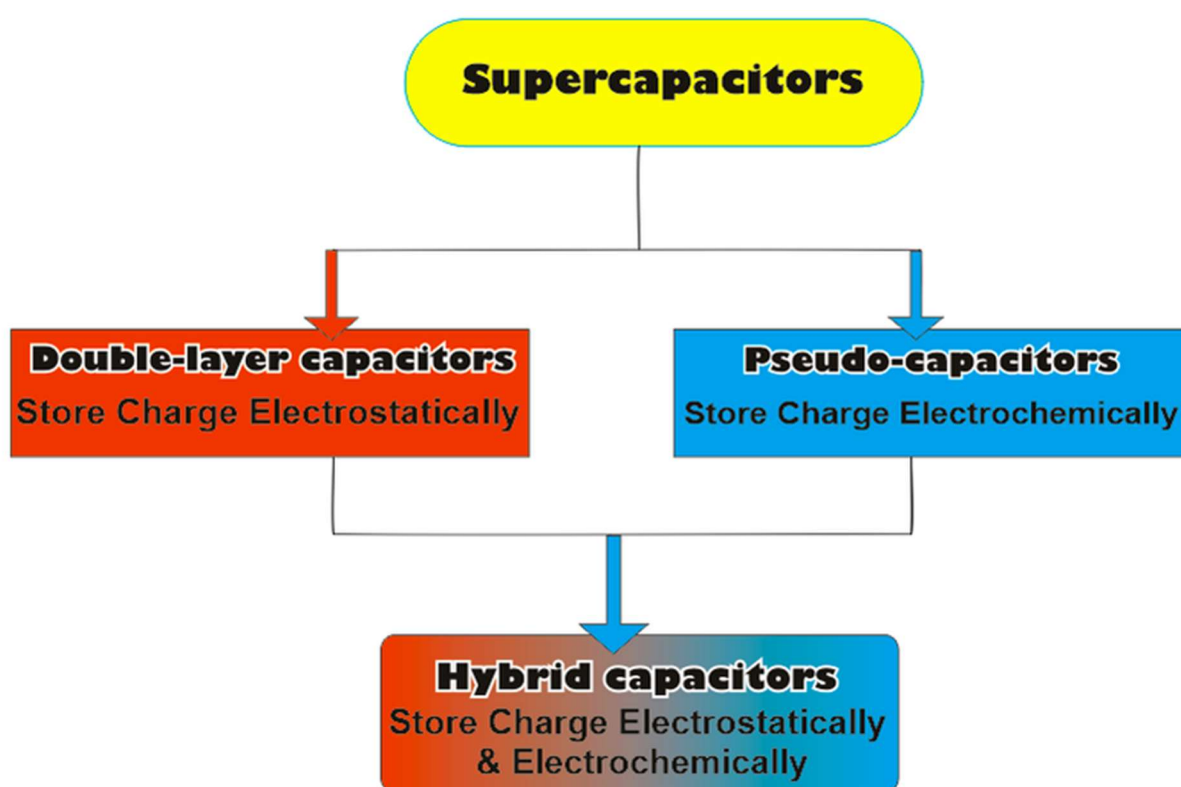


Figure 10.2 Classification of supercapacitors ³⁴⁵

There are three types of ultracapacitors based on the charge storing mechanism:

- electrochemical double-layer capacitors,
- pseudocapacitors, and
- hybrid electrochemical capacitors.

Electrochemical double-layer capacitors (EDLCs)

EDLCs use two similar electrodes based on active carbon to form two capacitors with the electrolyte. The conductive electrode is made of activated carbon and the space between the two electrodes is filled with an electrolyte. Electricity is generated by the process of adsorption and desorption of ions from the electrode surfaces. The ultracapacitor has no solid dielectric and avoids chemical reactions. This design results in a reduced impact on lifespan during rapid charging and discharging cycles, which can occur in milliseconds to seconds. While ultracapacitors typically do not require complex circuits for basic charging and discharging operations, they are highly sensitive to voltage. When multiple supercapacitor cells are connected to achieve higher power output, additional circuitry is often necessary to ensure proper voltage balancing across all cells, preventing overvoltage and ensuring safe operation. (Frost & Sullivan et al, 2020)³⁴⁶ They exhibit a fast response to charge/discharge and good cycling stability; however, they also exhibit a higher self-discharge rate, which is a concern as is high internal resistance, which makes it unusable for AC circuits. The performance characteristics of an EDLC can be adjusted for different applications by changing the electrolyte (Durvasulu et al, 2023)³⁴⁷.

Electric double layer capacitors are suitable for a wide range of applications, including memory backup in electronic devices, battery load levelling in mobile devices, energy harvesting, energy regeneration in automobiles, and more. (TDK, 2024)³⁴⁸

Pseudocapacitors (PCs)

PCs use transition metal oxide-based electrodes to form highly reversible redox (faradaic) reactions, which store energy by transferring charge between the electrode and the electrolyte. These faradaic processes allow PCs to achieve greater capacitances and energy densities than EDLCs, which involve only the electric double-layer effect at the electrode/electrolyte interface and no reactions at the electrodes. (Durvasulu et al, 2023)³⁴⁷ They bridge the gap between EDLCs and batteries as they can store higher energy while operating faster. They can charge and discharge between seconds to minutes. Electrochemical capacitors have a life cycle of 500,000 cycles. (Frost & Sullivan et al, 2020)³⁴⁶ **A pseudocapacitor is part of an electrochemical capacitor**, and forms together with an electric double-layer capacitor (EDLC) to create a supercapacitor. Pseudocapacitance and double-layer capacitance add up to a common inseparable capacitance value of a supercapacitor. These capacitors have the highest capacitance density as compared to other capacitors due to their special storage charge principles. So the sum of electric charge stored within a pseudocapacitance is linearly proportional to the voltage applied.

Pseudocapacitors are classified into **two types** based on electrode materials used to store charge within pseudocapacitors like the following.

- metal oxide
- conducting polymers. (El-Pro-Cus, 2024)³⁴⁹.

Representation of the transition from EDLC to Battery

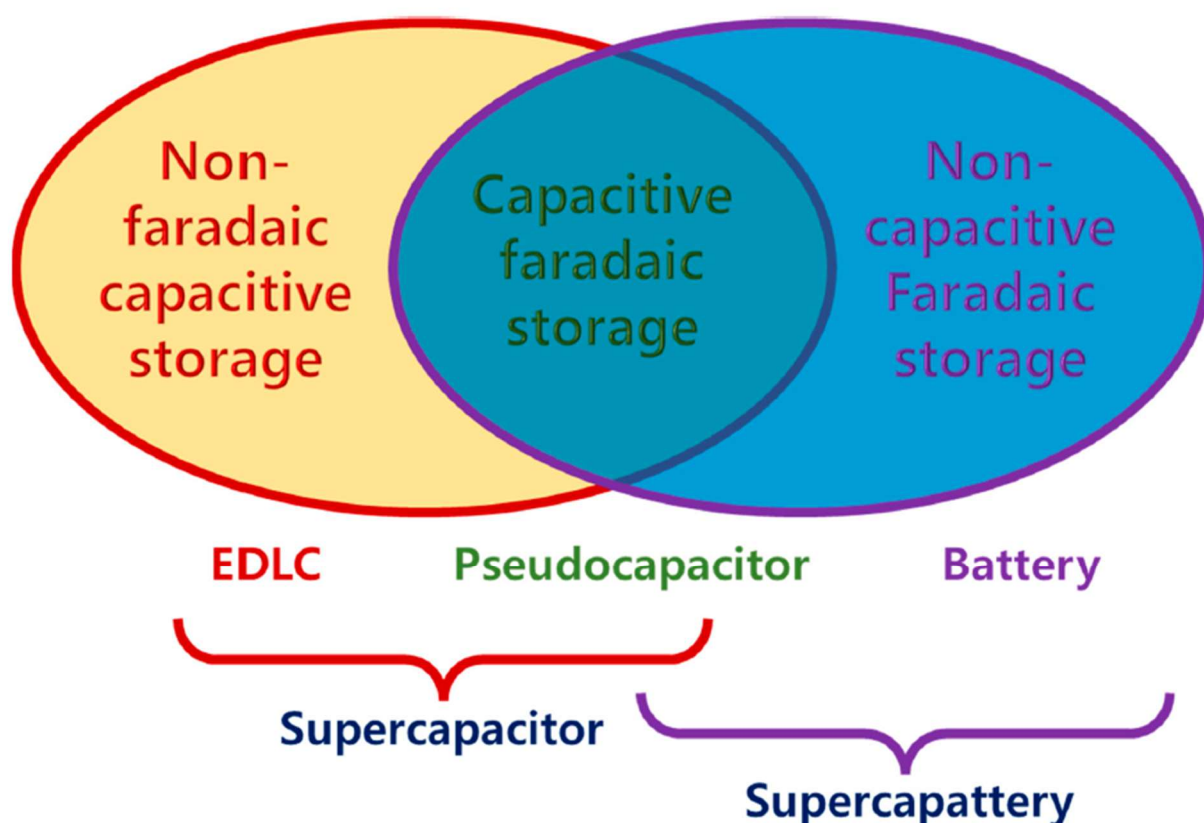


Figure 10.3 Schematic correlation between an EDL capacitor, pseudocapacitor, battery, and supercapattery according to charge storage processes³⁵⁰

Hybrid electrochemical capacitors (HECs)

HECs, also called asymmetrical capacitors, use different anode and cathode materials. The cathode is similar to EDLC and the anode is like that used in a metal oxide-doped carbon electrode. This asymmetry implements both faradaic and non-faradaic processes to store charge, leading to energy and power densities greater than EDLCs without sacrificing the cycling stability and affordability that have limited the success of PCs.” (Durvasulu et al, 2023)³⁴⁷ They combine the benefits of both EDLCs and pseudo-capacitors along with a longer and pollution-free lifespan. They have operating temperatures between -25 degrees Celsius and +60 degrees Celsius and have 95% efficiency, compared to only 70% for batteries.

This makes them suitable for use in high-power applications in the automotive and transportation space. (Frost & Sullivan et al, 2020)³⁴⁶ They are also used in power plant frequency regulation. (CNESA, 2023)³⁵¹

An interesting addition in the domain of HECs is the concept of **Supercapattery** (see Figure 10.3). Supercapatteries are an emerging hybrid energy storage technology that combines the high power density and long cycle life of supercapacitors with the higher energy density of batteries. The concept revolves around merging capacitive and Faradaic (battery-like) energy storage mechanisms within a single device, allowing it to perform with both high energy capacity and fast charge/discharge rates. These devices can utilize advanced materials like carbon nanotubes and transition metal oxides (TMOs), which help in achieving a balance between power and energy. For instance, supercapatteries can offer rapid energy delivery similar to supercapacitors while storing more energy, akin to batteries, making them a versatile solution for applications needing both high power and extended energy supply.

Supercapatteries are designed with the goal of addressing limitations in current energy storage technologies, especially in applications requiring both fast response and higher energy storage capacity. The development focuses on advanced materials that support both capacitive and non-capacitive charge storage, including nanostructured composites of battery materials (like manganese dioxide) and capacitive materials (like carbon nanotubes). This hybridisation allows supercapatteries to exceed the limitations of both traditional batteries and supercapacitors, enabling improved energy efficiency, longevity, and reliability in applications ranging from portable electronics to large-scale renewable energy storage.³⁵²

Comparison of attributes for three types of supercapacitors

Type	Charge Mechanism	Advantages	Disadvantages
Electrochemical double-layer capacitor (EDLC)	Physical surface adsorption and desorption	Fast charge/discharge; excellent cycle life (up to 1M cycle life); easy to fabricate, leading to a lower cost	Low energy density (less than 8 Wh kg ⁻¹), higher self-discharge rate
Pseudocapacitor	Highly reversible surface redox (faradaic) reactions	Higher energy density (more than 10 Wh kg ⁻¹) and capacitance compared with EDLCs, higher cost compared with EDLCs	Slightly lower cycle life (up to 200,000 cycles) [11]
Hybrid (composite, asymmetric, or battery-type) capacitor	Adsorption and desorption at one electrode and faradaic reactions at the other	Higher power and up to 10 times the energy density of EDLC [12], lower discharge rate	Lower cycle life compared with other types (up to 100,000 cycle life) [12]; complex design, leading to a higher cost

Table 10.1 Comparison of attributes for three types of supercapacitors Source: [US Department of Energy](#)

History

The concept of ultracapacitors, also known as supercapacitors, first emerged in 1853 when Hermann von Helmholtz observed the formation of an electrical double-layer at the interface between a metal electrode and an electrolyte solution. The key breakthrough occurred in 1957,

when General Electric's engineer H. Becker developed a "low voltage electrolytic capacitor with porous carbon electrodes." The innovation relied on activated carbon, which has a high surface area ideal for storing charge. Although Becker's patent described the process as storing energy in carbon pores, the precise mechanism, now known as the electrostatic double-layer effect, was not fully understood at the time. His work laid the foundation for future research into electrochemical capacitors, but immediate commercialisation was limited due to the low energy density of these early prototypes.³⁴⁷

In 1966, researchers at Standard Oil of Ohio (SOHIO) revisited ultracapacitor technology while working on experimental fuel cells. They filed a patent for what was described as an "electrical energy storage apparatus," which used activated carbon electrodes immersed in an electrolyte. This marked the development of the first true electrochemical capacitors, also known as electric double-layer capacitors (EDLCs). These capacitors leveraged the high surface area of carbon electrodes to store energy via the double-layer effect, where electric charges accumulated at the interface between the electrode and electrolyte. While the energy density remained relatively low, the ability to charge and discharge rapidly without significant wear made these devices ideal for specific applications.³⁵³

It wasn't until 1978 that the first commercial application of ultracapacitors came to market, thanks to NEC in Japan. The company introduced supercapacitors as backup power systems for computers, utilising their high power density and rapid discharge capabilities. Although these capacitors couldn't match the energy density of batteries, their ability to deliver short bursts of high power made them valuable in scenarios where reliability and longevity were critical. These early ultracapacitors had limited use cases, but they demonstrated the potential for broader applications in energy storage and power management.³⁴⁶

The late 20th and early 21st centuries saw significant advancements in ultracapacitor technology, driven by improvements in materials science and manufacturing techniques. The introduction of nanostructured carbons, hybrid electrode materials, and advancements in electrolytes increased the energy density and overall efficiency of ultracapacitors. This made them more viable for integration into hybrid energy systems, where they could complement batteries by providing quick power boosts and absorbing regenerative energy. In particular, the transportation sector began to adopt ultracapacitors for electric and hybrid vehicles, where their fast charge-discharge cycles were crucial for regenerative braking and acceleration.

Today, ultracapacitors are playing an increasingly important role in the transition to renewable energy and smart grid systems. Their ability to stabilise grid power, store energy from intermittent renewable sources, and provide quick-response energy during peak demand makes them a critical component of modern energy storage strategies. These advances and attributes now lead them to be used in a broad range of applications, including providing electric grid services. For example, supercapacitors were used in 2021 to provide a hydropower-based

distribution utility with black-start support when in a temporary microgrid configuration as part of a DOE-funded field demonstration. Supercapacitors also have been deployed in combination with solar photovoltaic generation to power the West Thumb Ranger Station in Yellowstone National Park.³⁵⁴

While they still face challenges, such as lower energy density compared to traditional batteries, ongoing research continues to push the boundaries of what ultracapacitors can achieve. With advancements in hybrid capacitor technology and cost reductions, ultracapacitors are poised to become a cornerstone in future energy storage solutions.

10.2 Main applications of UCs

Supercapacitors or ultracapacitors, are electrochemical energy storage devices that offer unique capabilities bridging the gap between conventional capacitors and batteries. They store energy electrostatically by accumulating ions on the surface of a porous electrode material that is immersed in an electrolyte. This mechanism differs from batteries, which store energy chemically, and traditional capacitors, which store energy in a dielectric material. The primary advantage of supercapacitors over batteries and capacitors is their ability to deliver significantly higher power densities. This, coupled with features such as fast charge-discharge rates, long cycle life, and wide operational temperature ranges, makes them suitable for a wide range of applications.

Supercapacitors have emerged as crucial components in various sectors, spanning from consumer electronics to electric vehicles and grid-scale energy storage. Their unique characteristics enable them to excel in applications requiring rapid charge and discharge cycles, high power bursts, and long operational lifetimes.

Ultracapacitors in Grid-Scale Applications: Decentralized Energy Storage Solutions

Ultracapacitors are increasingly being integrated into grid-scale applications, especially in decentralized energy storage systems. Their unique properties, such as **rapid charge and discharge rates, long operational life**, and the **ability to handle frequent power fluctuations**, make them highly suited for this evolving sector. As the global energy grid shifts toward decentralization, with more renewable energy sources and localized microgrids, ultracapacitors provide critical support in ensuring stability and reliability.

Grid Stabilization and Frequency Regulation

Frequency Regulation: Supercapacitors can act as highly responsive grid stabilizers, instantly injecting or absorbing power to counteract fluctuations in grid frequency. This is crucial for maintaining grid stability, especially with the increasing penetration of intermittent renewable energy sources like solar and wind.³⁴³

Voltage Support: Supercapacitors can help maintain voltage levels within acceptable limits, particularly in distribution grids where voltage fluctuations can be more pronounced. This ensures the reliable operation of sensitive electronic equipment and prevents power quality issues.³⁵⁴

Energy Storage in Microgrids

Microgrids are a key component of decentralized energy storage solutions, offering localized energy management and resilience, especially in remote areas or for critical infrastructure. Ultracapacitors can be integrated into microgrid energy storage systems alongside batteries to optimize performance. They help manage peak load events and provide fast bursts of energy when needed, reducing the strain on batteries. This not only improves the lifespan of batteries but also enhances the overall efficiency of the energy storage system.

In applications such as rural or isolated communities, where renewable energy sources like wind or solar are the primary power generators, ultracapacitors can rapidly absorb energy during periods of excess production and release it during sudden drops. This ensures continuous energy supply without the need for large-scale battery banks, making microgrids more cost-effective and sustainable.³⁴³

Renewable Energy Integration

Ultracapacitors are particularly well-suited to back up the short-term volatility of renewables and play an important role in integrating renewable energy into decentralized grids. Ultracapacitors help mitigate RES fluctuations by rapidly absorbing and delivering energy as needed, improving the overall power quality and reliability of the grid.

Ultracapacitors are used in conjunction with wind turbines to regulate power output, particularly during wind gusts. Around [100,000 wind turbines](#) now use super-capacitors to feather their blades. They are also employed in solar PV systems to smooth power output during cloud cover. By providing fast-response energy storage, ultracapacitors reduce the need for curtailing renewable energy production during periods of excess generation.

Another interesting option for RES integration are hybrid energy storage systems that combine the strengths of both batteries and ultracapacitors. In these systems, ultracapacitors handle short-duration, high-power tasks, while batteries are used for longer-term energy storage. This hybrid approach is particularly useful in decentralized grids, where energy storage systems must balance the needs for both quick energy release (to maintain grid stability) and sustained energy supply (to handle longer periods of low generation).³⁵⁴ In wind farms, ultracapacitors can be combined with batteries to provide pitch control, a system that adjusts the angle of turbine blades to optimize wind capture. Ultracapacitors provide fast-response energy to control the blades during turbulent wind conditions, while batteries store energy for longer-term use.

Black-Start Capabilities and Grid Resilience

Ultracapacitors also contribute to the resilience of decentralized energy systems by providing black-start capabilities. In the event of a grid outage, ultracapacitors can quickly provide the necessary power to restart generators or re-energize the grid. This application is particularly valuable in microgrids or islanded systems that rely on independent energy generation.

In large-scale power outages, ultracapacitors have proven their worth by providing backup power to critical infrastructure. They have been deployed in systems that require fast-response energy to power essential services, such as hospitals, communication networks, and transportation systems, during grid disruptions.

Beyond grid applications, supercapacitors play a vital role in various electronic devices and systems. In consumer electronics, they provide backup power for memory, enhance audio quality with instantaneous power delivery, and enable rapid image capture in digital cameras due to their fast charge-discharge rates.

In electric and hybrid vehicles, supercapacitors are crucial for efficient energy capture and release during braking, known as regenerative braking. Their high power density also provides an acceleration boost, enhancing the driving experience. Moreover, they facilitate seamless start-stop functionality in hybrid vehicles, reducing fuel consumption and emissions.

Industrial equipment also benefits from supercapacitors, which provide power for heavy lifting and rapid movements in forklifts and cranes, improving efficiency. In welding machines, they deliver high current pulses for consistent weld quality and reduced energy consumption. Additionally, they serve as backup power in uninterruptible power supplies (UPS), ensuring continuous operation of critical equipment during outages.

10.3 Technological barriers, regulatory framework and scalability

10.3.1 Technological barriers

Ultracapacitors hold great promise for decentralized energy storage systems due to their high power density, rapid charge/discharge capabilities, and long cycle life. However, several technological barriers limit their widespread adoption, particularly in decentralized systems where efficient and reliable energy storage is crucial for maintaining grid stability and integrating renewable energy sources.

1. Low Energy Density

One of the most significant challenges facing ultracapacitors is their inherently low energy density compared to batteries. While ultracapacitors excel at delivering quick bursts of power, their ability to store large amounts of energy for longer periods remains limited. In applications where sustained energy output is required, such as in microgrids or remote locations with

fluctuating renewable energy supplies, the low energy density of ultracapacitors can make them less competitive than batteries³¹⁹.

This barrier particularly impacts decentralized energy storage systems that rely on renewables, such as solar or wind. Without adequate long-term storage solutions, ultracapacitors alone cannot meet the energy demands during periods of low generation, limiting their role in such settings unless paired with other energy storage technologies like lithium-ion batteries.

2. High Capital Costs

The cost of manufacturing ultracapacitors remains a barrier to broader deployment, especially in cost-sensitive decentralized systems. The high price of activated carbon, graphene, and other advanced materials used in their construction drives up the cost of ultracapacitors. Additionally, the processing techniques required to create the high surface area necessary for energy storage further increase production costs.

While advancements in materials science, such as the development of carbon nanotubes and alternative activated carbon sources, are being explored to lower costs, these innovations are not yet widely adopted. For decentralized energy storage systems, which need to balance performance and cost-efficiency, the current high capital expenditure required to deploy ultracapacitors limits their competitiveness compared to more established technologies.³⁰⁸

3. High Self-Discharge Rates

Another significant limitation of ultracapacitors is their high self-discharge rate. Unlike batteries, which can hold a charge for extended periods, ultracapacitors tend to lose energy relatively quickly, even when not in use. This characteristic makes them less ideal for applications where stored energy needs to be available over long durations without frequent recharging.

In decentralized energy systems, where power may not always be available for frequent recharging, this self-discharge issue can become a major drawback. For instance, in remote microgrids or isolated renewable energy systems, energy storage devices need to retain power over extended periods, which ultracapacitors struggle to achieve without regular recharges.

4. Limited Voltage Tolerance

Ultracapacitors typically operate at lower voltage ranges, which limits their scalability for larger energy storage applications. While research is ongoing to develop higher-voltage electrolytes, commercial ultracapacitors generally handle between 2.7V and 3.0V. This limitation in voltage means that large arrays of ultracapacitors are required to store sufficient energy, further increasing system complexity and costs.

Decentralized energy storage systems, particularly those handling variable renewable energy, require flexibility in voltage management to accommodate different grid conditions. The limited

voltage tolerance of ultracapacitors complicates their integration into larger decentralized grids, where diverse and fluctuating power levels need to be efficiently managed.

5. Challenges with Hybridization

While hybrid energy storage systems that combine ultracapacitors with batteries are seen as a promising solution to overcome some of the limitations of ultracapacitors, integrating the two technologies effectively presents its own challenges. Hybrid systems require sophisticated power electronics and control systems to optimize the performance of both batteries and ultracapacitors. Managing the different charge/discharge profiles of each component can be complex, and the additional system components drive up costs.

Moreover, hybrid systems require careful design to ensure that the advantages of ultracapacitors (rapid response and high cycle life) are maximized without compromising the energy density and longer-duration storage capabilities of batteries. In decentralized energy storage solutions, where simplicity and reliability are often prioritized, these added complexities can pose a barrier to adoption.

10.3.2 Regulations

There are no specific regulatory barriers to UC system implementation within the EU.

Grid Integration and Energy Market Regulations One of the primary barriers to deploying ultracapacitor systems is the strict regulations governing grid integration and energy market participation. Ultracapacitors, which excel at providing fast-response energy storage, often fall into regulatory grey areas. For instance, EU directives such as the *Internal Electricity Market Directive (EU 2019/944)* and the *Clean Energy for All Europeans Package* set clear rules for battery storage and renewable energy systems, but the unique characteristics of ultracapacitors, like their short-duration energy storage capability, are not fully accounted for in these frameworks. However, this regulatory gap most likely does not pose a significant obstacle to implementation, as ultracapacitors can still be integrated within existing regulatory frameworks with minimal adjustments.

Environmental Regulations: The EU has stringent environmental regulations, such as the Restriction of Hazardous Substances (RoHS) directive, which restricts the use of certain hazardous materials in electrical and electronic equipment. These regulations influence the materials used in ultracapacitor manufacturing, promoting the development of environmentally friendly and sustainable ultracapacitor technologies. However, an interesting statement from the *The Role of Ultracapacitors in the Energy Transition* (Forst & Sullivan) study that environmental legislation in many cases is not strict enough to support the spread of UC technology: „Lead-acid batteries are still much cheaper than ultracapacitors and environmental legislation is not strong enough in many countries to push adoption.“³⁴⁶

10.3.3. Technological scalability

Supercapacitors and ultracapacitors are increasingly gaining attention as viable energy storage solutions due to their rapid charge-discharge capabilities, high power density, and long operational lifespan. However, scaling this technology for broader, more energy-intensive applications presents several challenges and opportunities. The scalability of ultracapacitors is closely tied to advancements in materials science, production costs, system integration, and regulatory considerations, especially when expanding their role from niche applications to grid-scale and large industrial systems.

“Two key elements are expected to change in the coming years as research and investment into ultracapacitors gains momentum. The most important one is cost. The production cost of ultracapacitors has dropped considerably in the past 15 years - by 65% -75% as per analysis done by various ultracapacitors manufacturers and this is expected to decrease by another 30% from 2019 to 2030. In comparison, battery costs are also expected to decrease, especially Li-ion battery costs, as increased volume of production is expected to reduce costs significantly over the decade, mirroring the costs of lead-acid batteries. Another important development will be the increasing energy density of ultracapacitors in the coming decade. The industry expects this to increase 10- to 30-fold, which will make ultracapacitors more competitive with batteries as increased research leads to the development of new types of ultracapacitors. (Frost & Sullivan et al, 2020).³⁴⁶

The compact size of ultracapacitors makes them particularly well-suited for miniaturization, enabling their integration into smaller devices and systems. This scalability potential is further enhanced by advancements in micro-supercapacitor (MSC) technology, which allows for even smaller and more flexible ultracapacitor devices. As a result, ultracapacitors can be seamlessly embedded into miniaturized electronic devices, wearable electronics, and other compact systems, expanding their application possibilities.

The scalability of ultracapacitors is also evident in their ability to meet the energy storage needs of various applications, from powering small electronic devices to supporting large-scale energy storage systems. This versatility is attributed to their modular design, which allows for easy integration and customization. Ultracapacitors can be connected in series or parallel to achieve higher voltage or capacity as needed, making them adaptable to different energy storage requirements.

Moreover, ultracapacitors offer scalability advantages in terms of modularity and integration. They can be easily combined in series or parallel configurations to achieve higher voltage or capacity as needed. This modularity allows for flexible integration into existing systems or the development of new energy storage solutions tailored to specific requirements.

In summary, the scalability potential of ultracapacitors, stemming from their compact size, advancements in micro-supercapacitor technology, and modular design, positions them as a versatile energy storage solution across a wide range of applications.

10.4 Resource restrictions

The primary raw materials used in ultracapacitors are:

Electrode materials:

- **Activated carbon:** This is the most common electrode material due to its high surface area, good electrical conductivity, and relatively low cost. Abundant and readily available globally. [Production is widespread](#), with major producers in China, United States, India, Germany and the Philippines. **The supply chain** for activated carbon is well-established, with raw materials such as coconut shells, wood, coal, and peat being widely used. The production process involves carbonization and activation of these raw materials, making it straightforward and efficient.
- **Graphene:** It is a newer electrode material that is being researched due to its extremely high surface area and excellent electrical conductivity. **Availability:** Becoming increasingly available as production technologies mature. However, high-quality graphene for ultracapacitor applications can still be limited and more expensive. **Supply Chain:** Developing rapidly, with key players emerging in China, the US, and Europe. Production methods include chemical vapor deposition, liquid-phase exfoliation, and reduction of graphene oxide. The production of graphene is complex and relies heavily on specific raw materials, primarily graphite, which is predominantly sourced from China, accounting for over 60% of global supply. This concentration raises significant geopolitical risks; any disruption in Chinese exports due to political tensions or resource nationalism could severely impact the availability and cost of graphene. In 2010 a [European Commission sponsored study group](#) identified 41 critical raw materials, of which 14 were considered of high supply risk and high economic importance, [among which there were graphite](#).
- **Carbon nanotubes (CNTs):** These are cylindrical molecules that have a high surface area and good electrical conductivity. They are often used in combination with other electrode materials to improve performance. The primary raw materials for CNT production include graphite and high-pressure carbon monoxide, both of which face the supply chain issues detailed above.

Electrolyte:

- **Aqueous electrolytes:** These are water-based electrolytes that are safe and environmentally friendly. They are typically used in lower-voltage applications.

- **Organic electrolytes:** These are non-aqueous electrolytes that offer a wider voltage window than aqueous electrolytes.
- **Ionic liquids:** These are salts that are liquid at room temperature. They have high ionic conductivity and a wide voltage window, making them suitable for high-performance ultracapacitors.

Availability: Aqueous electrolytes (e.g., potassium hydroxide, sulfuric acid) are widely available and low cost. Organic electrolytes and ionic liquids can have more specialized supply chains and higher costs.

Supply Chain: Varies depending on the specific electrolyte. Aqueous electrolytes have well-established, large-scale production. Organic electrolytes and ionic liquids often involve more specialized chemical manufacturing processes.

Separator:

- **Polymeric membranes:** These are thin, porous materials that separate the electrodes and prevent short circuits.

Current collectors:

- **aluminium :** This is a common current collector material due to its low cost and good electrical conductivity.
- **copper :** It is another common current collector material that offers high electrical conductivity.

The raw materials used in supercapacitors—activated carbon, graphene, carbon nanotubes, transition metal oxides, and advanced electrolytes—present both opportunities and challenges for scaling the technology. While some materials, such as activated carbon and manganese dioxide, are widely available and relatively cost-effective, others, like graphene, CNTs, and ruthenium oxide, face scarcity and high production costs. The future scalability of supercapacitors depends on improving material synthesis techniques, finding affordable alternatives, and developing sustainable production methods that can meet the growing demand for energy storage solutions.

10.5 UC energy storage costs

The cost forecast for ultracapacitors compared to Li-ion batteries from the Whitepaper from Frost & Sullivan paints a dark picture about current costs and future trends:

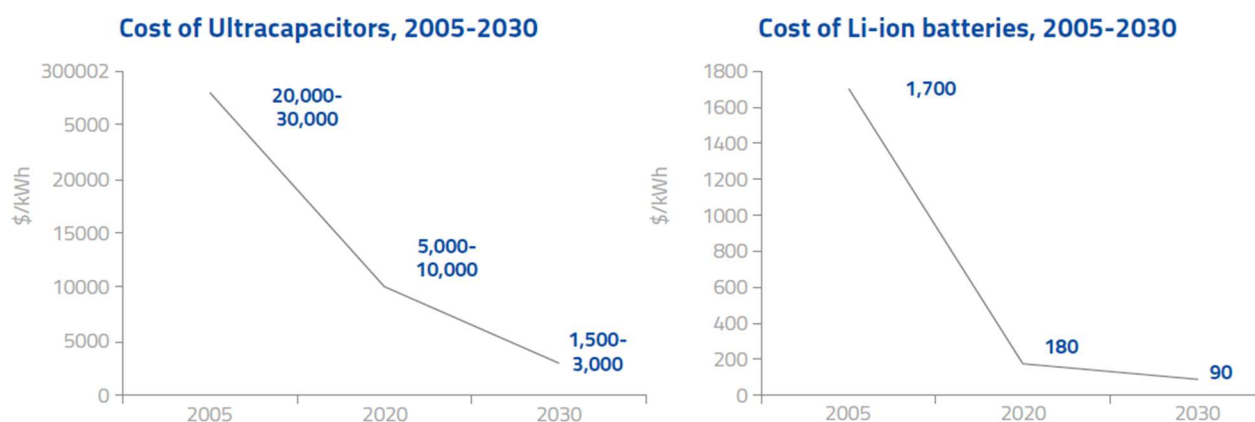


Figure 10.4 Cost forecast of ultracapacitors and Li-ion batteries Source: [Frost & Sullivan et al, 2020](#)³⁴⁶

10.5.1 Capital Expenditure (CAPEX)

CAPEX for ultracapacitors tends to be higher compared to battery energy storage systems, primarily due to the materials used and the current lack of economies of scale in production. Ultracapacitors are relatively more expensive in terms of cost per kilowatt-hour (€/kWh) but perform well in cost per kilowatt (€/kW) for power-centric applications.

- The **capital cost for ultracapacitors** ranges between €4,607 and €9,214 per kWh, which is significantly higher than lithium-ion batteries, which cost around €138 to €276 per kWh Frost & Sullivan (2020).³⁴⁶
- The report by Mongrid et al. (2019)³²³ further compares the costs of various energy storage technologies and shows that ultracapacitors have substantially higher energy capacity costs but benefit from lower degradation rates, reducing costs in long-term, power-specific applications.
- One of the reasons for the high CAPEX is the advanced materials, such as activated carbon electrodes and specialised electrolytes, which add to the production costs. The production costs are expected to decline over the next decade as material innovations and manufacturing scalability improve.

10.5.2 Operating Expenditure (OPEX)

Ultracapacitors have several characteristics that result in lower OPEX compared to traditional batteries:

- **Minimal Maintenance Costs:** Due to their lack of chemical degradation and high operational resilience, ultracapacitors require less frequent maintenance and replacement compared to chemical batteries. This makes their **OPEX relatively lower**,

particularly in environments with high cycling requirements, like grid stabilisation services - Frost & Sullivan (2020).³⁴⁶

- **Round-trip Efficiency:** The round-trip efficiency of ultracapacitors can exceed 95%, significantly higher than most battery technologies. This higher efficiency contributes to lower energy losses during operation, thereby reducing operational costs over the system's lifespan - Frost & Sullivan (2020).³⁴⁶
- **Energy Density Considerations:** While ultracapacitors have lower energy densities (around 5-10 Wh/kg) compared to lithium-ion batteries (100-250 Wh/kg), they are more efficient in rapid charge and discharge cycles, which allows them to be used in hybrid systems alongside batteries. This characteristic can lead to an overall reduction in operational costs, particularly in hybrid applications where batteries provide sustained energy while ultracapacitors handle peak power requirements - Frost & Sullivan (2020).³⁴⁶

10.5.3 Levelized Cost of Storage (LCOS)

The LCOS for ultracapacitors is distinct from that of traditional battery technologies due to their unique operational characteristics. LCOS represents the lifetime cost of the investment in a storage technology divided by the cumulative delivered electricity, reflecting the true economic efficiency of the system.

- According to Schmidt et al. (2019)³⁵⁵, the LCOS metric for energy storage quantifies the cost of energy provided by the storage system over its lifecycle, taking into account factors like investment costs, operating costs, and end-of-life disposal. Ultracapacitors exhibit lower LCOS when compared to many traditional storage technologies in applications that require rapid power discharge (e.g., frequency control in grid systems) due to their high power density and long cycle life.
- Frost & Sullivan (2020)³⁴⁶ noted that ultracapacitors offer a significant reduction in lifecycle costs when deployed in high cycling applications. They provide up to a million charge-discharge cycles without significant degradation, thus reducing replacement frequency and maintenance costs.

EDLCs are the most mature of the three supercapacitor types. Estimates for the baseline cost and performance parameters for EDLCs are based on 2025 estimates (Mongird et al, 2019)³⁵⁶. The size of the supercapacitor used to estimate the cost has a power rating of **1 MW, is able to discharge for 45 seconds, and is able to cycle 1 million times**.

Parameter	Value	Description
Storage block calendar life	16	Deployment life (years)
Cycle life	1,000,000	Baseline total number of cycles
Cycles per day	40	Number of charge-discharge cycles per day
Round-trip efficiency (RTE)	92%	Baseline RTE
Storage block costs	19,200	Baseline storage block costs (\$/kWh)
Balance of plant costs	7,600	Baseline balance of plant costs (\$/kWh)
Controls and communication costs ^a	33.04	Controls and communication costs (\$/kW)
Power equipment costs ^a	142.5	Power equipment costs (\$/kW)
System integration costs ^a	7,824	System integration costs (\$/kWh)
Project development costs ^a	11,058	Project development costs (\$/kWh)
Engineering, procurement, and construction (EPC) costs ^a	8,731	EPC costs (\$/kWh)
Grid integration costs ^a	27.73	Grid integration costs (\$/kW)
Fixed operations and maintenance (O&M) costs	1	Baseline fixed O&M costs (\$/kW-year)
Variable O&M costs	0.0003	Baseline variable O&M costs (\$/kWh)
Levelized cost of storage (LCOS)	0.443	Baseline estimate of LCOS (\$/kWh-cycle)

Table 10.2 EDLC cost and performance estimates for 1 MW, 45 seconds of storage
(2025 estimates) - [Durvasulu 2023](#)

10.5.4 Cost Trends and Future Outlook

Recent market trends indicate a decline in the production cost of ultracapacitors by 65-75% over the past 15 years, with further reductions expected as production scales up. By 2030, the cost of ultracapacitors is forecasted to decline by an additional 30%, making them more cost-competitive for power applications - Frost & Sullivan (2020).³⁴⁶

In the context of IoT energy storage solutions, ultracapacitors offer a promising alternative due to their robust cycling capabilities and resilience to temperature variations (up to 85°C), which make them ideal for environments where reliability is crucial, lower energy density is not an issue and frequent battery replacement is costly – Häggström et al, 2017³⁰⁸.

10.6 UC development perspective and environmental impact

10.6.1 UC development perspective

The development trajectory of UC technology has been evolving at a significant pace, driven by advances in material science and the increasing need for high-power energy storage solutions. Emerging trends from Lucintel³⁵⁷ indicate a focus on new forms of ultracapacitors such as flexible and micro-supercapacitors, which have found their way into portable and wearable electronics. These new formats, offering mechanical flexibility and enhanced electrochemical stability, are expanding the range of applications beyond traditional sectors, allowing for greater adaptability in future energy storage needs.

According to Frost & Sullivan³⁴⁶ „two key elements are expected to change in the coming years as research and investment into ultracapacitors gains momentum. The most important one is cost. The production cost of ultracapacitors has dropped considerably in the past 15 years - by 65% -75% as per analysis done by various ultracapacitors manufacturers, such as Skeleton Technologies and IOXUS - and this is expected to decrease by another 30% from 2019 to 2030. In comparison, battery costs are also expected to decrease, especially Li-ion battery costs, as increased volume of production is expected to reduce costs significantly over the decade, mirroring the costs of lead-acid batteries.”

Additionally, improving energy density has been a core objective in the UC industry. The energy density of ultracapacitors is expected to increase significantly by 2030—up to 10-30 times their current capabilities—thanks to innovations such as graphene electrodes. This increase in energy density can position UCs more competitively alongside lithium-ion batteries, enabling longer-term energy storage without compromising on the ability to deliver high bursts of power. This improvement could make ultracapacitors viable even for mainstream energy storage applications, not just high-power scenarios.

Energy density projections for ultracapacitors and Li-ion batteries

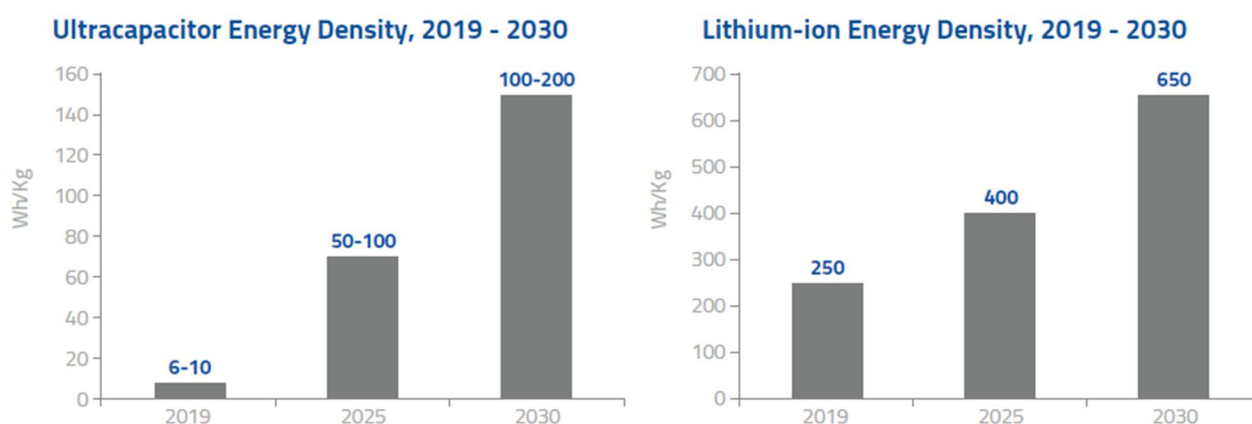


Figure 10.5 – Source: Frost & Sullivan et al, 2020³⁴⁶

10.6.2 UC environmental impact

Ultracapacitors/Supercapacitors are primarily made from lightweight, commercially available materials that are typically [RoHS](#) compliant. Their main energy storage material is carbon, which is abundant in nature and environmentally ubiquitous. Compared to many battery technologies, supercapacitors generally contain fewer hazardous materials and are typically easier to recycle, though proper recycling procedures should still be followed.

Ultracapacitors/Supercapacitors have specific environmental advantages when compared to lithium-ion and lead-acid batteries. Their main active material (carbon) requires less energy-intensive processing than battery materials like lithium compounds. They don't contain toxic heavy metals like lead or cadmium found in some battery types, and their longer cycle life - typically exceeding 100,000 cycles compared to 500-3000 for most batteries - means less frequent replacement and disposal.

However, manufacturing ultracapacitors/supercapacitors still involves environmental considerations. The production process consumes energy, requires industrial solvents and chemicals, and needs resource extraction for materials like aluminum and copper for current collectors. Additionally, proper recycling and disposal procedures are still necessary at end-of-life.

Their growing adoption in new energy applications stems from a combination of factors. Technical advantages like rapid charging/discharging and high power density are complemented by economic benefits such as long service life and low maintenance requirements. Environmental considerations, particularly their simpler recycling process compared to batteries, also play a role in their increasing deployment.

Based on the life cycle assessment (LCA) by Cossutta et al (2019)³⁵⁸ of graphene and activated carbon used in supercapacitors, the environmental impact of graphene-based supercapacitors was found to be significantly higher compared to their activated carbon counterparts. Specifically, the graphene-based supercapacitor demonstrated increased impacts in all evaluated environmental categories: greenhouse gas (GHG) emissions were 48% higher, and ozone depletion was 213% greater than that of the activated carbon-based device. The increased environmental burden is largely due to the high energy consumption involved in the graphene production process, which makes it more carbon-intensive—approximately 80 gCO₂ equivalent per gram compared to 5 gCO₂ equivalent per gram for activated carbon. Furthermore, the graphene material exhibited inferior specific capacitance, necessitating larger quantities of material and a heavier device, which further contributed to environmental burdens during the use phase - Cossutta et al (2019).³⁵⁸

However, the study also conducted a prospective scenario analysis, considering technological advancements and the decarbonisation of the electricity supply. With improvements in the specific capacitance of graphene to its theoretical maximum and the utilisation of renewable energy sources, the environmental impacts of the graphene-based supercapacitor could be significantly reduced. In such scenarios, the graphene-based supercapacitor exhibited a 36% reduction in GHG emissions, and overall environmental impacts were reduced—ranging from 14% less resource depletion to 43% lower photochemical ozone formation. These findings highlight that while graphene currently represents a less sustainable option due to its energy-

intensive production, it could become a more environmentally friendly alternative if production efficiencies are realised and renewable energy is utilised- Cossutta et al (2019).³⁵⁸

10.6.3 The Future - Intermittent Renewable Energy and Microgrids to Drive Adoption

The move towards renewable energy is expected to accelerate (especially solar and wind) and there is higher risk for grid fluctuations due to the intermittent nature of renewables. Hence, there will be a stronger need for devices such as ultracapacitors in the coming years. According to Frost & Sullivan, solar PV installations are expected to increase from 99 GW in 2019 to 128 GW in 2025, while wind power is expected to see annual additions between 55-70 GW between 2021 and 2025. These large RE additions to the global grid will lead to the increased need for power sources to address the frequency and voltage fluctuations and peak power requirements. (Frost & Sullivan, 2020)²⁹⁹

Ultracapacitors are increasingly becoming the standard choice for pitch control systems in wind turbines, with numerous manufacturers and operators already implementing this technology. The trend suggests that traditional battery systems in this application will be phased out entirely by 2030. What gives ultracapacitors the clear technological edge in this sector is their resilience to extreme temperatures and minimal maintenance requirements compared to batteries.

The rise of microgrids and distributed power generation across industrial sites and remote locations creates new opportunities for ultracapacitor implementation, particularly as these systems demand enhanced power quality and energy storage capabilities. Furthermore, the expanding network of IoT infrastructure, including smart meters and power quality monitoring sensors, requires reliable, long-term power solutions that minimize replacement needs.

The smart city movement, driven by governmental efforts to decrease energy consumption, is another catalyst for alternative power solutions. The integration of building energy management systems and enhanced energy controls will necessitate both battery and ultracapacitor solutions to enhance overall energy efficiency. While decreasing battery costs through recycling initiatives pose competitive challenges for ultracapacitor adoption, the industry is moving toward hybrid power systems for grid networks by 2030. In these hybrid systems, ultracapacitors will take on specific crucial roles, particularly in voltage and frequency stabilization, complementing rather than competing with batteries and generators.³¹¹

Looking forward, SC/UC technology will likely expand significantly, particularly in hybrid applications where both batteries and supercapacitors are used to provide a balanced energy solution. An example of this is [Skeleton Technologies' SuperBattery](#), which combines features of supercapacitors and lithium-ion batteries by using a patented Curved Graphene material. The SuperBattery delivers peak power within seconds and achieves an energy density of 65 Wh/kg,

along with a high power density of 4 kW/kg for 10-second durations. The technology is designed for applications requiring up to 15-minute energy storage cycles, such as electric vehicles, providing a much faster charge time (60 seconds) compared to lithium-ion batteries. With sustainability in mind, the SuperBattery is made without cobalt, copper, or graphite, and uses less than 5% lithium, making it a safer and more environmentally friendly option. Hybrid supercapacitors like the SuperBattery have the potential to bridge the performance gap between batteries and supercapacitors, particularly for high-power applications such as regenerative braking, electric turbochargers, and grid load balancing, highlighting a promising pathway for the future of energy storage technology.

Anticipated impact of ultracapacitors in the power industry

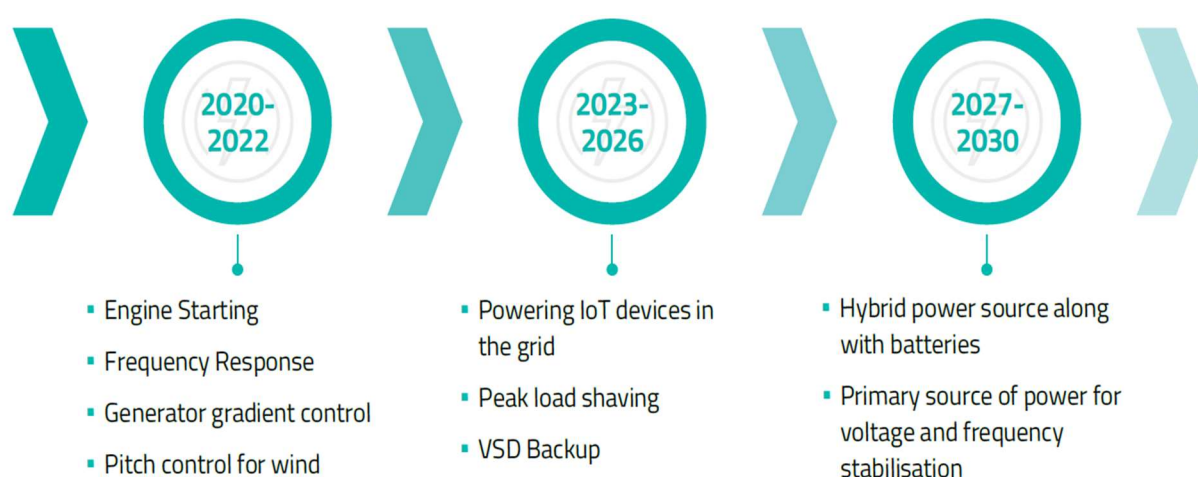


Figure 10.6 Anticipated impact of ultracapacitors in the power industry- Source: Frost & Sullivan, 2020 ³⁴⁶

10.7 Conclusions: advantages, disadvantages and recommendations for UC

10.7.1 Advantages and disadvantages

Advantages

- **Power Density and Charging Time** One of the most significant advantages of UC/SC systems over LIBs is their superior power density and fast charging capability. Ultracapacitors can achieve a power density of up to 10,000 W/kg (in some cases up to 4 kW/kg, as highlighted by [Skeleton Technologies' 2023 SuperBattery](#) brochure), making them ideal for applications requiring rapid bursts of power, such as regenerative braking in electric vehicles and peak power stabilization in grids. LIBs, by comparison, have a power density of around 0.5 kW/kg, which limits their performance in applications requiring quick discharge and recharge cycles.

UC/SC systems can also be fully charged in mere seconds. This ability to deliver and absorb energy quickly makes UC/SC systems particularly suitable for applications such as start-stop systems in vehicles, where quick bursts of energy are needed repeatedly. For instance, in industrial applications like cranes and elevators, ultracapacitors can provide efficiency gains of up to 34%, according to the Frost & Sullivan report (2020)³⁴⁶.

- **Cycle Life and Durability:** One of the defining benefits of UC/SC systems is their long cycle life. Ultracapacitors can endure up to 1 million cycles according to Frost & Sullivan report (however, the Skeleton Technologies SuperBattery Brochure states up to 50,000 cycles), whereas LIBs have a limited cycle life of fewer than 6,000 cycles before significant capacity degradation occurs. This makes ultracapacitors particularly well-suited for applications involving frequent charge-discharge cycles, such as hybrid electric vehicles or grid services that need constant cycling. The high cycle life of ultracapacitors results in lower maintenance and replacement costs, providing significant long-term cost benefits in applications where energy systems are heavily used.
- **Environmental Considerations regarding critical materials:** Ultracapacitors have advantages when it comes to environmental sustainability, particularly in terms of recyclability and lower risk of hazardous material use. Unlike LIBs, which use lithium and cobalt that can lead to environmental degradation, ultracapacitors are generally made from activated carbon, which is more environmentally friendly - Frost & Sullivan report³⁴⁶. Supercapacitors, like Skeleton's SuperBattery, are made without cobalt, copper, or graphite, and use less than 5% lithium, which mitigates the environmental impact associated with mining and material scarcity. Additionally, ultracapacitors have simpler chemical compositions, making them easier to recycle compared to LIBs, which often contain critical raw materials with limited recycling efficiency.
- **Safety:** Ultracapacitors have an inherent safety advantage over LIBs. LIBs are known for their thermal runaway risk, which can lead to fires or explosions if the battery is damaged or overheats. UCs do not store energy in a chemically reactive form, which drastically reduces the risk of fire or explosion during operation or after physical damage. The Frost & Sullivan report³⁴⁶ highlights that ultracapacitors can operate safely across a wide temperature range (-40 to +65 degrees Celsius), making them well-suited for harsh environments, such as those found in wind turbine pitch control systems and transportation sectors.

Disadvantages

Cons of Ultracapacitor (UC) and Supercapacitor (SC) Systems

- **Energy Density** In terms of energy density, UC/SC systems lag behind LIBs. While LIBs typically offer an energy density of around 205 Wh/kg, the energy density for ultracapacitors is significantly lower—ranging from 5-35 Wh/kg for most systems (65

Wh/kg for advanced systems like Skeleton's SuperBattery). This lower energy density limits the ability of UC/SC systems to store large amounts of energy, making them unsuitable for applications that require extended, steady energy supply over long periods, such as powering electric vehicles over long distances or storing solar energy for overnight use.³¹³

- **Initial Capital Expenditure (CAPEX)** The cost savings offered by longer cycle life must be weighed against the higher initial capital expenditure (CAPEX). According to the Frost & Sullivan white paper, the CAPEX for ultracapacitors remains significantly higher compared to LIBs, with costs ranging from \$5,000 to \$10,000 per kWh, whereas LIBs are much cheaper at \$100 to \$1,000 per kWh³¹³. This makes UCs less attractive in scenarios where energy storage capacity per dollar is the key metric, rather than cycle durability or power response.
- **Current Environmental Impact regarding manufacturing:** While ultracapacitors have the potential to be more environmentally friendly, the current production methods for advanced materials like graphene are energy-intensive and contribute significantly to greenhouse gas (GHG) emissions. A life cycle assessment (LCA) study comparing graphene-based and activated carbon-based ultracapacitors revealed that graphene supercapacitors currently have higher GHG emissions—approximately 48% more—compared to activated carbon-based counterparts (Cossutta et al., 2023)³²⁵. This high impact is largely due to the energy-intensive processes involved in graphene production.

The summary table of pros and cons of ultracapacitors



Figure 10.7 pros and cons of ultracapacitors - Frost & Sullivan, 2020 ³⁴⁶

Grid applications

A comparative table of pros and cons for UC/SC grid applications

Pros	Cons
- Ultracapacitors can be used to smooth out the variability of renewable energy and make it more reliable.	- Ultracapacitors have a lower energy density than batteries, meaning they cannot store as much energy for a given size or weight. This makes them less suitable for applications that require long-term energy storage, such as seasonal storage.
- Ultracapacitors can be used to store energy on the grid, which can help to improve grid stability and reliability.	- Ultracapacitors are currently more expensive than batteries. However, the cost of ultracapacitors is expected to continue to decline in the coming years.
- Ultracapacitors can be used as a backup power source in case of a power outage.	- The voltage of an ultracapacitor decreases linearly as it discharges. This can be a problem for some applications.

Table 10.3 Advantages and disadvantages for grid applications

10.7.2 Deployed UC/SC systems

Ultracapacitors, or supercapacitors, are increasingly being deployed in grid applications to enhance the integration of renewable energy sources like wind and solar power. These installations are particularly valuable for addressing the short-term volatility associated with renewable energy generation, which can fluctuate significantly due to changing weather conditions.

Key Installations and Case Studies

1. **Ireland Microgrid Test Bed:** This project has demonstrated the effectiveness of ultracapacitors in smoothing wind farm power output. By quickly absorbing excess energy during peak production and releasing it during lulls, ultracapacitors help maintain a stable supply to the grid.
2. **E-STATCOM Systems:** Enhanced Static Synchronous Compensators (E-STATCOMs) are being implemented in various locations to provide grid stabilization. These systems leverage ultracapacitors to offer fast voltage frequency support and synthetic inertia, crucial for managing the oscillations and fluctuations inherent in renewable-heavy grids. Supercapacitors in these systems can respond within milliseconds, making them suitable for real-time grid management.

3. **Skeleton Technologies' SkelGrid 2.0:** This modular system is designed for infrastructure environments, providing short-term backup power and enhancing power quality. It can deliver significant power outputs from compact setups, demonstrating the versatility of ultracapacitor technology in grid applications. SKELGRID ultracapacitors by Skeleton Technologies serve as energy storage systems, which improve power quality for industrial applications. Installed on the Scottish Island of Eigg, which is supplied with power from its own renewable energy-based microgrid system, SKELGRID enables fast-response backup power to the microgrid, thereby helping the island reduce its dependence on lead-acid batteries during peak power times. (Frost & Sullivan, 2020)³⁴⁶
4. **Grid-Scale Supercapacitor Energy Storage System (GSSESS) in Canada:** Atlas Power Technologies developed a [GSSESS project in Canada](#), focusing on providing grid ancillary services like voltage support and frequency regulation. This project aimed to demonstrate the commercial viability of supercapacitors for grid-scale applications.

With all these examples however, as of 2024 there are no utility-scale ultracapacitor or supercapacitor (UC/SC) energy storage systems primarily dedicated to bulk energy storage from renewable sources in Europe. Current UC/SC deployments are predominantly focused on power quality applications such as voltage stabilization, frequency regulation, and rapid-response power delivery. These installations are typically found in industrial settings, transit systems, and smaller grid-support applications where their high power density and rapid cycling capabilities are most valuable. While some renewable energy installations do incorporate UC/SC systems, these are primarily used for power smoothing and short-term stabilization rather than bulk energy storage. This differs from battery energy storage systems (BESS), which are increasingly being deployed at utility scale for renewable energy integration across Europe.

The absence of large-scale UC/SC systems for bulk energy storage is primarily due to their lower energy density compared to batteries, making them less economically viable for long-duration storage applications. Their strengths continue to lie in high-power, short-duration applications where frequent cycling is required.

10.7.3 Recommendations and WICE index

Despite being around for over 50 years and widely used across various applications, supercapacitors remain underutilised in power systems. The main reasons for this are their low energy density, high costs, and limited awareness of their benefits. Key innovations aimed at overcoming these challenges include:

- **Cost Reductions:**
 - Diversification of active materials and cost-effective purification and processing of activated carbon.

- Development of efficient module and cell packaging techniques designed for specific use cases.
- Design of Hybrid Energy Capacitor (HEC) cells tailored to different power system applications, focusing on specific capacities and cycle life.
- **Energy Density Improvements:**
 - Use of carbon nanotubes and graphene-based electrodes.
 - Development of curved graphene technologies for mass production.
- **Increased Awareness:**
 - Conducting analyses to identify where supercapacitors best serve grid needs.
 - Investigating hybrid energy storage solutions to balance cost and performance.
 - Funding demonstration projects to showcase practical use cases.

Additionally, Durvasulu and co-authors recommend demonstration support, customer education, increased capital to boost manufacturing, and policy changes to facilitate the use of supercapacitors.

Ultracapacitors have distinct advantages and limitations compared to other energy storage technologies, and the WICE index provides a structured way to measure their true potential. Let's evaluate ultracapacitors against various criteria to understand where they stand and how they could change the energy storage landscape.

1. **Energy Density** Ultracapacitor (UC) and supercapacitor (SC) systems generally have much lower energy density compared to lithium-ion batteries. The energy they can store per unit volume is limited, typically between 5-30 Wh/l, which means they are unsuitable for applications requiring long-duration energy storage. However, they excel in scenarios where rapid bursts of power are needed for short periods. Given this limitation in energy density compared to other storage technologies like batteries, ultracapacitors score relatively low in this category.

Score: 20

2. **Energy Retention Period** UC/SC systems are known for their ability to deliver energy almost instantly, but they have limited energy retention capacity over extended periods. Unlike batteries, which can hold energy for hours to days with limited self-discharge, UCs have a high rate of energy loss due to their natural self-discharge characteristics. This makes them ideal for very short-term energy applications but not for longer-term storage requirements. For energy retention extending beyond a few hours, lithium-ion batteries outperform UCs in terms of holding capacity without significant losses.

Score: 25

3. **Lifetime and Life Cycles** Ultracapacitors excel in terms of cycle life, as they can endure more than one million charge-discharge cycles without significant degradation. This is significantly better compared to lithium-ion batteries, which are typically limited to around 3,000-6,000 cycles. Moreover, UCs do not suffer from chemical wear, which makes them highly reliable and ideal for applications requiring frequent cycling, such as grid support or automotive functions. This robustness is reflected in their high score for lifetime and life cycles.

Score: 90

4. **Round-Trip Efficiency (RTE)** The round-trip efficiency of ultracapacitors is one of their standout features, typically ranging between 85-98%. This efficiency is higher than that of many other energy storage technologies because ultracapacitors have very low internal resistance and negligible energy losses during rapid charging and discharging. Despite this, the overall RTE is slightly lower compared to some advanced battery systems, especially when considering extended retention. Nevertheless, ultracapacitors remain an excellent option for applications demanding high efficiency in short cycles.

Score: 80

5. **Technological Maturity (TRL)** Ultracapacitor technology is mature for many niche applications, particularly in the automotive industry (e.g., start-stop systems), grid stabilization, and industrial machinery. With a TRL of around 8, UC/SC systems have proven capabilities and are commercially available, but their high cost and limited energy density have restricted broader adoption for large-scale grid storage compared to lithium-ion batteries.

Score: 75

6. **Capital Expenditure (CAPEX)** CAPEX for ultracapacitors is higher compared to lithium-ion batteries when considering cost per kilowatt-hour of stored energy, largely due to expensive materials like activated carbon and graphene. Although prices are gradually decreasing as manufacturing scales up, the high initial cost remains a barrier to wider adoption, particularly for grid-scale applications that require more economic energy storage solutions.

Score: 30

7. **Operational Expenditure (OPEX)** Once installed, the operational costs of ultracapacitors are relatively low. They require minimal maintenance, thanks to the absence of chemical reactions and mechanical parts that wear out over time. Their long lifespan and high

reliability result in reduced OPEX, making them particularly attractive for applications needing consistent, low-maintenance performance.

Score: 80

8. **Environmental Impact** Ultracapacitors have a relatively low environmental impact, especially compared to traditional battery systems. They do not contain toxic materials or rely on heavy metals like cobalt, which are associated with environmental and social concerns. However, the production process of advanced materials, such as graphene, remains energy-intensive and contributes to higher greenhouse gas emissions. Overall, they are considered a relatively green technology with room for improvement in production processes.

Score: 70

9. **Scalability** Ultracapacitors are highly scalable for small to medium applications, especially where high power but short energy bursts are needed. However, scaling up to grid-level applications presents challenges due to their low energy density and high costs. While modular systems can be created, the economics of large-scale deployment are currently less favourable compared to batteries, limiting their scalability in the broader energy storage market.

Score: 40

Using the weights provided, we calculate the weighted scores for each parameter:

Parameter	Weight	Score	Weighted score
Energy Density	0.1	20	2
Energy Retention Period	0.1	25	2,5
Lifetime and Life Cycles	0.1	90	9
Round-Trip Efficiency (RTE)	0.15	80	12
Technological Maturity (TRL)	0.2	75	15
Capital Expenditure (CAPEX)	0.1	30	3
Operational Expenditure (OPEX)	0.1	80	8
Environmental Impact	0.1	70	7
Scalability	0.05	40	2
Total	1		60,5

Impact potential of technology



At the beginning of this chapter, we noted that Elon Musk once predicted supercapacitors could outshine batteries in the future of electric vehicles, but our analysis suggests that Musk's crystal ball might need a bit of recalibration. While ultracapacitors excel in areas like rapid power delivery and cycle life, their limitations in energy density and high costs indicate they are not yet poised to dethrone lithium-ion batteries for large-scale applications. Though they certainly have their strengths, they may be better suited as sidekicks rather than taking the main stage.

11 Thermal Energy Storage (low-medium-high temperature) and cold storage (TES)

Summary of Metrics

Parameter	Technology: Thermal Energy Storage		
	Type		
	Sensible Heat Storage	Latent Heat Storage	Thermochemical Storage
Energy density per unit of volume [Wh/l]	15-200	30-90	180-1200
Power range	kW to hundreds of MW	kW to 100MW	10kW-1MW
Time of Permanent Energy Storage	hours to months	hours to days	months
Lifetime	15-50 years	20+ years	20-50 years
Discharge Time	hours	hours	hours
RTE (Round-Trip Efficiency)	50-98%	90-95%	45-63%
	heat to be corrected by electrical conversion		
RTE degradation	No data	No data	No data
Technology Maturity / Technological Readiness Level (TRL):	9 (water, some solids) 7-8 (molten salt)	6-8	4-7
System size Energy Capacity	kWh to 5 GWh (molten salts)	kWh to GWh (high temperature cPCM)	kWh to MWh
CAPEX per kW of Power Capacity [EUR/kW] LCOS - Levelized Cost of Storage	0.16 €/kWh – 0.39€/kWh LCOS with pathways to 0.05 €/kWh ³⁵⁹		
CAPEX per kWh of Energy [EUR/kWh]	0,1 – 10*	10 – 50*	8 – 100*
OPEX per kWh of Energy [EUR/kW/year]	No data	No data	No data
OPEX per kWh of Energy [EUR/kWh/year]			

Sources: Odukamaiya et. al 2021³⁹⁸, Sarbu & Sebarchievici 2018³⁶⁰ International Renewable Energy Agency – Innovation Outlook – TES³⁷⁹

* Without Heat to Electricity systems, average system cost is estimated 222 €/kWh in 2024 by [BloombergNEF](#)

11.1 Introduction

Thermal Energy Storage (TES) is a technology that captures and stores thermal energy for later use, either by heating or cooling a storage medium. This stored energy can be utilized for various applications such as heating, cooling, and power generation. TES is particularly useful in balancing the demand and supply of energy, which can fluctuate throughout the day and between seasons. By storing excess thermal energy during periods of low demand and releasing it during periods of high demand, TES systems can enhance the efficiency and reliability of to

TES can be classified into three main types based on the method of energy storage: sensible heat storage, latent heat storage, and thermochemical storage. Sensible heat storage involves changing the temperature of a storage medium, such as water or rocks. Latent heat storage uses phase change materials (PCMs) that absorb or release heat during phase transitions, such as from solid to liquid. Thermochemical storage involves reversible chemical reactions to store and release heat (Christenson, 2020).³⁶¹

Physics

Thermal Energy Storage (TES) is based on the fundamental principles of thermodynamics, specifically focusing on how heat is transferred, stored, and later retrieved. At its core, TES relies on the idea that thermal energy can be absorbed or released by changing the temperature of a substance. The simplest form of this is **Sensible Heat Storage**, where thermal energy is stored in a material by raising its temperature. This can be represented mathematically as:

$$Q = m * c * \Delta T$$

Where:

- Q: Thermal energy stored (in Joules)
- m: Mass of the storage medium (in kilograms)
- c: Specific heat capacity of the material (in J/kg·K)
- ΔT: Temperature change of the storage medium (in Kelvin or Celsius)

Here, m is the mass of the storage medium, c is the specific heat capacity of the material, and ΔT is the change in temperature. In essence, sensible heat storage utilises the inherent capacity of substances to hold heat when their temperature is changed. Common materials used include water, soil, and rocks. This method is simple and widely used, especially for low to medium temperature applications (Zhang et al., 2016)³⁶².

A more energy-dense form of TES is **Latent Heat Storage**, which involves phase change materials (PCMs). When a PCM, such as paraffin or ice, undergoes a phase change (like melting or freezing), it absorbs or releases a significant amount of energy without a change in temperature. This method can store large amounts of energy at a nearly constant temperature,

making it highly efficient. PCMs are particularly useful for applications where maintaining a specific temperature is crucial, such as in HVAC (Heating, Ventilation, and Air Conditioning) systems and industrial processes (Findik & Ermis, 2020³⁶³).

The energy stored in this process is given by:

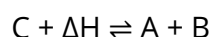
$$Q = m * L$$

Where:

- Q: Thermal energy stored (in Joules)
- m: Mass of the storage medium (in kilograms)
- L: Latent heat of the material (in J/kg)

Unlike sensible heat storage, latent heat allows for greater energy density since the thermal energy is stored at constant temperature, making it particularly useful for space-constrained applications.

Lastly, **Thermochemical Storage (TCS)** relies on reversible chemical reactions to store energy. During a chemical reaction, energy is either absorbed or released as bonds between atoms form or break. An example of this can be represented as:



Where:

- ΔH : Thermal energy stored or released during the reaction (in Joules)
- C: Thermochemical material undergoing dissociation
- A, B: Products formed from the dissociation of material C

In this reversible reaction, energy is stored when the compound dissociates into components and the energy can be retrieved by reversing the reaction. Thermochemical storage is advantageous due to its high energy density and minimal losses during long-term storage, making it particularly suitable for applications like seasonal energy storage. Thermochemical storage is suitable for high-temperature applications and has the potential for long-term energy storage, although it is still in the research and development stage (Abedin & Rosen, 2011)³⁶⁴.

History

The history of Thermal Energy Storage (TES) dates back centuries, with roots that trace to ancient practices of storing thermal energy for everyday use. One of the earliest recorded uses of thermal energy storage was by the ancient Greeks, who used large containers of water to store heat from the sun, releasing it later to warm their homes during cooler evenings. During the 19th century, the Industrial Revolution marked a significant leap in TES, as heat storage methods

were utilised to improve the efficiency of steam engines. By 1890, the use of ice storage became common in the United States, particularly for cooling applications in large buildings. This marks an early example of latent heat storage, where ice was harvested during the winter and stored for use during summer months. The introduction of phase-change materials (PCMs) in the mid-20th century began to open up new opportunities for higher-density thermal energy storage, a concept that would later play a critical role in TES technologies.

The architect Eleanor Raymond and the MIT engineer Maria Telkes designed the Dover Sun House in 1948. What looks like a second floor of windows was a huge heat-collecting panel that fed heated air into three “heat bins,” each in a different room on the floor below. In those bins, chemical salts would absorb the heat and store it for later use.

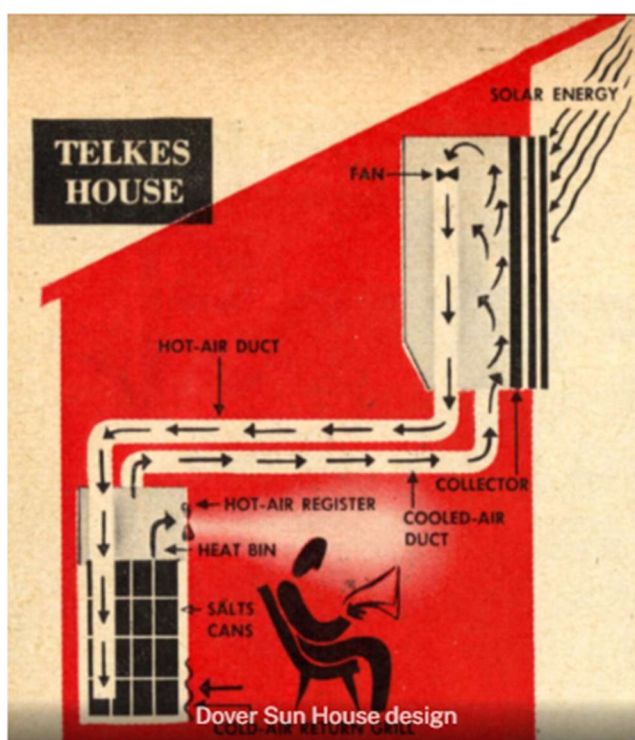


Figure 11.1 Dover Massachusetts, 1948 – Source: [Energy History Yale](#) - Eleanor Raymond and Maria Telkes, *Dover Sun House*, 1948, photograph, Dover, Massachusetts.

During the space race, NASA conducted extensive research on using phase-change materials for thermal regulation in spacecraft. Space missions required effective and lightweight thermal control systems, and PCMs were ideal for maintaining temperature stability by absorbing excess heat generated during spacecraft operation. Paraffin wax and other materials were experimented with to ensure that temperature variations did not affect onboard systems and astronauts. This was one of the most significant developments in PCM research, as NASA's work helped validate the use of PCMs for a variety of thermal management applications, highlighting their reliability and efficiency under extreme conditions.

In the 1970s, the oil crises drove a renewed interest in renewable energy and storage technologies, including TES. During this period, the potential for using solar power in conjunction with TES systems began to be explored in greater depth. Researchers began focusing on materials that could be used to store solar energy during the day and release it at night, providing a consistent energy supply. Molten salts emerged as a promising storage medium during this time, leading to the first experimental use of molten salt storage systems for concentrated solar power (CSP) applications in the 1980s. By the 1990s, TES had become more sophisticated, with various pilot projects across Europe and North America demonstrating the feasibility of large-scale heat storage for district heating, particularly in Denmark and Germany, which are leaders in renewable energy initiatives.

The 21st century has seen significant technological advancements and the commercialisation of TES systems. In the early 2000s, Concentrated Solar Power (CSP) plants using molten salt thermal storage began to gain traction, with [Spain's Gemasolar plant](#)³⁶⁵ becoming operational in 2011 as one of the first power plants to offer 24-hour solar power using TES.



Figure 11.2 Gemasolar Concentrated Solar Power, Seville

Molten salts (at 290°C), such as sodium and potassium nitrates, are stored in the cold storage tanks. Salts at 565°C are stored in the hot tanks. The tanks are up to 23m in diameter and 14m high.

The growth in renewable energy over the past two decades has also led to increased interest in thermochemical storage (TCS), which allows for long-term storage of energy with minimal losses. By the 2020s, TES had become integral to many renewable energy projects worldwide, with advances in PCM technology allowing for more compact and efficient storage systems. Additionally, innovations in thermochemical reactions are being actively researched, driven by the need for more efficient seasonal storage solutions to meet the challenges of balancing intermittent renewable energy supplies with grid demand.

Recent Advancements

Recent advancements in TES technology focus on improving efficiency, energy density, and cost-effectiveness. Significant progress has been made in the development of advanced materials and innovative storage methods.

One notable advancement is the enhancement of phase change materials (PCMs). Researchers are developing composite PCMs by incorporating nanoparticles to improve thermal conductivity and stability. This innovation addresses the common issues of low thermal conductivity and phase separation in traditional PCMs. Additionally, encapsulation techniques have been refined to prevent leakage and degradation of PCMs, further enhancing their practical application (Zhang et al., 2021)³⁶⁶.

In thermochemical storage, new materials and reactions are being explored to increase storage capacity and efficiency. Researchers are investigating metal-organic frameworks (MOFs) and other advanced sorbents that offer higher energy densities and better stability. These materials can significantly enhance the performance of thermochemical storage systems, making them more viable for commercial use (Palomba & Frazzica, 2019)³⁶⁷.

Sensible heat storage has also seen improvements, particularly in the context of concentrated solar power (CSP) plants. The use of molten salts as storage media has become more widespread due to their high heat capacity and relatively low cost. Innovations in heat exchanger design and materials have improved the efficiency and durability of these systems, making them more competitive with other energy storage technologies (Codd et al., 2020)³⁶⁸.

Moreover, hybrid TES systems that combine different storage methods are being developed to optimize performance. These systems leverage the strengths of each method—such as the high energy density of thermochemical storage and the simplicity of sensible heat storage—to create more efficient and flexible energy storage solutions (Ding et al., 2021)³⁶⁹.

Overall, the advancements in TES technology are driven by the need for more efficient, cost-effective, and sustainable energy storage solutions. The continuous development of new materials, improved system designs, and hybrid approaches will likely play a crucial role in meeting the growing energy demands and integrating renewable energy sources into the grid.

Current Technologies

Thermal energy storage (TES) technology is a versatile and evolving field, encompassing several methods and materials to store thermal energy effectively. Currently, there are three main types of TES technologies: sensible heat storage, latent heat storage, and thermochemical heat storage.

Sensible heat storage is the simplest form, involving the storage of thermal energy by changing the temperature of a storage medium such as water, air, or solid materials like rocks and concrete. This method is widely used due to its simplicity and cost-effectiveness. Water tanks are a common example, especially in residential and industrial applications for heating and cooling purposes (Sârbu & Sebarchievici, 2018)³⁶⁰.

Latent heat storage involves storing thermal energy through phase changes of materials, typically from solid to liquid or vice versa. Phase change materials (PCMs) such as paraffin, salts, and alloys are used because they can store and release large amounts of energy at nearly constant temperatures. This method is particularly beneficial for applications requiring precise temperature control, such as in HVAC systems and solar thermal power plants (Xu et al., 2015)³⁷⁰.

Thermochemical heat storage relies on reversible chemical reactions to store and release energy. This method offers high energy densities and can store energy for extended periods without significant losses, making it ideal for long-term storage applications. Materials such as metal hydrides, zeolites, and salts are commonly used in these systems. Although thermochemical storage is still under development, it holds great potential for future applications in both residential and industrial settings (Ding et al., 2021).³⁶⁹

11.1.2 Types of TES

Thermal energy storage (TES) encompasses various technologies designed to store thermal energy for later use. This can include both heat and cold storage, each serving different applications based on the temperature range and storage method.

Each classification of TES, from low to high temperature and including cold storage, serves specific industrial, residential, and commercial applications. Understanding the unique applications, advantages, and limitations of each TES type is crucial for effectively deploying thermal storage technologies in a rapidly transitioning energy landscape.

Storage Technology	Low Temperature (< 100°C)	Medium Temperature (100°C - 300°C)	High Temperature (> 300°C)
Sensible Heat Storage	Uses water, rocks; cost-effective but large volumes required; heat losses.	Uses concrete, rocks, thermal oils; moderate efficiency, thermal losses during cycles.	Uses molten salts, ceramics; withstands high temperatures; requires efficient insulation to minimize losses.
Latent Heat Storage	Uses paraffin, fatty acids, hydrated salts; high energy density in small volumes; issues with phase separation.	Uses molten salts, metallic alloys; higher energy density, improved over low-temp PCMs; thermal conductivity can be poor.	Uses chloride and fluoride salts; effective heat storage; high costs and challenges in enhancing conductivity.
Thermochemical Storage	Not commonly used; experimental stage at low temperatures.	Uses metal oxides, zeolites; high energy density; experimental, potential for long-term storage.	Uses metal oxides, metal hydrides; high energy density and controlled release; experimental and challenging reversibility.
Cold Thermal Energy Storage (CTES)	Uses chilled water, ice; efficient storage due to ice's high latent heat; suitable for refrigeration and AC.	Not applicable.	Not applicable.

Table 11.1 Summary table of TES classification

Low-Temperature Thermal Storage

Low-temperature thermal energy storage (TES) typically involves temperatures below 100°C and is often used in applications such as residential heating and cooling, as well as for storing excess energy from renewable sources. One common method for low-temperature TES is **sensible heat storage**, which involves raising the temperature of a storage medium, such as water or rocks. This method is straightforward but can require large volumes of material to store significant amounts of energy. For example, water tanks are a widely used technology due to their cost-effectiveness and reliability (Oro et al., 2012)³⁷¹. However, sensible heat storage suffers from efficiency losses, primarily due to the heat dissipation over time.

Latent heat storage, which uses phase change materials (PCMs), can store larger amounts of energy in a smaller volume by leveraging the heat absorbed or released during phase transitions. For low-temperature applications, materials such as paraffin, fatty acids, and hydrated salts are commonly used. These materials can efficiently store energy due to their high latent heat capacities and relatively stable thermal properties. Nonetheless, challenges such as

phase separation and leakage can affect system reliability and efficiency, and encapsulation techniques are being explored to address these issues.

Cold Thermal Energy Storage (CTES) is closely related to low-temperature TES but is designed specifically for cooling energy applications, such as air conditioning, refrigeration, and industrial cooling processes. Sensible heat storage for cold applications often uses chilled water, while **ice storage systems** are also popular due to the high latent heat of fusion of ice, allowing for compact and efficient energy storage (Sârbu & Sebarchievici, 2018)³⁶⁰[Error! Bookmark not defined.](#). Latent heat storage for cold applications uses PCMs such as eutectic salts³⁷², which undergo phase changes at low temperatures. Technological advancements, such as adding nanomaterials to improve thermal conductivity and using encapsulation techniques to prevent leakage, are ongoing areas of research to enhance the efficiency of CTES systems (Xu et al., 2019)³⁷³.

Medium-Temperature Thermal Storage

Medium-temperature thermal storage operates within the temperature range of 100°C to 300°C and is used in applications such as industrial process heat recovery and solar power plants. **Sensible heat storage (SHS)** in this range uses materials like concrete, rocks, and thermal oils. This method remains a viable option but faces challenges such as thermal losses during charging and discharging cycles. A key enhancement in this area involves using high-density storage media to minimize space requirements while ensuring sufficient thermal retention.

Latent heat storage (LHS) becomes more attractive at medium temperatures due to the higher energy densities achievable with PCMs. Materials like molten salts (e.g., NaNO₃-KNO₃ eutectics) and metallic alloys offer high energy storage capacities and stable thermal behavior (Hrifech et al., 2020)³⁷⁴. Although these PCMs provide increased energy density, issues such as poor thermal conductivity often limit their overall performance. Methods like embedding PCMs in high-conductivity matrices, such as metal foams, are being researched to improve their thermal transfer rates.

Thermochemical energy storage (TCES) is also a promising method in this temperature range. It involves storing energy through reversible chemical reactions, which can provide very high energy densities (ranging from approximately 305 kWh/m³ to 555 kWh/m³ for various materials). Materials such as metal oxides and zeolites are studied for their ability to store and release heat through endothermic and exothermic reactions, respectively. This method is still in the experimental stage but shows potential for long-term energy storage applications, particularly for its ability to store heat without significant losses over time (Zhang et al., 2016)³⁶². Efficiency remains a key challenge, and research is ongoing to identify materials with suitable thermal and chemical properties.

High-Temperature Thermal Storage

High-temperature thermal storage, exceeding 300°C, is essential for applications such as concentrated solar power (CSP) plants, where large amounts of thermal energy need to be stored and converted to electricity. **Sensible heat storage** at high temperatures often uses materials like molten salts, ceramics, and high-temperature concrete. These materials must withstand high temperatures without significant degradation or loss of thermal properties. While sensible storage at high temperatures is reliable, the substantial heat losses that occur due to radiation at these elevated temperatures necessitate efficient insulation solutions to improve overall efficiency.

Latent heat storage in this range employs PCMs like chloride and fluoride salts, which melt and solidify at high temperatures, providing efficient heat storage and transfer. The use of encapsulation techniques, such as embedding PCMs in high-conductivity matrices (e.g., metal foams), enhances heat transfer and system efficiency (Wu & Zhao, 2011)³⁷⁵. However, the high cost of PCMs for high-temperature applications often poses a barrier to their broader adoption.

Thermochemical storage for high-temperature applications often involves reactions between metal oxides, such as the redox reactions of metal hydrides and metal carbonates. These systems can store large amounts of energy and release it at controlled rates, which is crucial for balancing supply and demand in power generation. While the energy density of thermochemical storage is impressive, challenges remain in terms of achieving consistent reaction reversibility and optimizing reactor designs for continuous and efficient heat transfer. (IRENA Innovation Outlook TES).³⁷⁹

11.1.3 Practical implementations for electricity storage

Sensible Heat Storage Systems with Power Generation Integration

The amount of stored energy in SHS systems is proportional to the specific heat capacity of the material, its mass, and the temperature difference. These systems can be charged with electrical or thermal energy and generate electricity through various heat-to-power conversion cycles.

Main System Types and Their Power Generation Pathways:

1. Solid Media Storage Systems Storage Phase:

- Uses high heat capacity solids (concrete, rocks, ceramics)
- Direct electrical heating or heat transfer fluid
- Energy stored as temperature increase

Recovery Phase:

- Primary electricity generation options:

- Steam Rankine cycle for high temperatures. Typical efficiencies for modern steam power plants range from 35% to 45%.
- Organic Rankine Cycle for lower temperatures. Typical electrical efficiency range is around 10-20%.

2. Liquid Media Storage Systems Storage Phase:

- Uses oils, molten salts, or water
- Common materials: Solar Salt (NaNO₃-KNO₃), thermal oils
- Better heat transfer characteristics than solids

Recovery Phase:

- Multiple generation pathways:
 - Direct steam generation, Conventional steam turbines- electrical efficiency can range from around 30% to 40%.
- Advantages: Good heat transfer, natural convection

3. Two-Tank Storage Systems Storage Phase:

- Separate hot and cold tanks
- Usually with molten salts or thermal oils
- Most common in concentrated solar power

Recovery Phase:

- High-efficiency power generation:
 - Steam Rankine cycles
 - Combined cycle integration
 - Can achieve 35-45% electrical efficiency

Latent Heat Storage Systems with Power Generation Integration

These systems can be charged with electrical heating or direct solar thermal input and can generate electricity through various heat-to-power conversion cycles.

Main System Types and Their Power Generation Pathways:

1. Low-Temperature PCM Systems (0-120°C) Storage Phase:

- Uses organic PCMs (paraffins, fatty acids)
- Electrical input heats PCM above melting point

- Energy stored in phase transition

Recovery Phase:

- Primary electricity generation: Organic Rankine Cycle (ORC)
 - Heat transfer fluid extracts stored energy
 - Drives low-temperature ORC turbines
 - Achieves 10-20% electrical efficiency
- Secondary applications:
 - Combined heat and power systems
 - District cooling with power generation
 - Building-integrated systems

2. Medium-Temperature PCM Systems (120-300°C) Storage Phase:

- Uses inorganic salt hydrates or salt eutectics
- Common materials: NaNO₃-KNO₃ mixtures
- Higher energy density than organic PCMs

Recovery Phase:

- Main electricity generation options:
 - Advanced Organic Rankine Cycles
 - Kalina Cycle systems (The Kalina cycle is known for its higher efficiency compared to ORC systems, especially when dealing with low to medium-grade heat sources, such as industrial waste heat or geothermal energy. This is largely due to the use of a mixture of water and ammonia as the working fluid, which allows for better matching of the temperature profiles during heat addition and rejection.)
 - Typical electrical efficiency: 10-15% for temperature below 150°C , 20-30% above 150°C

3. High-Temperature PCM Systems (>300°C) Storage Phase:

- Uses metallic PCMs or high-temperature salts
- Materials: aluminum alloys, silicon, salt eutectics
- Highest energy density and power output potential

Recovery Phase:

- Multiple power generation options:
 - Conventional steam Rankine cycles
 - Supercritical CO₂ cycles (closed-loop thermodynamic cycle that utilises supercritical carbon dioxide as the working fluid to convert thermal energy into mechanical work, which can then be used to generate electricity. These systems are being actively researched and developed because they offer several advantages over traditional thermodynamic cycles, such as those using steam or organic working fluids. Supercritical Carbon Dioxide refers to CO₂ that is at a temperature and pressure above its critical point (approximately 31°C and 73.8 bar). Under these conditions, CO₂ exhibits properties that are intermediate between those of a gas and a liquid, allowing it to behave like a highly dense fluid.)
 - Can achieve 30-40% electrical efficiency
 - Integration with existing thermal power plants

LHS systems are more commercially mature than TCES, particularly in thermal applications. Power generation integration is well-established for high-temperature systems, while low and medium-temperature applications are gaining traction with improving heat-to-power technologies.

Main TCES System options with Power Generation Integration

These systems can release both heat and, through various conversion pathways, generate electricity when needed. This dual-output capability makes them particularly interesting for grid applications.

Main System Types and Their Power Generation Pathways:

1. Metal Hydride Based Systems Storage Phase:

- Electrical input from PV drives water electrolysis
- Hydrogen is absorbed into metal matrices (e.g., Mg, La-Ni alloys)
- Energy stored in metal-hydrogen bonds

Recovery Phase:

- Primary electricity generation: Fuel cell pathway
 - Controlled hydrogen release
 - Direct conversion in PEM or solid oxide fuel cells
 - Achieves 35-45% round-trip electrical efficiency

- Secondary heat-to-power option:
 - Uses exothermic heat from hydrogen absorption
 - Powers small-scale heat engines
 - Lower efficiency but simpler operation

2. Salt Hydration Systems Storage Phase:

- Uses electrical input to dehydrate salt hydrates
- Common materials: MgSO_4 , CaCl_2
- Lowest cost but also lowest grade heat storage

Recovery Phase:

- Main electricity generation through heat-to-power cycles:
 - Organic Rankine Cycle (ORC) for lower temperature outputs, Typical electrical efficiency range is around 10-20%.
 - Combined heat and power applications
- Best suited for applications requiring both power and heat

3. Ammonia-based Systems Storage Phase:

- Electricity drives ammonia decomposition
- Separated N_2 and H_2 storage
- Higher temperature operation (400-700°C)

Recovery Phase:

- Dual power generation options:
 - High-efficiency fuel cell pathway using H_2 (40-50% efficiency)
 - Conventional steam cycle using recombination heat
 - Can be integrated with existing power plant infrastructure

Most TCES systems with power generation are still in demonstration phase, with metal hydride and ammonia-based systems showing the most promise for efficient electricity recovery. The main challenges remain system complexity and overall round-trip efficiency, but the ability to provide both heat and power makes these systems attractive for many applications.

Sources: Pardo, P., et al. 2014³⁷⁶, Farulla et al. 2020³⁷⁷, Zsembinszki et al. 2018³⁷⁸, International Renewable Energy Agency – Innovation Outlook TES³⁷⁹

11.2 Main applications of TES

Main Applications of Thermal Energy Storage: Focus on Grid-Scale Applications

Thermal Energy Storage has emerged as a critical component for enhancing the flexibility, reliability, and efficiency of modern energy systems, particularly for grid-scale applications. As renewable energy sources such as solar and wind power grow in penetration, TES systems are increasingly being used to address the challenges associated with balancing supply and demand in electricity grids. By storing excess energy generated during periods of high renewable output and discharging it during peak demand, TES helps to stabilise the grid, improve energy efficiency, and reduce the reliance on fossil fuels. Below, we explore the primary grid-scale applications of TES, with a focus on pumped thermal energy storage (PTES), concentrated solar power (CSP), district heating and cooling, grid balancing, and the integration of renewable energy sources.

1. Pumped Thermal Energy Storage (PTES)

Among the emerging technologies for electricity storage, **Pumped Thermal Energy Storage (PTES)** stands out for its potential in grid-scale applications, especially for managing the intermittency of renewable energy sources. PTES involves storing electricity in the form of thermal energy through a heat pump, which moves heat from a low-temperature reservoir to a high-temperature one during the charging process. When energy is needed, the stored heat is converted back to electricity using a heat engine (Rabi et al., 2023)³⁸⁰. PTES offers several advantages, including **geographical flexibility** and **high round-trip efficiency (RTE)**, making it a promising alternative to traditional storage methods like Compressed Air Energy Storage (CAES) and Pumped Hydro Storage (PHS).

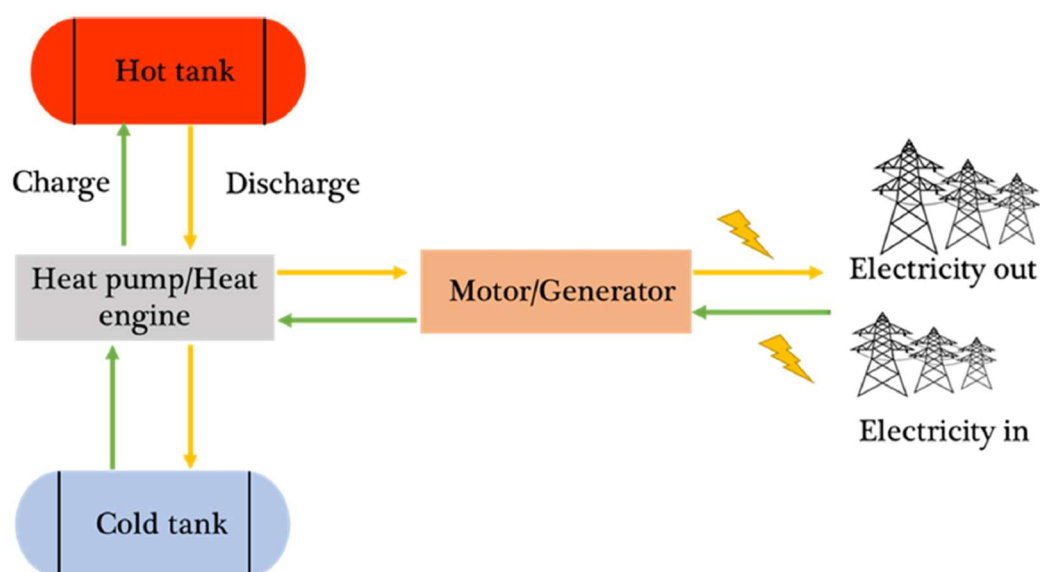


Figure 11.3 PTES standard layout and main components, charging and discharging cycle – Source: (Rabi et al., 2023)³⁸⁰

There are different PTES configurations based on thermodynamic cycles, including the **Joule-Brayton cycle**, the **Rankine cycle**, and the **transcritical Rankine cycle**. Each configuration has specific strengths and weaknesses. For instance, Brayton PTES systems can achieve a round-trip efficiency of 52% to 72%, with packed-bed sensible heat storage being commonly used to store thermal energy. Recent research indicates that **PTES systems with hybrid latent and sensible energy storage** could achieve even higher round-trip efficiencies, reaching up to **84.7%** under optimal conditions.³⁶⁸ PTES is particularly valuable for electricity storage at the grid level due to its **long cycle life**, lack of dependence on fossil fuels, and the ability to integrate with conventional power plants. These characteristics make PTES a highly adaptable and scalable solution for renewable energy integration, helping to smooth out variability and improve grid reliability.

2. Concentrated Solar Power (CSP) Plants

Another primary grid-scale application of TES is its use in **Concentrated Solar Power (CSP)** plants. In CSP systems, mirrors are used to concentrate sunlight and convert it into thermal energy, which can then be stored for later use. TES systems, particularly those using molten salts as the storage medium, allow CSP plants to generate electricity even during non-sunny periods or at night. This capability enhances the dispatchability of CSP plants, making them reliable power sources that can supply electricity on demand. A notable example of this application is the Gemasolar plant in Spain, which uses molten salt to store energy and achieve a 24-hour electricity generation cycle. This kind of grid-scale storage significantly improves the stability and flexibility of the power grid by providing a renewable energy source that can be dispatched like conventional power plants.

3. District Heating and Cooling

Another significant application of TES at the grid scale is in **district heating and cooling** systems. TES is used to store excess thermal energy generated by renewable or conventional sources and distribute it across residential, commercial, and industrial sectors as needed. In many European countries, including Denmark and Germany, large-scale water-based sensible heat storage tanks are used to store surplus heat produced by solar thermal plants, industrial processes, or combined heat and power (CHP) units (Lund et al., 2018)³⁸¹. These systems can store thermal energy during periods of low demand and distribute it when energy demand peaks, thereby improving the efficiency of the entire heating and cooling network. District heating systems have proven particularly effective in integrating renewable energy sources, such as solar and biomass, into the grid.

4. Grid Balancing and Peak Shaving

TES also plays a crucial role in **grid balancing** and **peak shaving**. During periods of high renewable energy production, such as sunny or windy days, TES can store excess electricity by

converting it into thermal energy through resistance heating or heat pumps. This stored energy can then be used to generate electricity during times of peak demand, reducing the load on conventional peaking power plants and maintaining grid stability. **PTES systems**, especially those employing Joule–Brayton or transcritical Rankine cycles, have gained attention as scalable and flexible solutions for grid applications. These systems can be co-located with renewable energy farms, enhancing grid stability by providing an energy buffer that smooths out the variability of wind and solar power (Rabi et al., 2023)³⁸⁰.

5. Renewable Energy Integration

The integration of renewable energy into the grid is another critical application of TES. Wind and solar energy are inherently variable, which can lead to grid imbalances and reliability issues if the generated power does not match consumption. TES provides a buffer that enables the storage of excess renewable energy and allows it to be used later, thereby ensuring a continuous supply of electricity. Recent research, as highlighted by Arévalo et al. (2024)³⁸², emphasizes that advancements in TES technologies are critical for supporting the integration of renewable energy into power systems. These advancements enable TES to manage surplus energy from solar and wind efficiently, thereby contributing to enhanced grid stability and energy security. The study by Arévalo et al. particularly stresses the role of TES in mitigating the intermittency of renewable energy and maintaining a reliable power supply during times of fluctuating generation. By providing this essential buffer, TES helps to balance production and demand, facilitating higher penetration of renewables in energy grids.

6. Frequency Regulation and Ancillary Services

In addition to its role in renewable integration and peak shaving, TES systems are also used for **frequency regulation** and other ancillary services that help maintain the operational stability of the power grid. By quickly releasing stored energy or adjusting their charging rates, TES systems can respond to fluctuations in grid frequency and provide ancillary services similar to battery storage systems. This capability makes TES a versatile and cost-effective solution for ensuring the stability of power systems with high renewable energy penetration.

Conclusion

The main grid-scale applications of Thermal Energy Storage include pumped thermal energy storage, concentrated solar power, district heating and cooling, grid balancing, renewable energy integration, and providing ancillary services. These applications demonstrate the versatility and value of TES in modern energy systems. By offering an effective means to store and manage excess energy, TES enhances grid stability, supports renewable energy deployment, and contributes to the overall efficiency and resilience of energy networks. As energy systems continue to transition towards more sustainable and renewable energy sources, TES—

particularly PTES—will play an increasingly important role in ensuring reliable and flexible electricity supply.

11.3 Technological barriers, regulatory framework and scalability

11.3.1 Technical Challenges

One of the key challenges in TES is converting stored thermal energy back into electricity, which is especially important when TES is used to balance supply and demand in renewable energy systems. This is typically done using Organic Rankine Cycle (ORC) systems, which are similar in principle to the traditional steam Rankine cycle but use an organic fluid with a lower boiling point than water. The ORC system is well-suited for TES applications because it can effectively convert low to medium-grade thermal energy into electricity. It works by heating the organic fluid, which then expands through a turbine to generate mechanical power, subsequently transformed into electricity by a generator. ORC systems are particularly advantageous for working with TES because they are capable of operating at relatively lower temperatures, which aligns with the temperature range of many TES materials like molten salts or phase-change materials.

However, the efficiency of converting heat back into electricity using ORC systems presents a notable challenge. The overall efficiency of this process is often in the range of 10% to 25%, depending on factors like the temperature of the heat source and the specific working fluid used. Compared to traditional fossil-fuel power plants, where the thermal-to-electric efficiency can be over 40%, the lower efficiency of ORC systems means that a significant portion of the stored thermal energy is inevitably lost during conversion. The Carnot limit, which represents the theoretical maximum efficiency of a heat engine, also imposes fundamental restrictions based on the temperature difference between the heat source and the cooling sink. The lower the temperature difference, the lower the efficiency, which is a typical limitation in TES where the stored heat might be well below the high temperatures used in conventional power plants. This efficiency issue means that while TES with ORC systems is practical for storing renewable energy, optimizing both the storage medium and the ORC process is crucial to make it more viable from a cost and performance perspective.

There are other emerging technologies that are being explored to overcome these limitations. For example, **supercritical CO₂ cycles**³⁸³ and **thermochemical energy storage methods** are gaining attention due to their potential to achieve higher efficiencies compared to ORC systems. Supercritical CO₂ cycles operate at higher efficiencies due to the unique properties of CO₂ at supercritical conditions, which allow for better energy extraction from heat sources. Including these alternatives provides hope for addressing the efficiency challenges faced by current TES systems.

In terms of economic feasibility, the lower efficiency of ORC systems has a direct impact on the **Levelized Cost of Storage (LCOS)**, making TES with ORC systems less competitive compared to other forms of energy storage, such as battery storage. The inefficiencies translate into higher operational costs and reduced economic attractiveness, especially for large-scale electricity storage applications. Therefore, ongoing research aims to lower costs by improving thermal conductivity, optimizing the design of the ORC cycle, and experimenting with different working fluids.

Heat Loss

One of the primary technical challenges associated with Thermal Energy Storage (TES) systems is efficiency, particularly concerning heat loss during the storage and retrieval processes. TES systems, whether sensible, latent, or thermochemical, face significant challenges in maintaining high thermal efficiency. For instance, sensible heat storage systems using water or rocks can experience substantial heat losses due to poor insulation or thermal conductivity issues. The efficiency of these systems is largely dependent on the quality of insulation and the thermal properties of the storage materials. A well-designed insulation layer is critical to minimize heat loss and maintain the overall efficiency of the storage system (Zanganeh et al., 2015)³⁸⁴.

Latent heat storage systems, which utilize phase change materials (PCMs), also encounter challenges related to thermal conductivity. PCMs typically have low thermal conductivity, which can lead to slow charging and discharging rates and uneven temperature distribution within the storage medium. This inefficiency can be mitigated by enhancing the thermal conductivity of PCMs through the incorporation of high-conductivity materials such as graphite or metallic nanoparticles. These modifications can significantly improve the heat transfer rate and overall efficiency of the TES system (Yi et al., 2019)³⁸⁵.

Thermochemical storage systems, which rely on reversible chemical reactions to store and release heat, face additional challenges related to the stability and reversibility of these reactions. Ensuring that the materials can undergo numerous cycles without significant degradation or loss of performance is essential for maintaining efficiency. Additionally, the design of these systems must address issues of thermal management to prevent excessive heat loss and ensure that the stored energy can be effectively utilized when needed (Stengler & Linder, 2020)³⁸⁶.

Safety and Reliability

Safety and reliability are paramount concerns for TES technologies. One major safety issue is the potential for thermal runaway in systems that use high-temperature storage media. In sensible heat storage systems, materials like molten salts can pose risks if the system's temperature control mechanisms fail, leading to overheating and potential containment breaches. Ensuring

robust safety measures, such as reliable temperature monitoring and control systems, is crucial to mitigate these risks.

Latent heat storage systems using PCMs can face reliability issues due to phase separation or supercooling, which can affect the material's ability to undergo consistent phase changes. Addressing these issues involves developing advanced PCM formulations that resist phase separation and ensuring that the system design supports uniform temperature distribution to prevent supercooling (Schwurack et al., 2019)³⁸⁷.

Thermochemical storage systems must contend with the stability of the chemical reactions used for energy storage. The materials must be capable of repeated cycles without significant degradation. Additionally, the systems must manage the safe handling and containment of reactive chemicals, which may require specialized materials and construction techniques to prevent leaks and ensure long-term reliability (Tosatto et al., 2022)³⁸⁸.

11.3.2 Regulatory framework

The regulatory landscape for thermal energy storage (TES) systems in the European Union is primarily governed by the Energy Performance of Buildings Directive (EPBD) and the Renewable Energy Directive (RED II). These frameworks recognize thermal storage as a crucial component in achieving the EU's decarbonization goals and energy efficiency targets. Under the EPBD's latest revision, thermal storage systems are explicitly included in the calculation methodologies for building energy performance certificates (EPCs), while RED II promotes the integration of TES with renewable heating and cooling systems through specific incentive mechanisms and mandatory requirements for renewable energy shares in buildings.

The technical standards and safety requirements for thermal storage installations are regulated through a combination of EU-wide regulations and national building codes. The harmonized standards developed by CEN (European Committee for Standardization) provide detailed specifications for thermal storage materials, system design, and installation procedures. These include EN 12977 for custom-built solar thermal systems and storage tanks, and EN 16147 for heat pumps with integrated storage units. Additionally, the EU's Ecodesign Directive imposes minimum energy performance requirements on storage heaters and hot water tanks, while the Energy Labelling Regulation mandates clear efficiency classifications to help consumers make informed choices.

The [Directive \(EU\) 2023/2413](#)³⁸⁹ on the promotion of renewable energy sources includes significant considerations regarding **thermal energy storage (TES)**, underlining its role in enhancing the efficiency and stability of renewable energy integration. Specifically, TES is recognised as an essential element for supporting flexibility in energy systems, particularly for storing excess renewable energy generated from sources like wind and solar. This aligns with the overarching objective of improving energy resilience while reducing dependence on fossil

fuels. The directive encourages member states to incorporate TES as part of their national renewable energy strategies, acknowledging its potential to mitigate the intermittency of renewable energy sources and enhance energy security across the European Union.

Moreover, the directive integrates TES into the broader framework of achieving **climate neutrality by 2050**, highlighting its role not only in electricity systems but also in **district heating and cooling** networks. TES technologies, including both sensible and latent heat storage, are pointed out as effective methods for storing surplus thermal energy during periods of high renewable output and redistributing it during peak demand. This allows for a smoother transition to renewable heating solutions and contributes to decarbonising the building and industrial sectors. The directive places an emphasis on using TES for both heating and cooling applications to ensure the broadest possible application of renewable energy, thereby boosting overall energy efficiency.

Finally, the directive underscores the importance of **research and innovation** in TES technologies, encouraging member states to support advancements in TES through funding and pilot projects. By reducing regulatory barriers and integrating TES into energy market mechanisms, the directive aims to foster the deployment of TES technologies throughout the Union. Specific provisions include simplifying administrative procedures for TES installations and ensuring that TES is effectively integrated with renewable energy generation projects. This regulatory environment is intended to create a favourable landscape for TES, encouraging its adoption to address the growing needs of renewable energy systems and support the EU's ambitious renewable energy targets.

11.3.3 Scalability

Scaling Up

Regarding **practical scalability**, ORC-TES systems are more suitable for specific, small to medium-scale applications rather than grid-scale deployment. They are often used for industrial waste heat recovery or medium-sized renewable energy plants rather than large grid-level storage projects. On the other hand, emerging approaches like **Pumped Thermal Energy Storage (PTES)** are more scalable for larger renewable integration projects, highlighting that different technologies may be appropriate depending on the scale and type of energy storage required.

To address the current limitations, optimization strategies are being actively explored. Examples include the enhancement of the thermal conductivity of TES materials through **nanoparticle additives**, which improve heat transfer rates, and the development of **hybrid latent and sensible storage systems** that combine the benefits of both methods to achieve greater overall efficiency. Moreover, tailoring the working fluid to better match specific temperature ranges can lead to performance improvements in ORC systems. These advancements are crucial for making

TES a more economically viable and technically reliable solution for balancing renewable energy integration into the grid.

Scaling up Thermal Energy Storage (TES) technologies from small pilot projects to large-scale commercial operations presents numerous challenges. One of the primary issues is the inherent complexity of TES systems, which increases significantly with scale. Pilot projects typically operate under controlled conditions with optimized parameters for a specific set of variables. When scaling up, maintaining the same level of control and optimization across a larger and more varied environment is challenging. For instance, large-scale TES systems need to handle higher volumes of thermal energy, which can introduce issues related to thermal stratification, heat loss, and system integration (Ochs et al., 2022)³⁹⁰.

Moreover, the physical infrastructure required for large-scale TES is considerably more demanding. This includes the need for substantial land area, particularly for technologies like molten salt storage or large-scale water tanks. Additionally, the construction of large-scale thermal storage facilities often involves complex engineering challenges related to ensuring structural integrity and thermal insulation over extended periods (Tosatto et al., 2022)³⁸⁸

The integration of large-scale TES into existing energy systems also presents significant technical hurdles. Effective integration requires compatibility with various energy generation sources, particularly intermittent renewable energy sources like solar and wind. This necessitates sophisticated control systems capable of balancing supply and demand, optimizing the charging and discharging cycles of the storage system, and ensuring seamless integration with the grid. The complexity of these systems increases with scale, making their management and operation more challenging (Achkar & Fadar, 2020)³⁹¹.

Economic and Logistical Factors

The economic and logistical challenges involved in scaling TES technologies are substantial. One of the primary economic barriers is the high initial capital cost required for large-scale TES installations. These costs include not only the materials and construction of the storage facilities but also the integration with existing infrastructure and the installation of advanced control systems. For instance, while tank TES systems offer high performance, their capital costs are significantly higher compared to pit storage systems, which can be a limiting factor for widespread adoption (Ochs et al., 2022).³⁹⁰

Logistical challenges also play a crucial role in the scalability of TES technologies. The transportation and installation of large-scale storage materials require significant logistical coordination. For instance, the transportation of materials like molten salts or large water tanks to remote areas where renewable energy plants are often located can be both challenging and costly. Additionally, the construction of large-scale TES facilities in urban areas faces regulatory

hurdles, land acquisition issues, and potential public opposition due to perceived environmental impacts.

11.4 Resource Restrictions

11.4.1 Natural Resource Requirements

The development of TES technologies relies heavily on the availability of specific raw materials, each of which comes with its own set of challenges, including supply constraints, geopolitical issues, and environmental impacts. Understanding these aspects is crucial for assessing the sustainability and scalability of TES technologies. This chapter is structured around the three main types of TES: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Energy Storage (TCES).

Sensible heat storage

Raw Materials and Availability: The primary materials used for Sensible Heat Storage (SHS) include water, molten salts, and natural minerals like rocks and concrete. Water is abundant and cost-effective, making it one of the most practical materials for low-temperature storage applications due to its high specific heat capacity. Molten salts, often a mixture of sodium nitrate and potassium nitrate, are commonly used in higher temperature applications, particularly in Concentrated Solar Power (CSP) plants, as they have a high heat storage density. Natural materials such as basalt rock or concrete are also used for thermal storage because of their high thermal capacity and wide availability (Hrifech et al., 2020)³⁷⁴

Supply and Geopolitical Considerations: The supply of water is relatively stable, although its availability can be geographically constrained, particularly in arid regions where water use for TES might compete with other critical needs. For molten salts, potassium and sodium nitrate are predominantly sourced from countries like Chile and Bolivia, which have vast natural salt deposits. This regional concentration poses potential geopolitical risks, as any political instability or export restrictions could impact global availability. The reliance on specific geographical regions makes the supply chain vulnerable to disruptions. In contrast, the abundance and wide geographic distribution of materials like water, rocks, and concrete help mitigate supply chain risks for SHS technologies.

Environmental Impacts: The use of water and natural minerals in SHS systems generally has a low environmental footprint, although the energy required for pumping and handling can contribute to emissions. However, the extraction of nitrate salts can have significant environmental impacts, including ecosystem disruption and pollution from mining operations. Additionally, high-temperature operations with molten salts can lead to thermal losses and spillage risks that need to be managed carefully to prevent environmental damage.

Latent heat storage

Raw Materials and Availability: Latent Heat Storage (LHS) systems typically rely on phase change materials (PCMs) such as organic paraffins, inorganic salts, and eutectics. These specialized PCM materials have high latent heat storage densities, allowing for more compact thermal storage compared to sensible heat systems. The availability and cost of these PCM raw materials can vary, with some organic and inorganic compounds being more widely available and affordable than others. Metals such as Al, Mg, Si and Zn and their [eutectics](#)³⁹² 88Al–12Si and 60Al–34Mg–6Zn were found to be highly suitable as PCMs for the duty considered (steam from 400–750 C). (Khare et al., 2012)³⁹³.

Supply and Geopolitical Considerations: The supply chains for many PCM raw materials are less developed and more concentrated geographically than those for SHS materials. This can introduce greater potential for supply disruptions and price volatility. Additionally, the production and processing of some PCMs may be limited to a small number of manufacturers or regions, creating potential bottlenecks.

Environmental Impacts: The environmental impacts of LHS systems depend on the specific PCM materials used. Some organic PCMs, such as paraffins, have relatively low environmental impact, while inorganic salts or eutectics may require more energy-intensive extraction and processing, leading to higher emissions. Proper handling, containment, and end-of-life management of PCMs are also important to mitigate potential environmental risks. (Li et al., 2017)³⁹⁴.

Thermochemical energy storage

Raw Materials and Availability: Thermochemical Energy Storage (TCES) systems often rely on specialized materials, such as metal hydrides, thermochemical salts, or other reversible chemical compounds. These materials tend to be less abundant and more geographically concentrated than those used in SHS or LHS systems. The supply chains for TCES raw materials are generally less mature, leading to higher costs and potential availability challenges.

Supply and Geopolitical Considerations: The reliance on specialized TCES materials, which may be sourced from limited geographical regions, introduces greater geopolitical risks compared to the more widely available SHS and LHS raw materials. Any disruptions in the supply of these critical materials could significantly impact the deployment and scaling of TCES technologies.

Environmental Impacts: The production, use, and disposal/recycling of TCES materials can have more significant environmental impacts than SHS and LHS systems. The extraction, processing, and handling of the specialized chemical compounds required for TCES may result in higher energy consumption, emissions, and potential environmental contamination risks that need to be carefully managed.

11.5 TES Energy Storage Costs

11.5.1 Initial Investment and Infrastructure - CAPEX

Based on the Comprehensive Review of Thermal Energy Storage study of Ioan Sarbu and Calin Sebarchievici³⁶⁰, cost of TES systems are summarized below:

1. Sensible Heat Storage (SHS)

- **Cost Structure:** €0.1–€10 per kWh, highly variable based on storage material, size, and specific application.
- **Key Materials and Cost Drivers:**
 - **Water:** Typically the least expensive material, especially effective at low to moderate temperatures (up to ~100°C) with a specific heat capacity of 4.19 J/g°C. Water-based systems benefit from low initial material costs but can incur added costs for storage tanks, insulation, and pressurisation for higher temperatures.
 - **Rocks, Sand, Concrete:** Used in larger-scale applications, especially in underground storage. Lower cost but generally less effective than water for heat retention per unit volume, requiring larger storage spaces.
 - **High-Temperature Media:** Oils and molten salts can be used for temperatures above 100°C. These are more expensive materials, contributing to the upper range of the cost spectrum (€5–€10 per kWh).
- **Efficiency for Heat Recovery:** 50–90%. Efficiency losses occur mainly due to heat dissipation over time, particularly in underground and large-volume storage setups.
- **Cost Considerations:**
 - SHS is typically chosen for its low upfront costs. However, total costs depend heavily on insulation and system design to minimise heat loss, as well as maintenance over the storage lifecycle.
 - Larger systems, such as district heating applications, can benefit from economies of scale, lowering the cost per kWh for extensive SHS solutions.

2. Latent Heat Storage (LHS) using Phase Change Materials (PCMs)

- **Cost Structure:** €10–€50 per kWh, driven by the choice and encapsulation of PCM materials.
- **Key Materials and Cost Drivers:**

- **PCMs** (e.g., paraffin wax, fatty acids, salt hydrates): Offer high energy density due to latent heat properties, but prices vary considerably depending on the material's stability, melting point, and ability to cycle without degradation. The difference between the pure PCM and the complete TES system is even higher for active PCM installations. As an example, the costs of a calcium–chloride storage system for heat rejected from a thermally driven absorption chiller includes the cost of calcium chloride, which is rather inexpensive (0.3 €/kg), and the cost of a container, a heat exchanger, and other components around €65 /kWh.
- **Encapsulation:** PCMs are often encapsulated to contain liquid phases and improve heat transfer, which adds manufacturing complexity and cost.
- **High-Purity Materials:** Organic PCMs (such as paraffins) tend to be more expensive due to purity requirements, while inorganic salts like salt hydrates are generally cheaper but may require additives to prevent supercooling and phase separation.
- **Efficiency for Heat Recovery:** 75–90%. LHS systems offer high efficiency for heat applications but are limited to narrow temperature ranges, affecting overall thermal yield in certain contexts.
- **Cost Considerations:**
 - LHS costs are concentrated on initial material costs, especially if high-performance PCM materials are selected. Maintenance costs can also rise if PCMs degrade over multiple cycles.
 - Thermal efficiency and cost-efficiency are optimised in compact applications where space is limited, as PCMs allow high energy density storage.
 - PCMs are ideal for systems requiring regular short-term cycling, such as daily heating/cooling cycles, though this raises total operational costs if material wear or stability is an issue.

3. Thermochemical Energy Storage (TCS)

- **Cost Structure:** €8–€100 per kWh, significantly influenced by chemical material costs, containment, and operational complexity.
- **Key Materials and Cost Drivers:**
 - **Chemical Compounds:** Commonly used compounds include magnesium sulphate, calcium chloride, and others, which store energy through reversible chemical reactions. Cost variability is high due to the compound's purity, stability,

and sourcing. Materials for TCS are usually expensive, as they have to be prepared (e.g., pelletized or layered over supporting structures).

- **Containment and Cycling:** TCS systems require durable containment to handle thermal cycling and ensure chemical stability. This can involve high-grade containment materials that increase initial setup costs. The containers and the auxiliary TCS equipment are expensive for both heat and mass transfer during energy charging and discharging. TCS systems can be operated as either open systems (i.e., basically packed beds of pellets at ambient pressure) or closed systems. Open systems are often the cheapest option, while closed systems need sophisticated heat exchangers.
- **High-Temperature Capabilities:** For applications above 100°C, costs rise sharply as specialised materials are needed to manage high-temperature chemical reactions and containment stability.
- **Efficiency for Heat Recovery:** 75–100%. TCS systems can theoretically reach high efficiencies, but practical applications often see lower effective efficiencies due to reaction inefficiencies and containment limitations.
- **Cost Considerations:**
 - High initial costs for chemical materials and system setup make TCS one of the more expensive TES options, but operational costs can be optimised in long-duration applications, such as seasonal storage, where regular cycling is less frequent.
 - The energy density advantage can lead to lower spatial and material costs for large-scale storage.
 - TCS systems are suited to specific industrial or utility-scale applications, where long-term storage and high energy density justify higher capital investment.

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible	10–50	0.001–10.0	50–90	days/months	0.1–10
Latent	50–100	0.001–1.0	75–90	hours/months	10–50
Thermochemical	120–250	0.01–1.0	75–100	hours/days	8–100

Table 11.2 Typical parameters of TES systems – Source: Sârbu & Sebarchievici, 2018³⁶⁰

11.5.2 Operational and Maintenance Costs

Long-term Costs

The long-term operational and maintenance (O&M) costs of Thermal Energy Storage (TES) systems are influenced by several factors including the type of TES technology, the materials used, and the specific application. These costs are critical in determining the overall economic viability and sustainability of TES systems over their lifecycle.

TES technologies offer varying levels of cost-efficiency over their lifecycle, which can be assessed through metrics such as levelized cost of storage (LCOS) and lifecycle cost analysis. **Sensible heat storage** systems, particularly those using low-cost materials like water and concrete, tend to be highly cost-efficient due to their relatively low operational and maintenance costs. These systems benefit from simple design and ease of maintenance, making them a cost-effective solution for large-scale thermal storage applications (Achkari & Fadar, 2020)³⁹¹

In **latent heat storage (LHS)** systems using Phase Change Materials (PCMs), the long-term costs can be higher due to the need for specialized maintenance of the PCMs. These materials can undergo phase separation or degradation over time, which can reduce their thermal performance. The cost of maintaining the structural integrity of containers and ensuring the proper functioning of the heat exchangers is also significant. Research indicates that the cost of lost energy due to inefficiencies and the cost of destroyed exergy (usable energy) represent major components of the lifecycle cost of PCM-based TES systems (Rezaei et al., 2013)³⁹⁵.

LHS systems, while having higher initial and operational costs, can offer significant energy savings and efficiency improvements. The ability to store large amounts of energy in a relatively small volume makes them suitable for applications where space is a premium. However, the cost-efficiency of PCM-based systems is highly dependent on the stability and thermal properties of the PCMs used. Innovations in PCM materials, such as the incorporation of nanomaterials to enhance thermal conductivity, are aimed at improving the cost-efficiency of these systems over their lifecycle (Mahfuz et al., 2014)³⁹⁶.

Thermochemical storage systems, which rely on reversible chemical reactions, face unique long-term costs related to the maintenance of the chemical reactants and reactors. These systems require precise control and regular monitoring to ensure that the reactions proceed efficiently and safely. The degradation of chemical reactants over multiple cycles necessitates periodic replenishment, adding to the operational costs. Moreover, the infrastructure required to handle and store reactive chemicals needs regular inspection and maintenance to comply with safety standards (Ding et al., 2021)³⁶⁹.

Specific CAPEX, LCOS values

Our literature review revealed few studies that calculate operating costs for Thermal Energy Storage (TES) systems. Moreover, we found no studies that analyze TES systems integrated with Organic Rankine Cycle (ORC) or Brayton cycle heat-to-electricity conversion systems.

Data on the current and projected LCOS for TES is limited, but some studies and reports have provided estimates. For example, a report published by the U.S. Department of Energy (DOE) in 2024 found that the projected baseline 2030 LCOS of all long-duration energy storage (LDES) technologies, including TES, exceeds the Storage Shot target of €0.048/kWh. However, the report also found that TES technologies have the potential to achieve significant cost reductions through innovation. The top 10% of LCOS-reducing innovations could potentially reduce LCOS by 12%–85% to €0.025/kWh–€0.24/kWh. These innovations include improvements in heat-to-electricity conversion, component standardization, and advanced materials development.³⁵⁹

[Another study](#)³⁹⁷ published by NREL in 2024 estimated an LCOS of \$0.07/kWh for a stand-alone, build-from-scratch particle TES system. The study also noted that the LCOS could be further reduced by integrating the TES system with a retired coal power plant, taking advantage of funding in the Inflation Reduction Act that incentivizes conversions of fossil energy to renewable energy. [[Long-duration thermal energy storage in sand begins NREL demo](#)]

The “*Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings*”³⁹⁸ study compared Levelized cost of energy storage on-site in buildings for EES (Electrical energy storage) and TES systems combined with heat pumps. The study found, that “while EES has the advantage of high utilization year-round due to the year-round presence of electric loads in buildings, state-of-the-art TES is still competitive with EES in terms of LCOS, due to lower capital cost and longer lifetime.”

LCOS comparison of TES + heat pump to EES + heat pump for four sets of TES

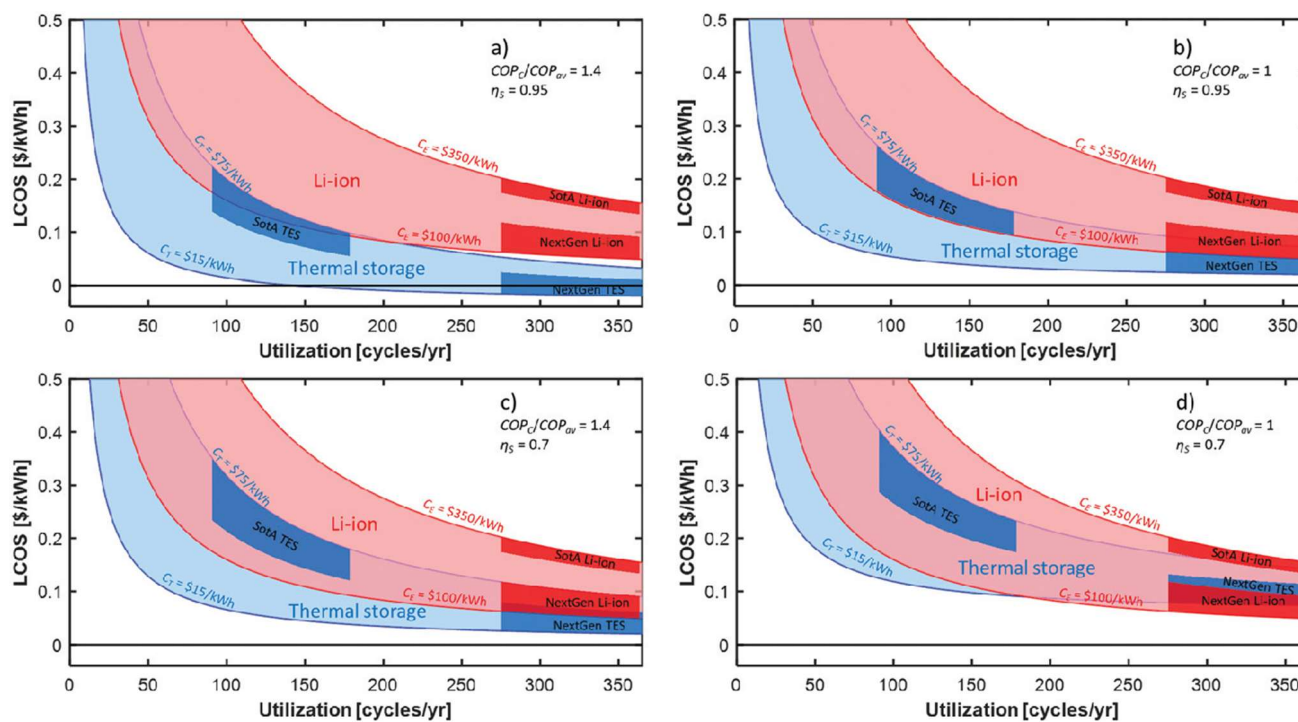


Figure 11.4 LCOS comparison of TES + heat pump to EES + heat pump for four sets of TES – Source: Odukumaiya et. al 2021³⁹⁸

For a case where the CAPEX is \$75/kWh_{th}, (71.68 EUR) and the utilization is 125 cycles per year, the LCOS is \$0.03/kWh_e (0.028EUR), \$0.15/kWh_e (0.14 EUR) and \$0.34/kWh_e, (0.32 EUR) for COP_{av} values (average coefficient of performance of the heat pump, which represents the ratio of useful heat output to the electrical energy input) of 1, 3, and 6, respectively.³⁹⁸

A detailed analysis of CAPEX and OPEX for Thermal Energy Storage (TES) systems, particularly those integrated with Organic Rankine Cycle (ORC) and Brayton cycle systems, will require further research. This analysis can be conducted during the development of the Comprehensive Catalogue of Sustainable Energy Storage Solutions, provided that TES is identified as a promising technology for distributed energy storage.

11.6 TES Development Perspective and Environmental Impact

11.6.1 Development Perspective

Current Research Trends

Current research trends in thermal energy storage (TES) are increasingly focused on enhancing the efficiency and applicability of various storage technologies, particularly in the context of renewable energy integration. One of the most significant advancements is the development of **Phase Change Materials (PCMs)**, which store and release thermal energy during phase

transitions, such as melting and solidifying. Recent innovations have led to the creation of organic, inorganic, and bio-based PCMs that exhibit improved thermal stability and higher energy storage capacities. These materials are being utilized in diverse applications, from building temperature regulation to large-scale energy management in power plants. The ongoing research aims to overcome limitations such as low thermal conductivity and containment issues associated with traditional PCMs, thereby broadening their practical use in TES systems.

Another prominent trend is the integration of TES with **renewable energy sources** like solar and wind. As these energy sources are inherently intermittent, TES systems provide a reliable means to store excess energy generated during peak production times for later use. This capability enhances grid stability and maximizes renewable energy utilization while reducing reliance on fossil fuels. Innovations in hybrid TES systems that combine different storage technologies—such as sensible heat storage and latent heat storage—are also gaining traction. These hybrid systems offer greater flexibility and improved energy density, making them suitable for a variety of applications, including residential heating and cooling.

Finally, advancements in **control systems** and software are playing a crucial role in optimizing TES operations. The incorporation of artificial intelligence (AI) and machine learning algorithms allows for real-time monitoring and management of energy storage processes, ensuring that thermal energy is stored and released at optimal times based on demand patterns. This tech-driven approach not only improves the efficiency of TES systems but also contributes to predictive maintenance, extending the lifespan of these technologies. With increasing regulatory support and investment in sustainable technologies, the future of thermal energy storage looks promising as it continues to evolve alongside advancements in materials science and system design.^{382, 399, 400}

Scalability and Integration

Sensible Heat Storage (SHS) is the most widely adopted form of thermal energy storage, primarily due to its simplicity and cost-effectiveness. The scalability of SHS systems is facilitated by their modular design, allowing for easy integration into existing infrastructure. For instance, in concentrated solar power (CSP) plants, SHS systems using molten salt can be scaled up to meet the energy demands of large facilities while providing reliable power generation even during non-sunny hours. As the market for sustainable energy solutions grows, SHS is projected to maintain a dominant market share, with a compound annual growth rate (CAGR) of 7.6% from 2023 to 2032, driven by increasing demand for renewable energy integration and efficient cooling solutions.⁴⁰¹

Latent heat storage (LHS). The scalability of LHS systems is enhanced by their high energy density compared to sensible heat systems, allowing for more compact storage solutions. Recent advancements in PCM materials are focused on improving thermal conductivity and operational

temperature ranges, making them suitable for various applications, from residential heating to industrial processes. Furthermore, the development of modular LHS units allows for tailored solutions that can be easily expanded or modified based on specific energy needs.³⁶²

Thermochemical storage - Although still in the early stages of development, thermochemical systems are being researched for their ability to minimize heat losses and provide robust scalability options. As researchers continue to explore new materials and reaction pathways, the integration of thermochemical storage into renewable energy systems could revolutionize how we manage thermal energy on a larger scale. The anticipated advancements in this area are expected to support sustainable practices and align with global efforts toward decarbonization. With ongoing investments and research focused on enhancing the efficiency and practicality of these systems, thermochemical heat storage may play a crucial role in future energy strategies. (Koushaeian et. al 2024)⁴⁰²

11.6.2 Environmental Impact

The environmental impacts of Thermal Energy Storage (TES) systems can be broadly categorised into the **environmental footprint of the materials used, impacts during system operation, and emissions avoided through system integration with renewable energy sources**. Each type of TES—Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Heat Storage (TCHS)—has distinct environmental considerations that need to be taken into account to assess the overall sustainability of the technology.

Materials Used in TES Systems

Sensible Heat Storage (SHS): The materials commonly used in SHS systems are **water, molten salts** (e.g., sodium nitrate, potassium nitrate), and natural minerals like **rocks** and **concrete**. Water is widely available and has a minimal extraction impact, but for molten salts, the environmental footprint is significantly higher. The mining of nitrates, primarily sourced from regions like Chile, can lead to **ecosystem disruption** and **soil degradation**. Additionally, the processing and refining of these salts contribute to **greenhouse gas emissions** and **water contamination**. The production of concrete also has a large **carbon footprint**, with approximately **0.93 kg of CO₂** released for every kilogram of cement produced, due to the high-temperature calcination process involved ([Lehne & Preston, 2018](#))⁴⁰³.

Latent Heat Storage (LHS): LHS systems rely on **Phase Change Materials (PCMs)**, such as **paraffin, fatty acids, hydrated salts, and metallic alloys**. **Paraffin waxes**, being petrochemical derivatives, have significant environmental impacts related to **oil extraction** and **refining**, which includes land degradation and emission of pollutants during refining. The use of **metallic alloys** (such as aluminium-zinc combinations) for high-temperature applications involves energy-intensive extraction and refining processes, contributing to both **carbon emissions** and **resource depletion**. The production of aluminium, for example, emits

approximately **16 kg of CO₂** per kg of aluminium **Globally**, but much less, **6.8 kg of CO₂ in Europe** due to the electrolysis process and high energy demands ([European Aluminium](#))⁴⁰⁴.

Thermochemical Heat Storage (TCHS): TCHS systems use **metal oxides** (e.g., calcium oxide, magnesium oxide), **zeolites**, and **salt hydrates**. The production of **calcium oxide** involves the calcination of limestone, which is highly energy-intensive and results in **direct CO₂ emissions** due to the breakdown of calcium carbonate (CaCO₃). **Magnesium extraction** is dominated by large-scale producers like China, and the **Pidgeon process** commonly used has a high environmental impact in terms of energy consumption and emissions. **Zeolite mining** can also have an environmental impact if not managed properly, particularly through **habitat destruction** and dust pollution during extraction.

Impact During Operation

- **Sensible Heat Storage (SHS):** Systems using molten salts may experience leakages of hot salts, potentially contaminating soil and groundwater if spills are not properly contained. Energy losses through radiation and convection can lead to inefficiencies, indirectly increasing the overall environmental burden.
- **Latent Heat Storage (LHS):** PCMs may degrade over time; for instance, organic PCMs like paraffin can break down into smaller hydrocarbons, potentially releasing volatile organic compounds (VOCs) if not properly encapsulated. Metallic PCMs and hydrated salts can undergo phase separation, necessitating periodic material replacement, which adds to the environmental impact over the system's lifetime.
- **Thermochemical Heat Storage (TCHS):** Involves materials undergoing endothermic and exothermic chemical reactions. The environmental impact during operation is relatively lower than SHS or LHS because these reactions can be controlled with minimal thermal losses. However, managing potential by-products or reaction residues is crucial for minimizing waste.

11.7 Conclusions: Advantages, Disadvantages, and Recommendations for TES

11.7.1 Advantages and disadvantages

Pros

Thermal Energy Storage (TES) offers several distinct advantages that make it an essential solution in the context of renewable energy systems and energy storage needs.

1. Versatility in Energy Sources

TES systems are highly versatile, capable of storing energy from multiple sources, including renewable electricity, industrial waste heat, and off-peak grid power. This adaptability allows TES to complement a wide variety of renewable energy systems, making it suitable for residential, commercial, and industrial uses. By effectively storing heat from renewable energy sources, TES helps mitigate the intermittency problems associated with renewable energy production, providing a reliable way to meet energy demands consistently.

2. High Energy Density and Efficiency

TES systems, particularly those employing latent heat storage using Phase Change Materials (PCMs), are notable for their high energy density. PCMs can store large amounts of thermal energy in relatively compact spaces, making these systems highly efficient. The ability to store thermal energy at near-constant temperatures is another benefit, which allows TES to provide a stable and reliable heat supply that's well-suited for applications requiring consistent temperature management, such as HVAC and industrial processes.

3. Improved Grid Stability and Renewable Integration

When TES is combined with technologies such as the Organic Rankine Cycle (ORC), it can convert stored thermal energy back into electricity, contributing to grid stability. This ability to shift energy supply by storing heat during periods of excess renewable generation and converting it back to electricity during peak demand is essential for maintaining a balanced power grid. This function is particularly advantageous for integrating renewable energy sources like solar and wind, which are inherently variable.

4. Long-Duration Storage Capability

One of the standout features of TES is its ability to store energy for extended periods with minimal loss. Unlike batteries, which tend to degrade over multiple cycles, TES systems can maintain their efficiency over long periods, making them a suitable option for seasonal energy storage. This long-duration capability is especially valuable for renewable energy integration, where the mismatch between energy production and consumption can span weeks or even months.

5. Scalability and Flexible Applications

TES systems are easily scalable to meet different energy needs, from small-scale residential heating applications to large industrial facilities. High-temperature TES solutions, such as those using molten salts, are scalable for utility-sized energy storage, which is beneficial for large-scale renewable energy projects like concentrated solar power (CSP) plants. This scalability ensures that TES can play a role in both distributed energy storage systems and large centralised renewable energy plants.

6. Cost Efficiency

In terms of capital and operational costs, TES can be highly competitive, especially for heating and cooling applications. Compared to electrochemical energy storage, TES often has a lower levelised cost of storage due to cheaper materials and a longer lifecycle. When integrated with renewable energy systems, TES can help reduce overall energy costs by providing an effective means for load shifting and managing energy peaks, which reduces the reliance on costly fossil-fuel-based peaking power plants.

7. Environmental Benefits

TES contributes to environmental sustainability by enhancing the efficiency of renewable energy use and reducing waste heat emissions. By storing excess thermal energy that would otherwise be lost, TES helps in reducing greenhouse gas emissions. Additionally, TES systems integrated with industrial processes can capture and reuse waste heat, thus improving the overall efficiency of energy use in sectors that are typically high in emissions.

Cons

While Thermal Energy Storage (TES) offers several benefits, it also faces some significant challenges and limitations, particularly when evaluated for its role in renewable energy storage and conversion. Below, we discuss some of the main disadvantages of TES, which can affect its feasibility and efficiency in different applications.

1. Low Technological Readiness Level (TRL) for Certain Systems

A major drawback of TES is that some of its most advanced configurations, such as high-temperature storage systems using molten salts or integrating with Organic Rankine Cycle (ORC) systems, have a relatively low Technological Readiness Level (TRL). This means that while promising, these technologies are often still in the pilot or prototype stage, requiring further research and development before they can be widely deployed. The lack of established, large-scale commercial systems can limit investor confidence and slow down the adoption of TES technologies in energy markets.

2. Low Round-Trip Efficiency (RTE) Due to Conversion Losses

TES systems suffer from relatively low round-trip efficiency, especially when the stored thermal energy needs to be converted back into electricity. Processes like the Organic Rankine Cycle (ORC) inherently introduce significant energy losses. As a result, the round-trip efficiency for TES is typically lower compared to other energy storage methods, such as batteries. For example, converting renewable electricity to heat and back to electricity often results in efficiency losses of 50% or more. These losses are particularly pronounced in sensible heat storage systems where heat dissipation can reduce overall efficiency. Furthermore, the thermal conductivity of storage materials can impact the rate at which energy can be stored and retrieved, with low thermal conductivity materials often resulting in slower response times.

3. System Complexity and Operational Challenges

The integration of TES systems, especially those that use high-temperature or multi-phase materials, can be complex and costly. Systems that involve molten salts or phase change materials (PCMs) require advanced thermal management and precise control of operating conditions, adding layers of complexity to their design and maintenance. Furthermore, integrating TES with electricity production processes, like ORC units, requires careful balancing of thermal cycles, which adds to operational challenges and may necessitate specialised skills that aren't as readily available in the current workforce.

4. High Capital Costs for High-Temperature Systems

While TES can be cost-effective in specific use cases, the initial capital expenditure for high-temperature storage solutions is often substantial. Technologies such as molten salt storage or those utilising advanced insulation materials demand a significant investment in both infrastructure and specialised equipment. This high upfront cost can deter stakeholders, particularly in smaller or distributed energy systems where financial flexibility is limited. Compared to electrochemical batteries, the cost per unit of energy stored can be higher, particularly when including the expense of converting heat back to electricity (Zhang et al., 2016).

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5. Thermal Losses Over Time

TES systems are susceptible to thermal losses during storage, especially when operating over extended periods. These thermal losses are mainly relevant for **Sensible Heat storage**, which relies on storing energy by changing the temperature of a material (e.g., water or rocks). Despite advancements in insulation technologies, thermal energy inevitably dissipates over time, reducing the effective energy available for later use. These losses are **less significant in Latent Heat Storage (LHS) and Thermochemical Energy Storage (TCHES)**, which involve storing energy in phase changes or chemical reactions, both of which inherently minimise thermal losses over time. These losses are particularly challenging in systems designed to store energy over days or weeks, as maintaining the high temperatures necessary for efficient operation can prove difficult.

6. Material Durability and Degradation

Repeated thermal cycling can lead to the degradation of materials used in TES systems. Molten salts, for example, can be corrosive, and over time, they may degrade storage tanks and piping, necessitating frequent maintenance or material replacement. Similarly, phase change materials (PCMs) can suffer from reduced performance after multiple cycles, affecting both the efficiency and the cost-effectiveness of the system. Such durability issues contribute to increased maintenance costs and can impact the overall lifecycle of TES systems.

7. Space Requirements

TES systems, especially those intended for large-scale energy storage, often require substantial physical space. Storing large quantities of thermal energy, whether as hot water, molten salt, or another medium, necessitates sizable tanks or other containment structures. This requirement can be a limiting factor in urban or densely populated areas where space is at a premium, thus making TES less feasible for some residential or commercial applications. In contrast, battery systems offer a more compact solution for equivalent energy storage.

8. Limited Suitability for Electricity-Only Applications

TES is most effective when the stored thermal energy can be used directly for heating or cooling. However, in scenarios where electricity is the desired output, the low efficiency of converting stored heat back into electricity becomes a significant disadvantage. This limits the applicability of TES in grid-scale electricity storage compared to batteries, which can store and discharge electricity more directly and with fewer losses. As a result, TES is often better suited for hybrid applications rather than serving as a standalone solution for electrical energy storage

11.7.2 Deployed TES systems

There are multiple TES systems deployed all over the World, however most of them are not serving the purpose of electrical energy storage. The most common implementation of RES coupled with TES systems including a heat to electricity cycle are CSP plants.

Concentrated Solar Power (CSP) Plants with TES in Europe:

1. [Andasol 1 Power Plants](#),⁴⁰⁵ Spain
 - One of the first commercial-scale CSP plants in Europe, completed in 2008
 - Uses 28,500 tons of molten salt in 2 tanks, 1,010 MWh capacity.
 - Nominal Turbine capacity of 50 MW with steam rankine power cycle
 - Provides up to 7.5 hours of thermal energy storage
2. [Gemasolar Thermosolar Plant](#)⁴⁰⁶, Spain, 2011
 - Thermal storage capacity: 670 MWh
 - Nominal Turbine capacity of 20 MW with steam rankine power cycle
 - [Thermal cycle efficiency: 40%](#)⁴⁰⁷
 - Able to provide up to 15 hours of full-load storage
3. Noor III CSP Plant, Morocco
 - 150 MW parabolic trough CSP plant

- Two-tank molten salt TES system
- Provides up to 7 hours of storage capacity

4. Crescent Dunes Solar Energy Project, USA

- 110 MW CSP tower plant with molten salt TES
- Able to store up to 10 hours of thermal energy

Other than CSP

Renewable Energy Integration with TES in Europe:

1. [Vatajankoski Thermal Storage, Finland](#) ⁴⁰⁸

- 8 MWh sensible heat storage facility using sand as material
- overall efficiency of approximately 60–70%
- provides heat for the district heating network

2. ENERSTORE Project, Germany

- Demonstrating hybrid TES with molten salts and PCMs
- Coupled with a 1.5 MW solar thermal plant
- Targets 8-12 hours of storage capacity

11.7.3 WICE index

Our scores reflect an average of the TES technology considering pros and cons of the three branches of the TES domain.

1. Energy Density

The energy density of TES depends on the specific storage method used. Sensible heat storage, using media such as water or rocks, has an energy density ranging from 10-100 kWh/m³, which is significantly lower compared to lithium-ion batteries (100-265Wh/kg). Latent heat storage, using Phase Change Materials (PCMs), offers moderately higher energy densities, but still falls short of batteries. Thermochemical energy storage, which involves reversible chemical reactions, holds promise for higher energy densities but is still in the research phase. Overall, TES scores low on energy density due to its focus on bulk, long-duration storage rather than compact energy storage.

Score: 30

2. Energy Retention Period

TES excels in retaining energy over long periods with minimal losses, especially in latent and thermochemical storage systems. Sensible heat systems, however, are more susceptible to thermal losses, which makes them less efficient for prolonged storage compared to latent or chemical methods. In this category, TES performs better than many other storage systems in terms of duration, although efficiency losses can occur over extended periods.

Score: 60

3. Lifetime and Life Cycles

The lifetime of TES systems can be quite extensive, depending on the specific technology employed. **Sensible heat storage** systems, such as those using molten salts or water, can have lifetimes of over 30 years, given their simple and robust construction with minimal moving parts. **Latent heat systems** using PCMs also have long lifetimes, although their performance can degrade over time with repeated phase transitions. **Thermochemical storage** systems are less mature, and their longevity is still being evaluated, but they promise extended operational periods due to the chemical nature of their storage process. Overall, TES has a longer lifetime compared to many battery technologies, which typically require replacement after several thousand cycles.

Score: 75

4. Round-Trip Efficiency (RTE)

TES has relatively low round-trip efficiency, primarily because of the conversion losses associated with transforming thermal energy back into electricity. Sensible heat systems, for example, often achieve efficiencies in the range of 40-60% with a much lower electrical efficiency considering conversion systems like ORC and others. Latent and thermochemical storage systems can achieve slightly higher efficiencies, but losses during charging and discharging phases remain a challenge. When compared to lithium-ion batteries, which have an RTE of 85-95%, TES systems are notably less efficient in scenarios requiring conversion back to electricity.

Score: 20

5. Technological Maturity (TRL)

The technological maturity of Thermal Energy Storage (TES) systems varies significantly across different types of storage methods, but overall, TES can be evaluated with a **maturity score of around 60 out of 100** when compared to the technological readiness of lithium-ion batteries, which are widely considered to be at the forefront of energy storage technology. **Sensible Heat Storage (SHS)** is the most mature TES technology, particularly when used with water or molten salts in Concentrated Solar Power (CSP) plants, contributing to its relatively high score. **Latent**

Heat Storage (LHS), using phase-change materials, is moderately mature, but still requires further optimization for broader commercial use, contributing to a slightly lower score. **Thermochemical Heat Storage (TCHS)**, despite its high theoretical energy density and potential, remains largely at the experimental or pilot stage, significantly lowering the overall maturity score of TES as a whole. The integration of TES into renewable energy systems is promising, but continued research and development are necessary to bring its technological maturity on par with more established technologies like lithium-ion batteries. For distributed storage applications focusing on renewable energy integration, the **maturity score of TES systems is approximately 50 out of 100**, indicating that while there is potential, significant technological development is still needed to match the readiness of more mature energy storage technologies.

Score: 50

6. Capital Expenditure (CAPEX)

While lithium-ion batteries typically have CAPEX costs (as low as [133€/kWh](#) in 2024 in Europe in average), TES systems generally show higher overall CAPEX figures when accounting for the complete heat-to-power conversion system ([222 €/kWh in 2024 according to BloombergNEF](#)). This higher cost structure primarily stems from the additional infrastructure required for TES, including heat exchangers, turbines, and thermal storage materials. The conversion efficiency losses in the heat-to-power cycle necessitate larger storage capacity and more complex equipment compared to the direct electrical storage of lithium batteries, driving up the capital expenditure. However, it's important to note that TES systems often demonstrate longer lifespans and lower degradation rates than lithium batteries, which can partially offset the higher initial investment over the system's lifetime.

Score: 30

7. Operational Expenditure (OPEX)

Operational costs for TES systems are generally low, particularly for sensible heat systems, which have minimal moving parts and use abundant, low-cost materials. The OPEX for thermochemical and latent heat systems can be higher due to maintenance requirements for handling reactive chemicals or ensuring effective phase transitions. On average, TES has an advantage over electrochemical storage in terms of operational costs, especially for long-term applications.

Score: 70

8. Environmental Impact

TES is often considered environmentally friendly, particularly when using materials like water or non-toxic PCMs. Sensible and latent heat systems have lower environmental impacts compared to lithium-ion batteries, mainly due to the lack of toxic materials and the recyclability of

components. Thermochemical systems can present challenges related to chemical handling and disposal but still generally have a smaller footprint than batteries. Overall, TES ranks well in this category for its sustainability.

Score: 80

9. Scalability

TES systems are highly scalable, which makes them suitable for a wide range of applications, from residential heating to industrial-scale energy storage. Sensible heat systems, in particular, are scalable for both small and large installations, such as district heating or CSP plants. Thermochemical systems, while promising, are still being scaled up and require further development before they can be used widely. Overall, TES shows good potential for scalability, particularly for large-scale applications.

Score: 70

Using the weights provided, we calculate the weighted scores for each parameter:

Parameter	Weight	Score	Weighted score
Energy Density	0.1	30	3
Energy Retention Period	0.1	60	6
Lifetime and Life Cycles	0.1	75	7.5
Round-Trip Efficiency (RTE)	0.15	20	3
Technological Maturity (TRL)	0.2	50	10
Capital Expenditure (CAPEX)	0.1	30	3
Operational Expenditure (OPEX)	0.1	70	7
Environmental Impact	0.1	80	8
Scalability	0.05	70	3.5
Total	1		51,00

Conclusion

Thermal Energy Storage systems receive a WICE score of 51 which places them among the lower-ranked technologies in our comparative study. The main reasons for this outcome are the high capital expenditure, low round-trip efficiency, and moderate technological readiness level, which collectively limit their current feasibility for efficient electrical energy storage. However, with advancements in technology, particularly in improving round-trip efficiency and reducing costs, TES could become a viable solution for electrical energy storage in the future. Until then, TES remains an excellent option for industrial applications and district heating, where its strengths in scalability, long lifetimes, and environmental benefits can be fully leveraged. With further research and development, TES could play an increasingly important role in supporting sustainable and flexible energy systems.

Impact potential of technology

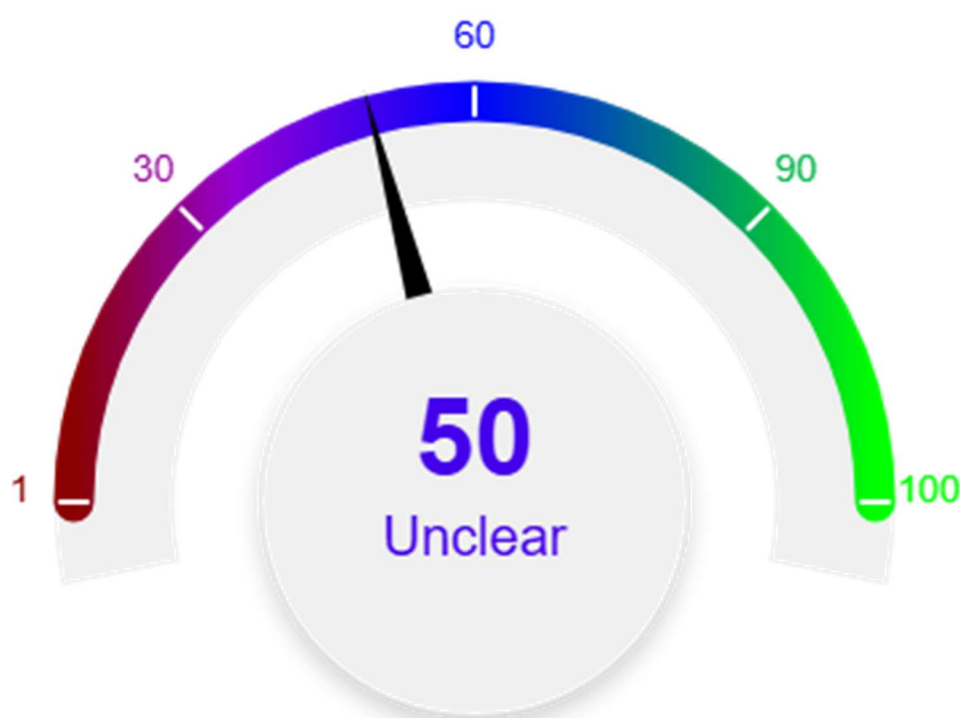


Figure 11.5

12. Comparison of solutions

The preceding chapters have delved into the intricacies of various energy storage technologies, each presenting a unique set of advantages and challenges. This chapter aims to provide a comprehensive comparison of these solutions, highlighting their key characteristics, performance metrics, and potential applications. The comparison focuses on the ten technologies discussed in Chapters 2 through 11, offering a holistic view of the energy storage landscape and aiding in informed decision-making for future energy projects.

Gravity Storage (GS)

- **Advantages:** Utilizes abundant materials, boasts a long lifespan, and offers high scalability, particularly for surface-based systems. It is environmentally friendly with minimal emissions during operation and can repurpose existing infrastructure like abandoned mineshafts.
- **Disadvantages:** High initial capital expenditure (CAPEX) is required, and energy density is relatively low compared to chemical batteries. Surface-based systems can have a significant land footprint and visual impact.
- **Applications:** Suitable for long-duration energy storage, grid stabilization, peak shaving, and renewable energy integration, especially in areas with suitable geological formations or available land.

Compressed Air Energy Storage (CAES)

- **Advantages:** Offers large storage capacity, long discharge duration, and is suitable for grid-scale applications. It can be integrated with renewable energy sources and provide backup power during emergencies.
- **Disadvantages:** Efficiency can be a challenge, especially in diabatic systems that rely on fossil fuels for reheating. It also requires specific geological formations for underground storage, limiting its geographical flexibility.
- **Applications:** Ideal for large-scale energy storage, grid stabilization, renewable energy integration, and industrial applications requiring high energy capacity and long discharge durations.

Liquid Air Energy Storage (LAES)

- **Advantages:** Provides high energy density, scalability, and long lifespan. It utilizes abundant air as the storage medium and can be integrated with industrial processes for waste heat recovery.
- **Disadvantages:** Round-trip efficiency is lower compared to some other technologies, and the initial capital cost can be high due to the need for cryogenic equipment.

- **Applications:** Suitable for medium to large-scale energy storage, grid balancing, peak shaving, and renewable energy integration, particularly in areas where geographical constraints limit other options.

Flywheel Energy Storage (FES)

- **Advantages:** Offers rapid response times, high power density, long cycle life, and high efficiency. It is environmentally friendly and has a wide operating temperature range.
- **Disadvantages:** Limited energy capacity restricts its use to short-duration applications, and the initial capital cost can be high due to the use of advanced materials and precision engineering.
- **Applications:** Ideal for grid stabilization, frequency regulation, uninterruptible power supplies (UPS), and applications requiring quick bursts of energy.

Hydrogen Energy Storage (H2ES)

- **Advantages:** High energy density, versatility in applications, and potential for long-duration and seasonal storage. It can be produced from renewable sources, offering a clean energy carrier.
- **Disadvantages:** Efficiency losses during production, storage, and conversion processes. It also requires significant infrastructure investments and poses safety challenges due to its flammability.
- **Applications:** Suitable for large-scale energy storage, grid balancing, renewable energy integration, transportation, and industrial applications.

Battery Energy Storage (BES) - Alternatives to Lithium

- **Advantages:** Offer potential for lower costs, improved safety, and reduced reliance on critical materials compared to lithium-ion batteries. They can be tailored to specific applications and offer environmental benefits through easier recyclability.
- **Disadvantages:** Many alternative battery chemistries are still in developmental stages, with lower energy densities, shorter lifespans, or efficiency issues compared to lithium-ion.
- **Applications:** Diverse applications ranging from portable electronics to grid-scale energy storage, depending on the specific battery chemistry and its performance characteristics.

Flow Batteries (VRFB)

- **Advantages:** Highly scalable, long lifespan, safe operation, and deep discharge capability. They are suitable for large-scale energy storage and offer flexibility in system design.
- **Disadvantages:** Low energy density compared to solid-state batteries, high initial costs due to the use of vanadium, and system complexity requiring pumps and flow management.

- **Applications:** Ideal for long-duration energy storage, grid integration of renewable energy sources, peak shaving, and load leveling.

Superconducting Magnetic Energy Storage (SMES)

- **Advantages:** Instantaneous response times, high efficiency, and excellent power quality improvement. It is suitable for grid stabilization and mitigating power disturbances.
- **Disadvantages:** High capital costs due to expensive superconducting materials and cryogenic cooling requirements. Limited energy capacity restricts its use to short-duration applications.
- **Applications:** Specialized applications requiring rapid power delivery and high efficiency, such as grid stabilization, power quality improvement, and sensitive industrial processes.

Ultracapacitors (UC)

- **Advantages:** Fast charging and discharging, high power density, long lifespan, wide operating temperature range, and environmental friendliness.
- **Disadvantages:** Low energy density compared to batteries, higher self-discharge rates, and higher cost per watt-hour of energy stored.
- **Applications:** Suitable for applications requiring rapid energy delivery and absorption, such as regenerative braking, UPS, and grid stabilization.

Thermal Energy Storage (TES)

- **Advantages:** Versatile in storing energy from various sources, enhances grid stability, offers high efficiency when combined with Organic Rankine Cycle (ORC), and provides long-duration storage capabilities.
- **Disadvantages:** Conversion efficiency limitations, high capital costs for high-temperature systems and ORC (and other electrical conversion) units, thermal losses over time, and potential material durability issues.
- **Applications:** Residential and commercial heating and cooling, industrial process heat recovery, concentrated solar power plants.

Our WICE score provides a generic comparison of solutions based on 9 parameters. We assessed individual scores for each technology and assigned weights that we consider reasonable for renewable energy integration and distributed energy storage.

After a diligent review of research literature by the StoreMore consortium, we were unable to find a recent comprehensive study incorporating all the selected energy storage technologies.

The summary table below presents our findings of the weighted scores for each technology:

Parameter	Weight	Lithium	Gravity	CAES	LAES	FES	H2ES	VRFB	SMES	UCES	TES
Energy Density	10%	5	2	2	2	3	10	3	1	2	3
Energy Retention Period	10%	5	10	5	8	5	8	10	3	2,5	6
Lifetime and Life Cycles	10%	5	10	7	6	10	7	10	8	9	7,5
Round-Trip Efficiency (RTE)	15%	7,5	6	4,5	4,5	7,5	4,5	6	7,5	12	3
Technological Maturity (TRL)	20%	20	10	6	14	9	12	8	14	15	10
Capital Expenditure (CAPEX)	10%	5	3	4	4	3	2	3,5	1	3	2
Operational Expenditure (OPEX)	10%	5	7	6	6	8	3	8	6	8	7
Environmental Impact	10%	5	9	7	8	9	6	9	6	7	8
Scalability	5%	2,5	2,5	1	3,5	2,5	4,5	2,75	2	2	3,5
Total	100%	60	59,5	42,5	56	57	57	60,75	48,5	60,5	51

Table 12.1 Summary table of weighted scores for storage technologies. Best performers in each category are highlighted

The five best-performing technologies overall are **Gravity Storage**, **Flywheel Energy Storage**, **Hydrogen Storage** from the chemical energy storage domain, **Vanadium Redox Flow Batteries**, and **Ultracapacitor/Supercapacitor** energy storage. Each of these solutions has different strengths and weaknesses and different optimal applications, therefore offering the potential for a flexible portfolio of distributed energy storage and hybrid applications. The StoreMore consortium will research these technologies further in the Comprehensive Catalogue of Sustainable Energy Storage Solutions.

Conclusion: Embracing a Multifaceted Future in Energy Storage

In an era defined by the rapid expansion of renewable energy and the pressing need for grid resilience, no single storage technology can adequately address the diverse challenges of modern energy systems. Embracing a multifaceted future in energy storage means integrating complementary solutions that offer long-duration capacity, rapid response, scalability, and minimal environmental impact. This holistic approach enables us to harness the unique strengths of various technologies, ensuring that energy can be stored efficiently and dispatched effectively to meet fluctuating demands. The strategic selection of technologies—Gravity Storage, Flywheel Energy Storage, Hydrogen-based storage, Vanadium Redox Flow Batteries, and Ultracapacitors—reflects our commitment to developing a robust and adaptable energy infrastructure that not only supports the integration of renewables but also paves the way toward a sustainable, low-carbon future.

After a comprehensive evaluation of ten energy storage technologies, our analysis has converged on a portfolio of five key solutions: Gravity Storage, Flywheel Energy Storage, Hydrogen-based storage, Vanadium Redox Flow Batteries, and Ultracapacitors. This selection reflects a careful balance between technical performance, scalability, environmental impact, and economic feasibility to support a diverse range of grid applications and renewable integration challenges.

During the review process, we assessed the merits and limitations of each technology, considering factors such as energy density, round-trip efficiency, operational lifespan, and the maturity of the technology. Although all ten options offer unique benefits, these five emerged as the most promising candidates to address the multifaceted needs of modern energy systems. By narrowing our focus, we aim to harness their complementary strengths to build a resilient, adaptive, and low-carbon energy infrastructure.

Gravity Storage is recognized for its potential to provide long-duration energy storage with minimal operational emissions. Leveraging the fundamental physics of gravitational potential, this technology can store energy over extended periods, making it particularly suited for balancing seasonal variations and integrating intermittent renewable sources. Its scalability, especially when implemented in surface-based or repurposed underground systems, positions it as a reliable backbone for grid stability, even though its energy density is lower compared to some chemical solutions.

Flywheel Energy Storage stands out due to its rapid response capabilities and high round-trip efficiency. Flywheels excel in applications that require immediate power delivery, such as

frequency regulation and transient grid support. Their ability to absorb and release energy within seconds makes them ideal for maintaining grid stability during sudden fluctuations. Despite their relatively lower energy capacity, flywheels contribute critical high-power, short-duration support, complementing other long-duration storage options.

Hydrogen-based storage offers a versatile approach by converting surplus renewable energy into hydrogen via electrolysis. This stored hydrogen can then be used directly as a fuel or reconverted into electricity, serving as both a seasonal storage solution and a cross-sector energy carrier. Although hydrogen systems face challenges regarding efficiency and infrastructure requirements, their flexibility in meeting diverse energy needs—from transportation to industrial applications—renders them a strategic component of a future low-carbon economy.

Vanadium Redox Flow Batteries bring a unique combination of scalability, safety, and durability. Their ability to decouple power and energy capacities enables flexible sizing for various applications. With a long operational life and deep discharge capability, vanadium systems provide reliable, medium to long-duration storage while mitigating some of the environmental concerns associated with conventional battery chemistries. This makes them an attractive option for large-scale grid applications where energy storage and dispatch are critical.

Ultracapacitors complement the portfolio with their capability for instantaneous energy delivery. Although they have lower energy density compared to chemical batteries, their extremely high power density and fast charge-discharge cycles make them invaluable for applications requiring burst power, such as voltage stabilization and peak shaving. The robustness and long cycle life of ultracapacitors enhance overall system reliability and provide rapid-response support where needed.

Collectively, these five technologies address a spectrum of grid challenges. Gravity Storage and Hydrogen offer long-term, seasonal support; Flywheels and Ultracapacitors deliver rapid, high-power bursts to manage transient disturbances; while Vanadium Redox Flow Batteries bridge the gap with scalable, reliable medium-duration storage. By combining these solutions, stakeholders can design a tailored, hybrid storage system that not only improves the reliability and efficiency of renewable energy integration but also mitigates the risks associated with reliance on a single technology.

In summary, this diversified approach is critical for modern energy systems. It ensures that energy storage solutions are robust enough to handle the variable nature of renewable energy, adaptable to specific regional and operational needs, and capable of supporting the transition toward a more sustainable and resilient energy future.

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Authors and peer reviewers

The Energy Outlook Study is prepared by:

Attila Fodor, PhD – University of Pannonia

Attila Magyar, PhD. – University of Pannonia

Endre Domokos, PhD – University of Pannonia

Ambrož Bogataj - Elektro Gorenjska d.d.

Blanka Odlazek – BSC Kranj, Regional Development Agency of Gorenjska

Zdeněk Hušek - ICUK - Innovation Center of the Ústí Region

Lukáš Eršil - ICUK - Innovation Center of the Ústí Region

Marek Hart - ICUK - Innovation Center of the Ústí Region

Jasmina Bešić - Center for Energy, Energy Efficiency and Environment

Tímea Bartucz – Békéscsaba Energia ESCO Kft.

Viktor Szilágyi – Békéscsaba Energia ESCO Kft.

Jenő Szécsi – Békéscsaba Energia ESCO Kft.

Peer reviewers

Hrvoje Mikulčić, Petar Lonić, - University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

Bane Popadic - University of Novi Sad Faculty of Technical Sciences

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¹²⁹ HHV: Includes the energy released when the water vapor produced during combustion condenses back into liquid water. This is a theoretical maximum.

¹³⁰ LHV: Does not include the condensation energy, representing the actual usable energy released.

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