

Interreg Danube StoreMore Catalogue of Sustainable Energy Storage Solutions (CSESS)

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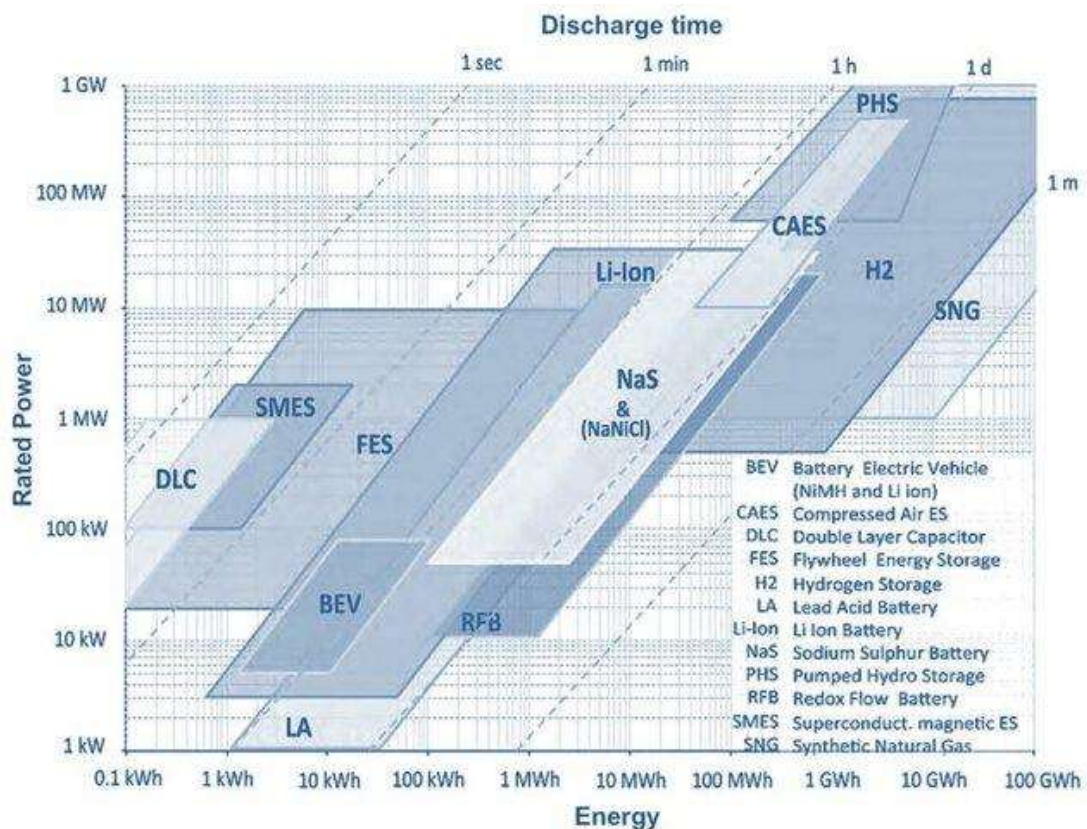
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Executive Summary

The Catalogue of Sustainable Energy Storage Solutions (CSESS) has been developed as part of the Interreg Danube StoreMore project by CTU UCEEB as a contractor for ICUK. Its primary goal is to offer a comprehensive resource for stakeholders seeking efficient, sustainable, and financially viable energy storage solutions. The catalogue evaluates five advanced energy storage technologies: Gravity-Based Energy Storage (GES), Flywheel Energy Storage (FESS), Hydrogen Energy Storage (HES), Vanadium Redox Flow Batteries (VRFBs), and Ultracapacitors (Supercapacitors) and one baseline technology – battery energy storage systems (BESS). Each technology is analyzed across technical, financial, environmental, and stakeholder relevance dimensions, providing guidance for investors, and policymakers.



The analytical framework employs a multi-dimensional evaluation combining technical feasibility, financial viability, environmental sustainability, and stakeholder input. Data sources include cooperation with technology partners, publicly available studies (e.g., IEA, IRENA, BloombergNEF, PNNL), life cycle and environmental databases (e.g., Ecoinvent, GREET), and an internal technical knowledge base.

Technology Overviews

Gravity-Based Energy Storage (GES): GES converts surplus electricity into potential energy by lifting masses, which are later lowered to regenerate electricity. Three configurations are examined: tower-based, shaft-based, and inclined-plane systems. GES demonstrates high round-trip efficiencies (80-90%), long lifespans (>50,000 cycles), and scalability from tens of MWh to GWh, with CAPEX ranging from \$130 to \$220 per kWh. While initial capital costs are high and suitable sites are limited, reuse of abandoned mines presents significant opportunities. Technology suffers from quite low TRL.

Flywheel Energy Storage (FESS): FESS stores energy as kinetic energy in rapidly spinning rotors. Flywheels excel in short-duration, high-power applications like grid stabilization and frequency regulation, with rapid response times (milliseconds), high efficiencies (85-95%), and virtually unlimited cycle life. Although they offer lower energy density and higher CAPEX per kWh (typically \$1,000-3,000), their long lifespan and low OPEX make them cost-effective for specific niche high-cycle, short-duration use cases.

Hydrogen Energy Storage (HES): Hydrogen provides a highly flexible medium for long-duration and seasonal storage via power-to-gas-to-power (P2G2P) systems. Technologies covered include electrolyzers (AEL, PEM, AEM), multiple storage methods (compressed gas, metal hydrides), and reconversion options (fuel cells, gas turbines, CHP units). While current system round-trip efficiencies remain moderate (20-30%), hydrogen holds long-term strategic potential for decarbonization across multiple sectors as an energy vector and key enabling technology for some

specific niche areas and industries. CAPEX for electrolyzers is estimated at €1,200-1,800/kWe, with high storage costs (e.g., €540-720/kg H₂ for pressure vessels). The economics of green hydrogen is currently debatable as it was mostly overblown in the past 5 years and expectations are not being met.

Vanadium Redox Flow Batteries (VRFBs): VRFBs offer excellent scalability, decoupling power and energy capacities. They are ideal for medium-duration storage (4-10 hours), providing stable performance over tens of thousands of cycles without capacity degradation. While their energy density is lower (20-35 Wh/L), their safety, recyclability (~100% vanadium recovery), and predictable long-term costs position VRFBs as strong candidates for renewable integration. CAPEX estimates range from \$400-600/kWh, with LCOS between \$100-150/MWh.

Ultracapacitors (Supercapacitors): Ultracapacitors provide rapid charge-discharge capability and extremely long cycle life (millions of cycles). They are best suited for grid frequency regulation, hybrid storage systems, and high-power industrial applications. Although their energy density is much lower than batteries, ongoing material advances (e.g., graphene electrodes) are improving storage capacity. Their lack of toxic materials and recyclability make them environmentally favorable.

Policy Implications The CSESS highlights that no single technology fits all scenarios. Instead, a diversified portfolio combining short-duration (flywheels, ultracapacitors), medium-duration (VRFBs), and long-duration solutions (hydrogen, gravity storage) will best support renewable energy expansion for the civilization. Policymakers are encouraged to develop supportive regulatory frameworks, de-risk investments, and create regional innovation ecosystems that leverage the unique strengths of each technology rather than benchmarking everything based on a single number or a few. Every technology has its own place but none is omnipotent. **The catalogue serves as a data-driven decision-support tool for energy storage investments and policy across the Danube Region and beyond.**



1 Introduction

1.1 Purpose of the Catalogue

This document is designed to serve as a comprehensive resource for stakeholders seeking practical, efficient, and environmentally responsible energy storage options. By focusing on five pivotal technologies—Gravity-Based Storage, Flywheel Energy Storage, Hydrogen Storage, Vanadium Redox Flow Batteries, and Ultracapacitors—the catalogue provides an in-depth evaluation of their financial, environmental, and technical dimensions. This targeted approach ensures stakeholders can access actionable insights tailored to their specific needs, facilitating informed decision-making in a rapidly evolving energy landscape.

This catalogue is integral to achieving the StoreMore project's broader objectives, which include promoting the integration of renewable energy sources and addressing the challenges posed by their inherent intermittency. By analysing and documenting real-world case studies, stakeholder perspectives, and innovative solutions, the CSESS aspires to bridge the gap between cutting-edge energy storage technologies and their practical deployment. Moreover, it highlights opportunities for sustainable investments and identifies pathways to overcome existing barriers, such as high costs and regulatory hurdles.

As a forward-looking tool, the CSESS also emphasises adaptability and scalability, recognising the diverse energy needs across the Danube Region and beyond. It is not merely a snapshot of current technologies but a dynamic platform designed to evolve with advancements in the field. By incorporating mechanisms for updates and user feedback, the catalogue aims to remain a relevant and reliable guide for energy planners, policymakers, and industry leaders as they navigate the transition towards sustainable energy systems.

1.2 Scope and Methodology

The Catalogue focuses on evaluating five cutting-edge energy storage technologies—Gravity-Based Storage, Flywheel Energy Storage, Hydrogen Storage, Vanadium Redox Flow Batteries, and Ultracapacitors. These solutions were selected based on their potential to address the critical needs of renewable energy source (RES) operators and investors, the primary audience for this catalogue. By prioritising technologies that balance economic feasibility, environmental sustainability, and technical practicality, the CSESS aims to guide stakeholders in implementing energy storage systems that enhance grid stability, optimise renewable energy integration, and deliver long-term returns on investment.

This catalogue also serves as a resource for policymakers, the secondary audience, offering insights into the practical applications and benefits of these energy storage technologies. While technical and academic details are minimised to maintain accessibility, the analysis remains robust and grounded in real-world data. The geographical focus of the study is the Danube Region, encompassing diverse energy needs and socio-economic contexts. By concentrating on scalable and adaptable solutions, the CSESS addresses both regional and broader challenges in achieving a sustainable energy transition. This targeted scope ensures the catalogue is directly relevant to those making critical investment and operational decisions in the renewable energy sector.

1.2.1 Technology selection

The **Gravity-Based Storage** technology is a possible black swan choice for the catalogue due to its novelty and future potential. Its scalability, deployability on almost any location (on surface option) long-duration storage potential, and minimal reliance on rare materials make this technology too tempting not to include in our catalogue. By utilising gravity to store energy in elevated masses, this solution provides an efficient and environmentally friendly alternative to traditional batteries. Its adaptability for various settings, such as repurposing abandoned

mineshfts or constructing surface-based structures, makes it particularly relevant for regions with diverse geographical features like the Danube Region. This technology aligns well with the goals of enhancing renewable energy integration while minimising environmental impact.

Flywheel Energy Storage was selected for its unparalleled ability to provide instantaneous energy delivery and stabilise grid performance. Flywheels store energy in the rotational motion of a high-speed rotor, offering a durable and efficient solution for short-duration applications such as frequency regulation and power quality improvements. This technology is highly sustainable, with long lifespans and recyclable components, making it a suitable choice for RES operators seeking rapid-response storage options without significant environmental drawbacks.

Hydrogen Storage represents a versatile energy carrier with broad applications across electricity, transportation, and industry. Produced through renewable energy-driven electrolysis, hydrogen can be stored for extended periods and used to address both short- and long-term energy demands. Its potential to decarbonise multiple sectors and serve as a medium for surplus renewable energy makes it a cornerstone technology for a sustainable energy future. The selection of hydrogen highlights its role in mitigating variability in renewable energy generation while fostering resilience and energy independence.

Vanadium Redox Flow Batteries (VRFBs) are included in the catalogue for their scalability and durability, especially in large-scale grid applications. By storing energy in liquid electrolytes, VRFBs enable flexible storage capacities and offer extended lifespans with minimal degradation. Their ability to deliver consistent performance over tens of thousands of cycles ensures cost-effectiveness and reliability for operators. Additionally, VRFBs use non-flammable and recyclable materials, aligning with the project's sustainability goals and providing a practical alternative to conventional lithium-ion batteries.

Ultracapacitors (also known as supercapacitors) were selected for inclusion in the catalogue due to their unique ability to provide rapid charge and discharge cycles, making them highly suitable for applications requiring immediate energy delivery. Unlike traditional batteries,

ultracapacitors store energy electrostatically rather than chemically, allowing them to achieve millions of charge-discharge cycles with minimal degradation. This durability makes them a cost-effective solution for applications where longevity and reliability are crucial. Their high power density enables them to support grid frequency regulation, bridge power gaps in renewable energy integration, and enhance the efficiency of hybrid storage systems. While their energy density is lower than that of conventional batteries, ongoing advancements in material science, such as graphene-based electrodes, are steadily improving their storage capacity.

A key advantage of ultracapacitors is their environmental sustainability. They contain no toxic heavy metals, making them easier to recycle and reducing the environmental impact compared to conventional battery technologies. Additionally, their ability to function in extreme temperatures without significant efficiency losses makes them well-suited for deployment in harsh climatic conditions. This characteristic enhances their relevance for the Danube Region, where diverse climate zones require adaptable storage solutions. Their use in hybrid storage systems, where they complement batteries by handling high-power bursts, demonstrates their potential in reducing wear on traditional storage technologies, ultimately improving the lifecycle performance of the entire energy system.

The inclusion of ultracapacitors in the **CSESS** reflects their growing importance in the energy storage landscape. While they may not be suitable for long-duration storage, their strengths in rapid energy response, durability, and environmental friendliness make them an essential part of the evolving storage ecosystem. Their ability to enhance grid stability, support industrial applications, and integrate seamlessly with renewable energy sources ensures that ultracapacitors will play a pivotal role in advancing energy resilience and sustainability in the Danube Region.

1.2.2 Methodology for data collection

The credibility and utility of the Catalogue of Sustainable Energy Storage Solutions (CSESS) rest on a robust and comprehensive methodology for data collection. To deliver accurate technical, financial, and environmental analyses, the catalogue draws on a diverse range of data sources and

approaches, ensuring its findings are both reliable and relevant. By combining inputs from technology partners, independent studies, industry events, and publicly available resources, this methodology establishes a balanced framework for evaluating each storage solution. Furthermore, the inclusion of stakeholder insights and advanced modelling ensures that the catalogue reflects practical realities and anticipates future trends. The following sections outline the core methods employed to gather, verify, and analyse data for the selected energy storage technologies.

1.2.2.1 Technology Partner Database and Cooperation

A key pillar of the data collection methodology is the establishment of a **Technology Partner Database**, fostering active cooperation with manufacturers, developers, and integrators of energy storage systems. This partnership-driven approach ensures access to high-quality, up-to-date data directly from the creators and operators of the selected technologies. By formalising relationships with key industry players, the catalogue benefits from first-hand insights into technical specifications, performance metrics, and deployment scenarios, thereby increasing its reliability and relevance. The formal document for the cooperation is the Cooperation Framework Agreement prepared by the StoreMore consortium during Period 2 of the project.

Through this database, technology partners are encouraged to share critical information, such as system designs, lifecycle data, and financial details, including CAPEX, OPEX, and maintenance costs. These contributions form the foundation of the catalogue's financial and technical analyses, offering stakeholders real-world, validated data to guide their decision-making. Regular data exchanges, facilitated through structured agreements, also ensure that the catalogue remains dynamic and up-to-date, accommodating advancements in technology and evolving market conditions.

To strengthen collaboration, the consortium can host periodic bilateral meetings and feedback sessions with its partners. Moreover, the database provides an avenue for technology partners to

showcase their innovations and establish credibility within the renewable energy sector. By fostering a collaborative environment, this approach ensures that the catalogue reflects the collective expertise of the energy storage community, while offering stakeholders an authoritative and practical resource.

1.2.2.2 Reference to Studies and Manufacturer Brochures

The catalogue draws extensively on publicly available studies and databases to ensure a robust foundation for its evaluations. Key sources include reports from organisations such as the [International Renewable Energy Agency \(IRENA\)](#), which provides detailed analyses of renewable energy technologies, and the [International Energy Agency \(IEA\)](#), whose [World Energy Outlook](#) and [Energy Storage Roadmap](#) offer insights into global trends and future scenarios. Additionally, the [BloombergNEF](#) platform is frequently referenced for its in-depth market analysis on the cost and performance of energy storage systems, particularly lithium-ion alternatives. Access to these comprehensive studies allows the catalogue to integrate globally recognised benchmarks and projections into its assessments.

For technical specifications and real-world performance data, the catalogue relies on databases such as [Battery 500](#), which compiles detailed comparisons of energy storage technologies, and [DOE Global Energy Storage Database](#), managed by the [US Department of Energy](#), which tracks deployments worldwide. These repositories provide access to information on project designs, capacity, and operational performance, helping to contextualise technology advancements within practical settings.

Manufacturer brochures serve as an additional source of specific system details. Companies like [Energy Vault](#), [Highview Power](#), and [Sumitomo Electric](#) offer publicly accessible materials outlining their gravity-based storage, liquid air systems, and VRFBs, respectively. These materials provide essential data on system design, efficiency, and scalability. However, to ensure objectivity, the information from these brochures is cross-validated with independent studies and case

reports from sources like [Fraunhofer Institute](#), which conducts neutral performance evaluations. This layered approach ensures the catalogue is both grounded in academic rigour and reflective of industry realities.

1.2.2.3 Stakeholder Surveys and Interviews

Building on the findings of the **Danube Region Stakeholder Map**, developed under Activity 1.1 of the StoreMore project, stakeholder surveys and interviews form a crucial component of the methodology. This foundational deliverable categorised stakeholders into three segments: those with installed storage capacity, those recognising the need for storage solutions, and those unaware of the need. These insights guide the targeted engagement of key actors such as renewable energy operators, municipalities, and private investors, ensuring the catalogue reflects real-world needs and priorities.

Surveys and interviews aim to collect detailed, qualitative data on stakeholder challenges, expectations, and experiences with energy storage. For example, renewable energy operators with installed storage systems are consulted on operational challenges like CAPEX and grid integration. Simultaneously, interviews with municipalities and private investors focus on perceived barriers, such as regulatory complexity and economic risks. This mixed-method approach captures the diverse perspectives across the Danube Region, ensuring a comprehensive understanding of the market landscape.

Using the **Stakeholder Map** ensures that outreach efforts are focused and effective. By engaging with identified groups such as industrial associations, equipment suppliers, and energy management companies, the project gains insights into their investment tendencies, expected returns, and technology preferences. This data informs the financial, environmental, and technical analyses of the catalogue, while also shaping its practical recommendations. The surveys further support future project activities, such as identifying sites for best-practice visits and recruiting testers for the RES optimisation tool, reinforcing the StoreMore project's overall impact.

1.2.2.4 Industry Conferences and Events

Engaging with industry conferences and events is essential for staying abreast of the latest developments in energy storage technologies and market dynamics. These gatherings offer unparalleled opportunities to connect with experts, innovators, and decision-makers, facilitating the exchange of knowledge and fostering collaborations that can enhance the quality and relevance of the catalogue.

In 2025, several key events in Europe and the Danube Region are particularly noteworthy:

- **Energy Storage Summit 2025**: Scheduled for 17–19 February 2025 in London, this summit is recognised as Europe's foremost event in the energy storage sector, bringing together over 2,000 stakeholders to explore challenges and opportunities in the journey towards net-zero emissions.
- **World Sustainable Energy Days 2025**: Taking place from 5–7 March 2025 in Wels, Austria, this conference focuses on energy efficiency and renewable energy, offering insights into policies, markets, and technologies that drive the energy transition.
- **WindEurope Annual Event 2025**: Set for 8–10 April 2025 in Copenhagen, Denmark, this event gathers industry leaders to discuss advancements in wind energy, including integration with storage solutions to enhance grid stability and efficiency.
- **Energy Storage Summit Central Eastern Europe**: Planned for 23–24 September 2025 in Warsaw, Poland, this summit focuses on the unique opportunities and challenges in the Central and Eastern European energy storage markets, making it highly relevant for stakeholders in the Danube Region.
- **Energy Storage Global Conference 2025**: Scheduled for 14–16 October 2025 in Brussels, Belgium, this conference offers the latest insights on energy storage policies, markets, technologies, and applications, providing a comprehensive overview of the global energy storage landscape.

Participating in these events will enable the project team to gather firsthand information on emerging technologies, regulatory frameworks, and market trends. Additionally, these platforms facilitate networking with potential technology partners and stakeholders, enriching the data collection process and ensuring the catalogue reflects the most current and relevant industry insights.

1.2.2.5 Publicly Available Data and Case Studies

Publicly available data and case studies provide a critical foundation for analysing energy storage technologies within the CSESS. These resources offer insights into real-world applications, operational challenges, and best practices, enabling a nuanced understanding of the performance and scalability of various storage systems. Key databases and repositories contribute validated data on technical, financial, and environmental aspects, making them indispensable for the catalogue's analysis and recommendations.

Among the most relevant data sources, the [DOE Global Energy Storage Database](#) stands out for its comprehensive collection of global storage projects, including project-level details on capacity, technology type, and location. The [IRENA Renewable Energy Statistics Database](#) is another invaluable resource, offering aggregated data on renewable energy generation and storage capacities. For European-specific insights, the [European Energy Storage Database \(EASE\)](#) from the European Association for Storage of Energy provides detailed case studies and market reports, focusing on advancements and deployments within the EU.

Case studies sourced from publicly available reports are particularly valuable for illustrating the practical applications and challenges of energy storage technologies. For example, the [Fraunhofer Institute](#) offers impartial evaluations of pilot projects, providing insights into the economic feasibility and environmental impact of storage systems. Similarly, the [Energy Transition Tracker](#) delivers region-specific case studies that highlight the integration of storage solutions into renewable energy projects. These case studies not only validate the catalogue's

analyses but also serve as examples for stakeholders exploring similar investments or deployments.

By combining data from these repositories and case studies, the CSESS ensures that its findings are grounded in practical experiences and supported by credible, publicly accessible evidence. These resources also allow for a dynamic and comparative evaluation, enhancing the catalogue's relevance and utility for its target audience.

1.2.2.6 Life Cycle and Environmental Databases

Life cycle and environmental databases play a crucial role in evaluating the sustainability of energy storage technologies for the CSESS. These databases provide scientifically validated data on material use, energy consumption, emissions, and waste across the lifecycle of energy storage systems. By leveraging these resources, the catalogue can assess the environmental impact of each technology from production to disposal, ensuring that sustainability considerations are integrated into decision-making.

One of the most widely used databases is [Ecoinvent](#), which offers comprehensive lifecycle inventory (LCI) data for various industries, including energy storage. Ecoinvent provides detailed insights into resource extraction, manufacturing processes, and end-of-life impacts, making it an essential tool for life cycle assessment (LCA) studies. Similarly, the [GREET \(Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation\) Model](#) developed by Argonne National Laboratory is highly relevant for analysing emissions and energy use associated with transportation-related storage technologies like hydrogen and battery systems.

For region-specific data, the [European Life Cycle Database \(ELCD\)](#) offers datasets aligned with European policies and standards, covering materials, energy production, and waste management relevant to storage technologies. The [US Life Cycle Inventory Database](#) complements these resources by providing a detailed inventory of energy and material flows for various energy systems, including batteries and fuel cells.

These databases are supplemented by tools such as [Simapro](#) and [GaBi](#), which offer user-friendly platforms for conducting LCAs based on comprehensive datasets. By integrating data from these sources, the catalogue can provide an accurate assessment of the environmental footprint of each energy storage technology, identifying areas for improvement and ensuring alignment with sustainability goals. These resources enable a data-driven approach to evaluating environmental impacts, strengthening the credibility and utility of the CSESS for its stakeholders.

To further enhance the environmental analysis, the involvement of external expertise from internationally recognised organisations can provide valuable insights and ensure credibility. Collaborating with renowned environmental protection groups such as the [World Wildlife Fund \(WWF\)](#), the [International Union for Conservation of Nature \(IUCN\)](#), and [Greenpeace International](#) can add depth to the assessment of lifecycle impacts. These organisations bring extensive experience in evaluating environmental footprints, developing sustainability strategies, and advocating for eco-friendly practices. Engaging such experts can also aid in identifying overlooked environmental risks and ensuring that the catalogue aligns with global sustainability standards and best practices.

1.2.2.7 Technical Simulations and Modelling

Technical simulations and modelling play a pivotal role in assessing the performance, scalability, and integration potential of energy storage technologies under diverse scenarios. By employing advanced modelling tools, the CSESS evaluates how these technologies function under varying geographic, climatic, and operational conditions. Simulations can predict system behaviour, identify performance bottlenecks, and provide insights into optimal configurations for specific use cases, such as grid stabilisation, renewable energy integration, or industrial applications.

Among the tools that can be utilised, [HOMER Energy](#) stands out for its ability to model microgrid and energy system designs, incorporating storage, renewable energy, and grid components. Similarly, [EnergyPLAN](#) offers comprehensive simulations of national and regional energy systems,

focusing on the integration of renewable energy sources and storage. For assessing battery-specific performance, [Battery Design Studio](#) provides insights into cell design, performance optimisation, and lifecycle modelling. These tools enable a detailed evaluation of energy storage technologies across technical, economic, and environmental dimensions.

By integrating simulation results with real-world data, the CSESS ensures that its recommendations are grounded in both theoretical and practical evidence. For instance, simulations can model the impact of deploying a vanadium redox flow battery system in a solar-rich region or the efficiency of hydrogen storage in colder climates. Additionally, technical modelling allows for scenario testing, such as predicting how storage systems respond to fluctuating energy demands or grid disruptions. This data-driven approach helps stakeholders understand the feasibility and benefits of different storage options, ensuring that the catalogue's findings are robust, actionable, and aligned with real-world applications.

1.2.2.8 Third-Party Certification and Testing Results

Third-party certification plays a vital role in establishing trust and confidence in energy storage technologies. These certifications verify that systems meet recognised safety, quality, and performance standards, making them essential for stakeholders such as renewable energy operators and investors. Globally acknowledged organisations, such as [TÜV Rheinland](#) and [Underwriters Laboratories \(UL\)](#), offer certifications tailored to energy storage technologies, ensuring compliance with international standards like **IEC 62619** for battery safety and **ISO 14040** for lifecycle assessments. These certifications provide an unbiased validation of manufacturer claims, helping to ensure the reliability and safety of deployed systems.

Independent testing results from specialised facilities offer further assurance by examining technologies under real-world and extreme conditions. For instance, the [Intertek Group](#) conducts rigorous testing to assess system performance, durability, and operational safety. Another key player, [DNV GL](#), provides specialised testing and certification services for energy storage systems

through their [GRIDSTOR Recommended Practice](#). This framework evaluates storage solutions on parameters such as lifecycle performance, grid compliance, and environmental sustainability, making their findings highly relevant for inclusion in the catalogue.

Incorporating certified data into the catalogue ensures a robust and unbiased foundation for comparing technologies. For example, systems certified by TÜV Rheinland or UL for operational safety and grid compliance can be highlighted as benchmarks for best practices. Certification also supports stakeholders by reducing risks, simplifying regulatory approval processes, and improving market accessibility, especially in regions with evolving energy storage policies like the Danube Region. This emphasis on independently verified data ensures that the recommendations in the catalogue are both credible and actionable, catering to the practical needs of its users.

1.2.2.9 Continuous Feedback Loop

The **Continuous Feedback Loop** is vital for ensuring the CSESS remains accurate and up-to-date while reflecting the dynamic nature of energy storage technologies and market trends. Designed for a consortium of 11 partners and a dedicated team of around 10 people, the feedback mechanism is streamlined for efficiency, balancing collaboration and workload.

1. Need for a Feedback Mechanism

The energy storage landscape evolves rapidly with technological advancements, regulatory updates, and shifting stakeholder needs. A simplified feedback mechanism ensures the catalogue adapts to these changes, maintaining its relevance for renewable energy operators, investors, and policymakers. This system prioritises actionable updates and minimises redundancy, aligning with the team's capacity.

2. Stakeholder Contributions

Stakeholders play a central role in the feedback loop by providing practical insights and highlighting emerging challenges. The consortium will:

- Host **online discussions** with key stakeholders to discuss updates, challenges, and future needs.
- Provide an **online feedback form** accessible through the catalogue's platform for continuous, ad hoc submissions.

3. Data Review and Integration

The process for reviewing and integrating updates is scaled for a small team:

1. **Initial Screening:** Submissions are reviewed monthly by a dedicated member to identify relevant and high-quality inputs.
2. **Validation:** Subject matter experts within the consortium validate technical, financial, and environmental data for accuracy and relevance.
3. **Team Review:** Validated data is discussed in quarterly consortium meetings to decide on its inclusion.
4. **Update Schedule:** The catalogue is updated semi-annually, ensuring consistent yet manageable revisions.

4. Technology Partner Engagement

The consortium will establish agreements with select technology partners to provide regular updates on system performance, advancements, and case studies. Communication will be maintained through **monthly email updates** and **partner check-ins**, leveraging existing relationships to reduce administrative burdens.

5. Governance and Oversight

The **Innovation Centre of the Usti Region (ICUK), Czech Republic**, serves as the coordinator for the governance and oversight of the feedback loop, leveraging its extensive expertise in energy, innovation, and stakeholder engagement. As the executive body of the regional RIS3 strategy, ICUK is uniquely positioned to oversee the integration of stakeholder feedback, data updates, and external expertise into the CSESS. Its strong network within the energy and hydrogen sectors,

combined with a history of successful collaborations, ensures a robust and credible governance process.

ICUK will act as the central hub for managing all aspects of the feedback loop, supported by its established connections with businesses, research institutions, and policymakers. To enhance the catalogue's financial analyses, ICUK will hire external experts to provide in-depth evaluations and ensure data accuracy. These specialists will validate submitted data and contribute insights on economic feasibility, CAPEX/OPEX modelling, and lifecycle costs for energy storage technologies. This ensures that all financial data incorporated into the catalogue meets rigorous standards.

All feedback and updates will be managed through the **ClickUp project management platform**, providing a transparent and organised system for tracking progress and ensuring timely follow-ups. ICUK will facilitate quarterly consortium meetings to review proposed updates, discuss validation outcomes, and plan for upcoming revisions. Additionally, they will lead annual stakeholder workshops, ensuring that the catalogue reflects the evolving needs of its users. By centralising governance with ICUK, the feedback loop remains efficient, transparent, and aligned with the objectives of StoreMore while benefiting from the region's pioneering role in energy innovation and hydrogen strategy development.

1.2.3 Analytical framework

The **Analytical Framework** serves as the foundation for evaluating the technical, financial, and environmental performance of the selected energy storage technologies: Gravity-Based Storage, Flywheels, Hydrogen, Vanadium Redox Flow Batteries, and Ultracapacitors/Supercapacitors. This framework provides a structured approach to compare these technologies, ensuring that the evaluations are objective, consistent, and aligned with the specific needs of the target stakeholders—renewable energy operators, investors, and policymakers. By integrating diverse metrics and data sources, the framework aims to deliver actionable insights that support informed decision-making and investment strategies in energy storage solutions.

The framework's objectives are twofold: to enable a detailed assessment of each technology's feasibility and to facilitate comparative analyses that highlight their relative strengths and weaknesses. It achieves this by incorporating a multi-dimensional evaluation, covering technical efficiency, economic viability, and environmental sustainability. Additionally, the framework is designed to be adaptable, allowing for the inclusion of new technologies, evolving market conditions, and stakeholder priorities. This ensures the analytical process remains relevant and responsive, supporting the StoreMore project's overarching goal of advancing sustainable energy storage solutions in the Danube Region.

1.2.3.1 Key Evaluation Metrics

The **Technical Feasibility** evaluation in the Catalogue is grounded in a set of industry-accepted metrics, ensuring a consistent and objective comparison of the selected energy storage technologies. These metrics provide detailed insights into the operational capabilities, efficiency, and long-term reliability of each system, enabling stakeholders to assess their suitability for specific applications within the energy sector. The parameters outlined in the **Energy Storage Outlook** form the foundation of this analysis, with additional indicators included for deeper exploration of each technology's potential.

Key Metrics for Evaluation

1. Energy Density per Unit of Volume [Wh/L]:

- This metric quantifies the amount of energy that can be stored within a given physical volume. Technologies with higher energy density, such as **Ultracapacitors/Supercapacitors** or **Vanadium Redox Flow Batteries (VRFBs)**, are often preferred for space-constrained applications, while lower-density solutions, like **Gravity-Based Storage**, may require larger installations but offer advantages in scalability..

2. Power Output [MW]:

- This parameter measures the system's minimum and maximum power delivery, indicating its capability to meet varying grid service demands. **Flywheel systems**, for example, excel in delivering high-power outputs for short durations, making them ideal for frequency regulation, whereas **Hydrogen Storage** systems are suited for large-scale, long-term energy delivery. **Ultracapacitors**, with their exceptionally high power density, provide instantaneous energy bursts, making them highly effective for peak shaving and grid stability applications.

3. **Energy Retention Period [hour]:**

- The retention period reflects how long energy can be stored with minimal losses. Long-duration storage options like **Hydrogen** or **Gravity-Based Systems** provide extended retention periods, supporting applications such as seasonal energy shifting, while technologies with shorter retention times serve immediate response needs. **Ultracapacitors**, due to their electrostatic storage mechanism, have very short retention periods, making them ideal for applications where immediate charge and discharge cycles are required rather than long-term energy storage.

4. **Lifetime [years/cycles]:**

- The operational lifespan of a technology is critical for understanding its long-term value. Systems with high cycle counts and extended lifetimes, such as **VRFBs**, offer reduced replacement costs and higher reliability, making them attractive for both grid and off-grid applications. Ultracapacitors significantly outperform batteries in this category, as they can withstand millions of charge-discharge cycles without noticeable degradation, providing near-unlimited longevity in comparison to chemical storage solutions.

5. **Discharge Time [hour]:**

- This metric determines how quickly stored energy can be discharged. **Flywheels** can release energy within seconds, supporting high-speed grid stabilisation, while

Ultracapacitors excel in delivering ultra-fast discharge bursts, making them ideal for frequency regulation and backup power applications.

6. Round-Trip Efficiency (RTE) [%]:

- RTE measures the energy retrieved versus the energy stored in a full charge/discharge cycle. Higher RTE indicates greater efficiency, with technologies like **Flywheels** achieving near-instantaneous efficiency, whereas long-duration solutions may trade off some efficiency for capacity. Ultracapacitors have exceptionally high RTE, often exceeding 95%, as they store and release energy electrostatically rather than through chemical reactions, reducing energy losses.

7. RTE Degradation:

- Over time, repeated cycling can reduce the efficiency of energy storage systems. Technologies with minimal RTE degradation, such as **VRFBs**, maintain consistent performance over their lifetimes, enhancing their cost-effectiveness. Ultracapacitors exhibit virtually no RTE degradation, as their charge-discharge process does not involve chemical wear and tear, making them one of the most durable energy storage technologies available.

8. Technology Maturity / Technological Readiness Level (TRL):

- TRL indicates the development stage of a technology, ranging from experimental (TRL 1–4) to commercially deployed (TRL 9). This metric helps stakeholders evaluate risks and timelines for implementation. For instance, **Gravity-Based Storage** is emerging in the commercial space, while **Hydrogen Storage** has reached broader adoption in specific applications. Ultracapacitors are commercially mature (TRL 9) in many applications, such as transportation, industrial power backup, and frequency regulation, though ongoing advancements in materials science are further expanding their capabilities.

Supplementary Indicators

In addition to the standard metrics, the CSESS incorporates additional parameters for deeper analysis:

- **Response Time:** The time required to activate the system and begin discharging energy.
- **Scalability:** The ability of the technology to scale up or down to meet specific energy demands.
- **Integration Complexity:** The ease with which the system can integrate with existing grid infrastructure and renewable energy sources.

Analytical Process

Each technology is assessed using these metrics in a consistent framework, with data sourced from validated industry reports, independent testing results, and real-world case studies. Comparative evaluations highlight trade-offs between technologies, providing stakeholders with actionable insights tailored to their unique operational requirements.

This structured approach ensures that the technical feasibility assessment is both rigorous and practical, aligning with the StoreMore project's goal of advancing sustainable energy solutions in the Danube Region and beyond.

1.2.3.2 Financial Viability:

Financial viability is a key determinant for the adoption and implementation of energy storage solutions. According to stakeholder interviews conducted during the StoreMore project, investors prioritise a clear understanding of the potential return on investment (ROI), making financial analysis a critical component of the Catalogue of Sustainable Energy Storage Solutions (CSESS). This chapter provides a detailed assessment of the economic performance of the selected technologies by examining key financial indicators. By incorporating these metrics, stakeholders can make informed decisions that balance upfront costs, operational expenses, and long-term value.

1.2.3.2.1 Key Financial Indicators

1. **Return on Investment (ROI):** ROI is a widely used indicator to evaluate the profitability of an investment relative to its cost. For energy storage systems, ROI highlights the financial benefits (e.g., energy savings, grid services revenue) compared to the initial capital expenditure.

Formula:

$$ROI (\%) = \left(\frac{Net\ Benefits - Initial\ Investment}{Initial\ Investment} \right) \times 100$$

2. **Levelised Cost of Storage (LCOS):** LCOS is a comprehensive metric that accounts for the total cost of operating a storage system over its lifetime, divided by the total energy stored and discharged. This indicator helps stakeholders compare technologies with varying lifespans, costs, and efficiencies.

Formula:

$$LCOS \left(\frac{\text{€}}{\text{kWh}} \right) = \frac{Total\ Costs\ (CAPEX + OPEX + Replacement\ Costs)}{Total\ Lifetime\ Energy\ Delivered\ (kWh)}$$

Where:

- Replacement Cost is decreased by residual value
- Total Lifetime Energy Delivered (kWh) = Lifetime [cycles] x Capacity [kWh] x Roundtrip efficiency [%]

3. **Payback Period:** The payback period measures how long it takes for an investment to generate sufficient savings or revenue to cover its initial cost. This indicator is particularly important for stakeholders focused on short- to medium-term returns.

Formula:

$$\text{Payback Period (years)} = \frac{\text{Initial Investment (CAPEX)}}{\text{Annual Net Savings or Revenue}}$$

4. **Net Present Value:** NPV calculates the total value of future cash flows generated by the storage system, discounted to reflect their present value. Positive NPV indicates a financially worthwhile investment.

Formula:

$$NPV = \frac{\sum \text{Net Cash Flow}_t}{(1 + r)^t} - \text{Initial Investment}$$

Where **r** is the discount rate, and **t** is the year.

1.2.3.2.2 Analytical Approach

The financial viability assessment includes:

- **Data Collection:** CAPEX, OPEX, and expected lifetime costs are obtained from manufacturer data, stakeholder interviews, and independent reports.
- **Scenario Modelling:** Sensitivity analyses are conducted to account for variables such as fluctuating energy prices, changing regulations, and varying market demands.
- **Comparative Analysis:** Technologies are ranked based on their ROI, LCOS, and payback periods to provide a clear picture of economic performance.

By prioritising these financial metrics, the CSESS equips stakeholders with the tools to evaluate investment opportunities comprehensively. This rigorous financial analysis aligns with the StoreMore project's goal of encouraging economically sound energy storage deployments in the Danube Region.

1.2.3.3 Environmental Sustainability:

Environmental sustainability is a cornerstone of the evaluation framework for the Catalogue. This component assesses the ecological impact of each storage technology, ensuring that selected solutions align with broader goals of decarbonisation and resource efficiency. By focusing on lifecycle emissions, material recyclability, and resource dependency, the CSESS provides stakeholders with critical insights into the environmental trade-offs of each technology.

1.2.3.3.1 Key Metrics for Evaluation

1. Lifecycle Emissions:

- This metric evaluates the greenhouse gas (GHG) emissions produced throughout the lifecycle of a storage system, from raw material extraction to manufacturing, operation, and end-of-life disposal. Lower lifecycle emissions are preferable, particularly for systems designed to integrate renewable energy sources.
- **Example: Vanadium Redox Flow Batteries (VRFBs)** typically have low lifecycle emissions due to the durability and reusability of vanadium electrolytes, making them suitable for sustainable long-term energy storage solutions. **Ultracapacitors** also exhibit low lifecycle emissions, as they do not rely on chemical reactions and do not require rare or hazardous materials, reducing their overall environmental footprint.

2. Material Recyclability:

- Recyclability assesses the ability to recover and reuse materials at the end of the system's lifecycle. Technologies using widely recyclable materials, such as Vanadium Redox Flow Batteries (VRFBs), which allow nearly 100% recovery of vanadium, offer significant environmental advantages over less recyclable options.

- **Example: VRFBs** allow nearly 100% recovery of vanadium, making them one of the most recyclable battery technologies. **Ultracapacitors** also stand out for their recyclability, as they are primarily made of carbon-based materials and do not contain toxic heavy metals, simplifying end-of-life processing and minimising environmental impact.

3. Environmental Impact Ratings:

- Environmental impact ratings evaluate factors such as land use, water consumption, and resource dependency. For instance, **Gravity-Based Storage** requires significant land or infrastructure but uses abundant and inert materials, making it a low-impact option in appropriate contexts. **Ultracapacitors**, due to their long operational lifespan and absence of hazardous materials, contribute to reduced resource depletion and waste generation, further enhancing their environmental viability in sustainable energy systems.

1.2.3.3.2 Tools and Databases

To assess these metrics, the CSESS relies on robust lifecycle assessment (LCA) tools and environmental databases:

- **Ecoinvent Database**: Offers comprehensive LCA data on materials, energy flows, and emissions.
- **European Life Cycle Database (ELCD)**: Provides datasets aligned with EU standards for evaluating environmental impacts across industries.
- **GREET Model**: Specialises in analysing GHG emissions and energy use for technologies such as batteries and hydrogen systems.

Environmental certifications further validate sustainability claims. Certifications like the **Environmental Product Declaration (EPD)** and **Cradle-to-Cradle Certification** offer

independent assessments of a system's environmental footprint, ensuring transparency and accountability.

1.2.3.3.3 Analytical Approach

1. **Lifecycle Assessment:** Each technology undergoes a lifecycle analysis to quantify its emissions, resource use, and end-of-life impact.
2. **Comparative Analysis:** Technologies are ranked based on their environmental performance, enabling stakeholders to weigh ecological considerations against technical and financial metrics.
3. **Scenario Testing:** Environmental impacts are modelled under various conditions, such as urban versus rural deployment, to reflect real-world applications.

By focusing on these metrics and tools, the environmental sustainability assessment ensures that stakeholders can make informed decisions aligned with both economic and ecological goals. This approach supports the StoreMore project's mission to drive sustainable energy storage solutions in the Danube Region and beyond.

1.2.3.4 Stakeholder Relevance:

The **Stakeholder Relevance** chapter evaluates how the selected energy storage technologies—**Gravity-Based Storage, Flywheels, Hydrogen Storage, Vanadium Redox Flow Batteries (VRFBs), and Ultracapacitors**—align with the priorities, capabilities, and needs of renewable energy operators, investors, and policymakers in the Danube Region. This analysis synthesises insights from stakeholder mapping, surveys, and interviews conducted under **Activity 1.1 of the StoreMore project**, ensuring that the catalogue reflects real-world applicability and market readiness.

Understanding Stakeholder Needs

Renewable energy operators emphasise the usability of storage systems in diverse operational contexts, favouring solutions with seamless integration capabilities, low maintenance requirements, and compatibility with existing renewable energy infrastructure. Investors, on the other hand, prioritise technologies that demonstrate clear financial returns, manageable risk profiles, and potential for scalability. Policymakers focus on technologies that align with regional decarbonisation targets, energy independence goals, and socioeconomic benefits such as job creation.

Key Metrics for Stakeholder Relevance

1. Usability in Stakeholder Contexts:

- Evaluates how easily a technology can be deployed, operated, and maintained. For example, **Flywheels** are noted for their **low maintenance** and suitability for frequency regulation, while **Gravity-Based Storage** provides adaptability in settings like legacy mineshafts. **Ultracapacitors**, with their high-power density and rapid charge-discharge capabilities, offer strong advantages in grid balancing and industrial applications where immediate response is crucial.

2. Alignment with Regional Policies:

- Measures how well the technology supports goals such as the EU Green Deal, regional hydrogen strategies, and renewable energy integration targets. Hydrogen Storage, driven by green electrolysis, is a standout due to its role in decarbonising multiple sectors.

3. Market Acceptance:

- Assesses the readiness of stakeholders to adopt the technology, considering factors like awareness, perceived risks, and cost-effectiveness. Technologies like VRFBs, which offer long lifespans and high recyclability, are increasingly gaining traction among operators seeking sustainable solutions.

Stakeholder Engagement Outcomes

The analysis of stakeholder feedback revealed varied levels of interest and readiness for adoption:

- **Operators** highlighted a preference for technologies that improve grid reliability and support peak demand management.
- **Investors** expressed strong interest in scalable technologies with predictable returns, such as VRFBs.
- **Policymakers** favoured solutions that provide regional energy security, such as Hydrogen Storage and Gravity-Based Storage, which leverage existing resources and infrastructure.

1.2.3.5 Comparative Scoring

The **Comparative Scoring** approach within the Catalogue provides a structured methodology to evaluate each technology across technical, financial, environmental, and stakeholder relevance metrics. Rather than ranking technologies universally, this approach focuses on establishing a clear score for each indicator, reflecting the relative performance of the technology. This allows stakeholders to compare solutions based on their specific priorities and contexts, ensuring flexibility and practicality in decision-making. Scores may be presented as fixed values or ranges, depending on the variability of the indicator across different locations and scenarios.

Flexibility and Context-Specific Scoring

Recognising the variability in some metrics, the comparative scoring system incorporates ranges where fixed values are not appropriate. For example, the lifecycle emissions of a Gravity-Based Storage system can vary significantly depending on the source of construction materials and the energy mix used during installation. By providing ranges, the scoring system acknowledges these variations while maintaining transparency and consistency. This flexibility ensures that stakeholders receive realistic and actionable insights that are directly relevant to their specific geographical, operational, and economic contexts.

Transparent Reporting of Results

To ensure usability, the scores and their underlying assumptions are presented transparently in the catalogue. Each metric is accompanied by a description of the data sources, the rationale for the assigned weight, and any context-specific considerations. This transparency not only builds trust but also enables stakeholders to adapt the scoring system further if required, reinforcing the CSESS as a robust decision-support tool. This comparative scoring approach ensures that technologies are evaluated holistically while maintaining the flexibility to address diverse stakeholder needs.

1.2.3.6 Data Validation and Quality Assurance

Ensuring the accuracy and reliability of data is a cornerstone of the CSESS. All data utilised in the evaluation process is validated by external experts or sourced from credible, industry-recognised databases such as **Ecoinvent** and the **DOE Global Energy Storage Database**. These sources provide scientifically vetted information on lifecycle emissions, energy flows, and performance metrics, ensuring consistency and credibility. External validation further enhances this process by incorporating peer-reviewed studies and expert opinions, especially for metrics where variability or complexity might introduce uncertainty.

To maintain the integrity of the data, the framework includes a rigorous process for cross-referencing manufacturer claims with independent testing results. For example, performance metrics like round-trip efficiency and lifecycle costs are compared against findings from third-party testing facilities such as **UL** or **Intertek**. This cross-referencing approach ensures that any discrepancies are identified and addressed, reducing the risk of overestimating performance or underestimating costs. By implementing these validation protocols, the CSESS ensures that stakeholders have access to reliable and actionable data, reinforcing its role as a trusted tool for evaluating energy storage technologies.

1.2.3.7 Scenario Testing and Sensitivity Analysis

Scenario testing and sensitivity analysis are integral components of the **Analytical Framework**, designed to evaluate the adaptability and resilience of energy storage technologies under diverse conditions. Scenario testing simulates the performance of technologies across varying geographic and climatic contexts, energy demand profiles, and operational conditions. For instance, the performance of Hydrogen Storage systems might be tested in regions with high solar availability versus colder climates, where heating requirements affect efficiency. Similarly, Gravity-Based Storage can be assessed for deployment in urban environments compared to rural or industrial settings, where infrastructure and land availability differ. These simulations provide stakeholders with insights into the practical viability of each technology under real-world conditions.

Sensitivity analysis complements scenario testing by examining how changes in input parameters influence the performance and economic feasibility of the storage technologies. Parameters such as fluctuating energy prices, regulatory incentives, and shifts in carbon taxation are evaluated to understand their impact on key metrics like ROI, LCOS, and lifecycle emissions. By incorporating these analyses, the CSESS ensures stakeholders can anticipate risks, adapt to changing circumstances, and make informed decisions about the suitability and scalability of each technology. This proactive approach enhances the robustness of the catalogue's recommendations, empowering stakeholders to navigate the complexities of the energy transition with confidence.

1.2.3.8 Visualisation and Reporting

Effective visualisation and reporting are essential for translating complex analytical findings into actionable insights within the **Analytical Framework**. The Catalogue employs advanced data visualisation techniques, such as radar charts, heat maps, and comparative bar graphs, to clearly present the performance of energy storage technologies across multiple metrics. For instance, a radar chart might illustrate the trade-offs between technical feasibility, financial viability, and

environmental sustainability for a given technology, while a heat map could highlight regional suitability based on geographic and climatic conditions. These visual tools ensure that stakeholders can quickly grasp key insights without needing to navigate dense technical data.

In addition to visualisations, the CSESS provides concise, well-structured summaries of the strengths and weaknesses of each technology. Each summary highlights critical attributes such as energy density, lifecycle emissions, scalability, and cost-effectiveness, offering stakeholders a clear understanding of where a particular technology excels and where it might face limitations. These summaries are designed to be accessible, avoiding overly technical language while retaining accuracy and depth. By integrating visualisation and clear reporting, the CSESS ensures that its findings are not only robust but also user-friendly, enabling stakeholders to make informed decisions with ease and confidence.

1.2.3.9 Framework Flexibility

The **Analytical Framework** of the CSESS is designed with adaptability at its core, ensuring its continued relevance in a rapidly evolving energy landscape. The framework can seamlessly incorporate new technologies as they emerge, updated metrics reflecting advancements in the field, and shifts in stakeholder priorities. For instance, as novel storage solutions such as solid-state batteries or hybrid systems become commercially viable, their inclusion in the catalogue can be facilitated without disrupting the overall structure. Similarly, if stakeholders begin prioritising metrics like supply chain transparency or embodied carbon, the framework can integrate these considerations into its evaluation criteria.

Flexibility is further enhanced through the incorporation of the **Continuous Feedback Loop**, which allows for iterative improvements based on stakeholder input and real-world data. Regular updates, facilitated through mechanisms such as stakeholder workshops, surveys, and technology partner contributions, ensure the framework evolves in response to changing conditions. For example, as regulatory landscapes shift or market conditions fluctuate, the scoring system and

weighting of metrics can be recalibrated to reflect the new context. This iterative, dynamic approach ensures that the framework remains robust, practical, and aligned with the StoreMore project's mission to support sustainable energy storage solutions in the Danube Region and beyond.

1.2.4 Stakeholder involvement

Purpose of Stakeholder Involvement

Stakeholder involvement is fundamental to the creation of a catalogue that is both practical and impactful in addressing the real-world challenges and priorities of energy storage adoption. Renewable energy operators, investors, policymakers, and other key actors provide unique perspectives and expertise, enabling the catalogue to reflect the practical needs and aspirations of its users. By actively engaging stakeholders, the StoreMore project ensures that assumptions are validated, data is enriched with insights from on-the-ground experiences, and the selected metrics and methodologies align with the diverse contexts in the Danube Region. This collaborative approach not only enhances the credibility of the catalogue but also ensures that its recommendations are actionable, realistic, and responsive to evolving market conditions. Moreover, involving stakeholders fosters a sense of ownership and trust, increasing the likelihood of the catalogue's adoption and sustained relevance. Their input shapes the evaluation framework, highlights region-specific challenges, and helps identify opportunities for deploying energy storage solutions effectively, making stakeholder involvement an indispensable pillar of the catalogue's development process.

Stakeholder Engagement Process

Mapping and Identification

The stakeholder mapping process, conducted as part of Activity 1.1, was pivotal in identifying and categorising key actors across the Danube Region to ensure their diverse needs and perspectives

were adequately represented. Stakeholders were divided into three primary segments: those with installed energy storage capacity, those who have recognised the need for storage solutions, and those who remain unaware of such needs. This categorisation enabled the project to target stakeholders at varying levels of awareness and involvement, fostering a comprehensive understanding of the current landscape. The mapping drew on desk research from sources such as regional development strategies, innovation strategies (e.g., RIS3), and energy management plans, complemented by insights from industrial associations, NGOs, and energy management companies.

Consultation Methods

To capture stakeholder input effectively, a combination of desk and field research was employed. Desk research involved analysing reports and policies, while field research included in-depth interviews with 25–30 stakeholders per partner region. Interviewees ranged from municipalities seeking energy independence to private operators aiming to optimise profits and industrial associations providing broad insights into sectoral needs. These interviews revealed diverse perspectives, such as the interest of Slovenian stakeholders in thermal storage systems for grid stability and the emphasis by Hungarian actors on return on investment (ROI) expectations. The findings highlighted the financial and regulatory barriers, as well as opportunities, across different contexts.

This robust engagement process ensured that the stakeholder perspectives directly shaped the development of the CSESS, enhancing its relevance and usability for the diverse energy landscapes within the Danube Region.

Role of Stakeholders in the Catalogue

Stakeholders play a pivotal role in shaping the Catalogue by providing critical input on metrics, validating data, and offering insights into practical use cases. Their feedback directly influenced the selection and weighting of metrics, ensuring alignment with real-world priorities. For example,

investors highlighted the importance of **return on investment (ROI)** as a decisive factor, leading to its prioritisation in the financial analysis framework. Renewable energy operators emphasised operational usability, while policymakers focused on environmental metrics aligned with decarbonisation goals. This collaboration ensured the catalogue's evaluation criteria reflect diverse stakeholder needs, enhancing its utility and relevance.

Beyond shaping metrics, stakeholders were instrumental in validating the data used in the catalogue. Their feedback was vital for refining technical assumptions, ensuring the real-world applicability of case studies, and identifying best practices. For instance, insights from industrial associations and municipal energy planners helped validate lifecycle emissions data for various technologies, such as Gravity-Based Storage and Hydrogen Storage. Stakeholders also contributed to refining pilot project concepts, providing location-specific considerations that informed the catalogue's usability recommendations. These contributions added a layer of credibility to the catalogue, making it more robust and adaptable to regional and operational contexts.

The collaboration outcomes underscore the strength of stakeholder involvement, which improved the catalogue's alignment with market needs and policy objectives while enhancing its adoption potential through integrated industry expertise. The diversity of feedback received from across the Danube Region reflected varying economic, regulatory, and environmental conditions, ensuring the catalogue addresses regional nuances. To maintain this engagement, stakeholders will remain central to the project's Continuous Feedback Loop. Following the national workshops, the catalogue will be updated with stakeholder feedback, ensuring its relevance and adaptability. Plans for annual updates and collaborative pilot projects will further sustain this dynamic engagement, reinforcing the catalogue's role as a living resource that evolves alongside the energy storage landscape.

1.2.5 Limitations and assumptions

The evaluation of energy storage technologies in the CSESS is subject to several inherent limitations and assumptions. These arise from the challenges of accessing operational data for novel technologies, the reliance on theoretical studies, and the use of manufacturer-provided information. While every effort has been made to ensure accuracy and reliability, it is important to acknowledge that some uncertainties remain. By addressing these limitations, the CSESS aims to provide stakeholders with a clear understanding of the context and scope of the analysis.

Emerging energy storage systems often lack extensive real-world performance data, as they are either newly commercialised or still in developmental stages. The data used in the analysis relies on a combination of available research studies, which are theoretical in nature, and input from manufacturers, whose cooperation is sometimes limited and often motivated by commercial interests. Additionally, the rapidly changing global landscape—including fluctuations in energy prices, geopolitical tensions, and technological advancements—introduces dynamic factors that may affect the relevance of the findings over time. These considerations underline the importance of interpreting the catalogue's results as indicative rather than definitive, while recognising its adaptability for future updates.

1.2.5.1 Data Constraints

1. Challenges in Data Availability

Obtaining operational data for novel and under-commercialised energy storage technologies poses significant challenges. Many of these systems are either in early developmental stages or have been deployed in limited, specialised settings, resulting in a lack of publicly available performance data. Manufacturers, who often hold the most detailed operational information, are frequently reluctant to share proprietary data without compensation, prioritising their competitive advantage over open collaboration. This limits access to critical insights that could validate or refine the analysis.

As a result, the data used in the CSESS relies heavily on theoretical research, simulations, and case studies. While these sources provide valuable insights, they may not fully capture the variability and complexities of real-world performance. Factors such as geographic conditions, energy demand profiles, and system integration challenges often differ significantly from controlled or simulated environments. Consequently, the findings should be interpreted as indicative rather than definitive, particularly for emerging technologies with limited commercial experience.

2. Dependence on Manufacturer-Provided Data

For some technologies, the analysis is based on data provided by a small number of cooperative manufacturers willing to share information. While this data is essential for understanding system capabilities and metrics such as energy density, round-trip efficiency, and lifecycle costs, it introduces an additional layer of uncertainty. Manufacturers may selectively highlight favourable metrics or provide incomplete datasets to support their commercial objectives.

To address these limitations, the accuracy of manufacturer-provided data has been assumed in cases where independent validation was not feasible due to resource and access constraints. Although efforts have been made to cross-reference claims with publicly available studies and testing results, not all discrepancies could be resolved. This reliance underscores the importance of ongoing validation and iterative updates to the catalogue as more operational data becomes available and partnerships with industry stakeholders evolve.

1.2.5.2 Dynamic and Evolving Context and Assumptions

The energy landscape is inherently dynamic, shaped by rapidly changing global factors such as geopolitical shifts, fluctuating energy prices, and the emergence of transformative technologies. Recent advancements, including the integration of artificial intelligence in energy systems, are driving significant innovation in areas like grid optimisation and predictive maintenance. However, these developments also introduce uncertainties that can significantly influence the adoption and performance of energy storage technologies. The Catalogue reflects a snapshot of the **current**

state of energy storage, relying on the most up-to-date data and projections available. While it provides a robust framework for evaluation, it is essential to recognise that external conditions, such as regulatory changes, economic disruptions, and new technological breakthroughs, may shift the relevance of its findings over time.

The analysis presented in the catalogue is underpinned by several key assumptions to address the challenges of limited data availability and evolving contexts. **Research studies and theoretical models** form the basis for many calculations and comparisons, and their accuracy is assumed unless credible evidence suggests otherwise. Similarly, **data provided by manufacturers**, while critical to understanding specific technologies, is taken at face value unless inconsistencies are identified during validation efforts. Furthermore, the economic and environmental metrics used reflect present-day conditions and known trends, without attempting to forecast disruptive innovations or major policy shifts. These assumptions ensure the feasibility of the analysis while acknowledging its limitations, reinforcing the importance of iterative updates and continuous stakeholder engagement to maintain the catalogue's relevance and utility.

1.2.5.3 Scope and Applicability of Findings:

The findings and recommendations presented in the Catalogue are most relevant to the specific regions, climates, and market conditions for which data was available during the analysis. The focus on the **Danube Region** ensures that the evaluations reflect the unique challenges and opportunities of this area, such as its energy mix, economic dynamics, and regulatory frameworks. Technologies like Gravity-Based Storage or Hydrogen Storage, for example, have been assessed in contexts where geographic features, such as abandoned mineshafts or solar energy potential, are prominent. Similarly, financial and environmental metrics are tailored to regional conditions, ensuring their practical relevance to stakeholders within these environments.

However, caution should be exercised when extrapolating these findings to other contexts, as key factors may differ significantly. Variables such as energy prices, climate conditions, and

infrastructure availability can greatly influence the performance, feasibility, and suitability of the technologies evaluated. For instance, the lifecycle emissions of a technology could vary substantially in regions with different energy generation mixes, while economic viability might shift in markets with varying incentive structures. Stakeholders are encouraged to consider these findings as a guide, complemented by localised assessments, to ensure the most accurate and effective application of the catalogue's insights. This measured approach enhances the reliability and utility of the CSESS across diverse scenarios.

1.3 Structure of the Catalogue

The Catalogue is organised into a detailed and consistent structure for each of the selected energy storage technologies—Gravity-Based Storage, Flywheels, Hydrogen Storage, Vanadium Redox Flow Batteries, and Ultracapacitors. This approach ensures comprehensive coverage of each technology's attributes, challenges, and opportunities while providing stakeholders with a clear, navigable format to guide decision-making. The structure highlights key technical, financial, environmental, and practical aspects of each technology, addressing the diverse priorities of renewable energy operators, investors, and policymakers.

Each chapter begins with an **Overview**, offering a concise summary of the technology, including its operational principles, technological maturity (measured using the TRL scale), scale, capacity, and overall efficiency. This sets the foundation for a deeper exploration of each technology's characteristics. The **Financial Analysis** section provides a detailed breakdown of capital expenditure (CAPEX), operational expenditure (OPEX), and the levelized cost of storage (LCOS), with an emphasis on economic viability across diverse regional and market contexts. This analysis incorporates stakeholder priorities, such as return on investment, ensuring its practical relevance. The **Environmental Impact** section evaluates each technology's lifecycle emissions, site-specific impacts, and potential mitigation strategies to reduce its ecological footprint. Following this, the

Technical Implementation chapter examines key design features, scalability, and integration potential, while addressing challenges and presenting viable solutions. The inclusion of **Practical Case Studies** further enriches the catalogue by showcasing successful deployments, real-world performance, and lessons learned, offering tangible insights into the application of each technology.

Finally, the **Stakeholder Insights** section captures perspectives and recommendations from industry actors, investors, and policymakers, synthesising their input to enhance the applicability of the findings. This comprehensive structure ensures that each technology is examined holistically, providing stakeholders with a reliable, actionable resource tailored to the evolving energy storage needs of the Danube Region and beyond.

Table of content for each technology

1.3.1 Overview

The **Overview** chapter provides a foundational understanding of each energy storage technology, introducing its operational principles, current development stage, and technical specifications. This section sets the stage for deeper analysis by establishing the essential characteristics that define the technology's functionality, scalability, and applicability. See: 1.2.3.1

- **Technology Overview**

This subchapter explains the fundamental principles of the energy storage technology, including its working mechanism, primary components, and potential applications. It provides stakeholders with a clear understanding of how the technology operates, its unique features, and the contexts in which it is most effective (e.g., grid stabilisation, renewable energy integration, or off-grid storage).

- **Technological Maturity – TRL**

The Technological Readiness Level (TRL) framework is used to assess the development stage of each technology, ranging from early research (TRL 1–3) to full commercial deployment (TRL 9). This subchapter evaluates the current TRL of the technology,

highlighting its maturity, potential risks, and the timeline required for widespread adoption. It helps stakeholders gauge the reliability and market readiness of the system.

- **Scale and Capacity**

This section examines the scalability of the technology, including its suitability for different project sizes and energy demands. Metrics such as energy storage capacity (kWh) and power output (kW or MW) are used to describe its potential to meet varying operational requirements. It also discusses the economy of scale, where larger installations may offer improved efficiency or reduced costs per unit.

- **Efficiency and Performance**

Efficiency and performance indicators provide a quantitative assessment of the technology's effectiveness in storing and delivering energy. Metrics like round-trip efficiency (RTE), energy retention duration, and discharge time are explored to evaluate how well the technology converts, stores, and supplies energy. This subchapter also highlights factors influencing performance, such as operating conditions and system design.

1.3.2 Financial Analysis

The **Financial Analysis** chapter evaluates the economic aspects of each energy storage technology, focusing on costs, financial performance, and applicability in varying market conditions. This section provides stakeholders with essential insights into the investment and operational expenses associated with the technology, enabling informed decision-making. See:

1.2.3.2

- **CAPEX and OPEX Breakdown**

This subchapter outlines the upfront capital expenditure (CAPEX) and ongoing operational expenditure (OPEX) required for the deployment and maintenance of the technology. CAPEX includes costs related to the installation of components such as storage units, power

electronics, and control systems. OPEX accounts for expenses like regular maintenance, replacements, and operational labour. By breaking down these costs, stakeholders gain a clear understanding of the financial commitment involved over the technology's lifecycle.

- **Investment Return Indicators**

The Levelised Cost of Storage (LCOS) is a critical metric that evaluates the cost per unit of energy delivered over the lifetime of the system. This subchapter explains how LCOS is calculated, integrating CAPEX, OPEX, replacement costs, and total energy output. It offers a comprehensive view of the technology's economic efficiency, enabling comparisons across storage options. The LCOS metric is particularly useful for assessing long-term financial performance, especially in contexts where energy prices or market conditions fluctuate.

Indicators: ROI, Payback Period, Net Present Value

- **Economic Viability in Diverse Contexts**

This section explores the financial feasibility of the technology in different geographic and market settings. It considers variables such as local energy prices, availability of incentives or subsidies, and regional regulatory frameworks. By analysing how the technology performs under diverse conditions, this subchapter highlights where it is most viable and identifies potential economic challenges or opportunities for its deployment.

1.3.3 Environmental Impact

The Environmental Impact chapter examines the ecological effects of each energy storage technology, providing stakeholders with critical insights into their sustainability and alignment with decarbonisation goals. This section evaluates the full lifecycle of the technologies, considers site-specific environmental challenges, and explores strategies to mitigate potential negative impacts. It enables stakeholders to balance ecological considerations with technical and financial performance in their decision-making process. See: 1.2.3.3

- **Lifecycle Impact Assessment**

This subchapter evaluates the environmental footprint of the technology across its entire lifecycle, from raw material extraction and manufacturing to operation and end-of-life disposal. Key metrics include greenhouse gas emissions, resource utilisation, and waste generation. The analysis also highlights opportunities for improvement, such as using recycled materials or transitioning to cleaner manufacturing processes. By assessing lifecycle impacts, this subchapter provides a comprehensive view of each technology's contribution to sustainability goals.

- **Site-Specific Impacts**

Energy storage systems can have varying environmental effects depending on their deployment context. This subchapter explores site-specific impacts, such as the use of legacy mine shafts for Gravity-Based Storage versus the challenges of deploying storage systems in urban areas. Factors like land use, local biodiversity, noise, and visual impacts are considered to provide a nuanced understanding of how different settings influence the environmental performance of each technology.

- **Mitigation Strategies**

This subchapter identifies practical strategies to minimise the environmental impacts associated with each technology. These strategies include improved recycling processes, alternative material choices, and optimised system designs to reduce emissions or land requirements. It also considers policy and regulatory measures, such as environmental certifications and incentive programs, that encourage sustainable practices. By addressing potential challenges with proactive solutions, this subchapter supports stakeholders in making environmentally responsible decisions.

1.3.4 Technical Implementation

The **Technical Implementation** chapter explores the practical aspects of deploying each energy storage technology, focusing on design, operational challenges, and scalability. This section

provides stakeholders with detailed insights into the technical considerations required for integrating these systems into various energy networks and use cases. By addressing both strengths and limitations, this chapter ensures that the technologies are evaluated for their real-world feasibility.

- **Key Design Features**

This subchapter outlines the essential design elements that define the functionality and efficiency of the technology. It highlights components such as storage media, power electronics, and control systems, explaining their roles in achieving performance goals. For example, the design of Flywheels emphasises mechanical durability and precision engineering, while Hydrogen Storage systems focus on high-pressure containment and safety features. Ultracapacitors, by contrast, utilise electrostatic energy storage mechanisms with high-surface-area electrode materials, requiring advanced power electronics for precise energy discharge management. This section gives stakeholders a clear understanding of how each technology operates from a structural and engineering perspective..

- **Challenges and Solutions**

This section discusses the technical hurdles associated with deploying and operating the technology, along with proposed solutions to overcome them. Challenges such as material degradation in VRFBs or land requirements for Gravity-Based Storage are explored in detail. For Ultracapacitors, one challenge is their lower energy density compared to chemical batteries, limiting their ability to provide long-duration storage. However, ongoing advancements in electrode materials, such as graphene-based structures, are gradually improving their storage capacity. Potential solutions across technologies include advances in materials science, improved system designs, or operational adaptations. This subchapter provides stakeholders with a realistic view of what to expect when implementing the technology and the strategies available to mitigate these challenges.

- **Scalability and Integration Potential**

This subchapter evaluates how well the technology can scale to meet different energy demands and how easily it integrates with existing infrastructure. Metrics such as modularity, grid compatibility, and adaptability to renewable energy sources are considered. For example, Hydrogen Storage systems are noted for their scalability in industrial applications, while Gravity-Based Storage is assessed for its integration potential in specific geographic settings like mines or mountainous regions. Ultracapacitors, due to their high power output and near-instantaneous response times, are particularly well-suited for grid balancing applications, where rapid energy discharge is essential for stabilising fluctuations in renewable energy supply. This analysis helps stakeholders understand the flexibility and long-term viability of each technology.

1.3.5 Practical Case Studies

The **Practical Case Studies** chapter provides real-world examples of how each energy storage technology has been deployed successfully, highlighting their performance, challenges, and outcomes. By presenting tangible evidence of operational systems, this chapter offers stakeholders a deeper understanding of the technologies' applicability and effectiveness in diverse scenarios. The case studies illustrate best practices and provide valuable insights for future projects.

- **Successful Deployments**

This subchapter focuses on detailed accounts of projects where the technology has been successfully implemented. Each case study includes information on the deployment context, such as geographic location, system size, and application (e.g., grid stabilisation, renewable energy integration, or industrial use). Key performance indicators like efficiency, reliability, and return on investment are highlighted to showcase the benefits of the technology. For example, a VRFB installation in a solar farm or a Gravity-Based Storage

system utilising a legacy mine shaft demonstrates how these solutions have been adapted to specific needs.

- **Lessons Learned**

Building on the successful deployments, this subchapter analyses the challenges encountered during implementation and the strategies used to address them. It explores issues such as unforeseen costs, integration hurdles, or maintenance complexities, along with the lessons learned to mitigate these problems in future projects. This section is invaluable for stakeholders, offering practical advice and reducing the learning curve for similar implementations. By reflecting on both successes and setbacks, this subchapter ensures that the catalogue serves as a comprehensive guide for real-world applications.

1.3.6 Stakeholder Insights

The **Stakeholder Insights** chapter provides a synthesis of the feedback, perceptions, and recommendations gathered from stakeholders during the development of the catalogue. This section captures the perspectives of renewable energy operators, investors, policymakers, and other key actors, offering a qualitative lens through which the technologies can be evaluated. By integrating these insights, the chapter highlights how each technology aligns with stakeholder expectations and identifies areas for improvement or further exploration.

- **Perceptions of Technology**

This subchapter delves into stakeholder perceptions of the technology, including its strengths, weaknesses, and overall appeal. For example, Gravity-Based Storage might be praised for its scalability and use of local resources, but concerns could be raised about land requirements or initial investment costs. Similarly, Flywheels might be recognised for their rapid response times but viewed as limited in capacity for long-term storage. These insights are drawn from surveys, interviews, and workshops conducted as part of the

StoreMore project, reflecting the diverse priorities of stakeholders across the Danube Region.

- **Stakeholder Recommendations**

Building on their perceptions, this subchapter presents actionable recommendations from stakeholders for improving the deployment, performance, and adoption of the technology. Recommendations might include policy incentives, such as subsidies or tax breaks, to encourage investment; technical innovations, like improving materials to enhance efficiency; or educational efforts to raise awareness of the technology's benefits. This section not only summarises stakeholder input but also provides a roadmap for aligning the technology with real-world needs, making it a practical tool for decision-makers.

2 Gravity-based Energy Storage

As renewable-generation capacity expands, matching intermittent supply to variable demand has become a key challenge of the 21st century. **Gravity-based energy storage (GES) uses the surplus electricity by mechanically lifting heavy masses—converting electrical power into gravitational potential energy—and releasing it on demand by controlled descent to regenerate electricity.** Among different energy storage technologies, GES stands out as a promising and acceptable technology because of its significant energy storage capacity, high cycle efficiency, simplicity, and potential to expansion. The biggest downside of the technology is its high capital investment costs, reasonable arguments for low reliability and public inacceptance due to the visual impact. The solid gravity energy storage technology originates from pumped hydro energy storage (PHES) systems, which has been utilized for a long time and currently contains about 90.3 % of installed energy storage capacity globally. [1] Even though the mechanical principle of PHES is identical to GES, any technology type that includes hydropower was excluded from this catalogue section.

It can be observed that the number of patents and scientific articles related to gravitational energy storage is relatively low. Still, both have increased recently, as shown in Fig. 2.1. During 2013–2017, there were eight scientific articles, compared to 71 published during 2018–2022. Historically, the number of patents has exceeded the number of scientific articles; however, in 2022, the number of articles surpassed the number of patents by approximately 50 %. Despite the low number of innovation and research outputs, the presence of several pilot and demo plants indicates that industry has been the driving force. However, academia's role may increase in the future. **Overall the industry has been the primary driver up to 2025.**

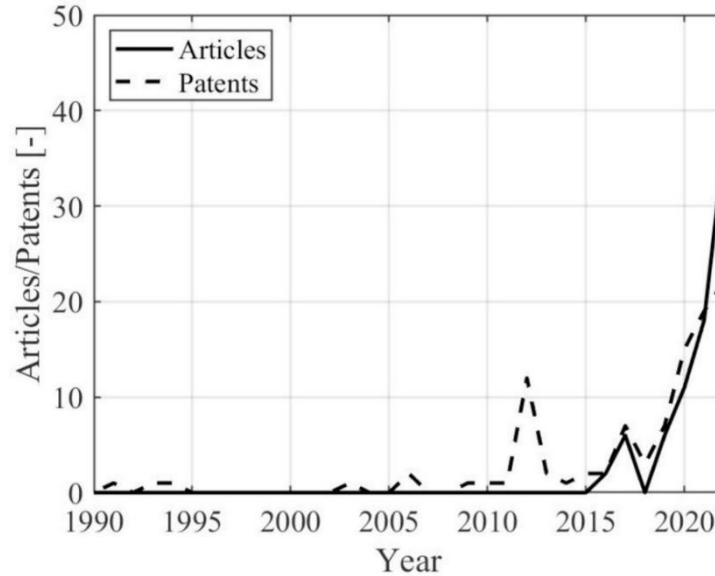


Figure 2.1 Development of scientific articles and patents related to gravity energy storage as a function of time. [2]

2.1 Overview of Gravity-Based Energy Storage

2.1.1 Technology overview

The core principle of gravity energy storage is the bidirectional conversion between electrical energy and gravitational potential energy. During periods of surplus electricity the extra power drives a mechanism that lifts a substantial mass to a higher elevation, thereby storing energy as potential energy (see Eq. 2.1).

$$E_S = mg\eta_s h \quad \text{Eq. (2.1)}$$

When demand on the grid increases, the mass is released and allowed to descend, and its downward motion powers generators to reconvert that stored potential energy back into electricity as shown in Fig. 2.2 (a) and (b).

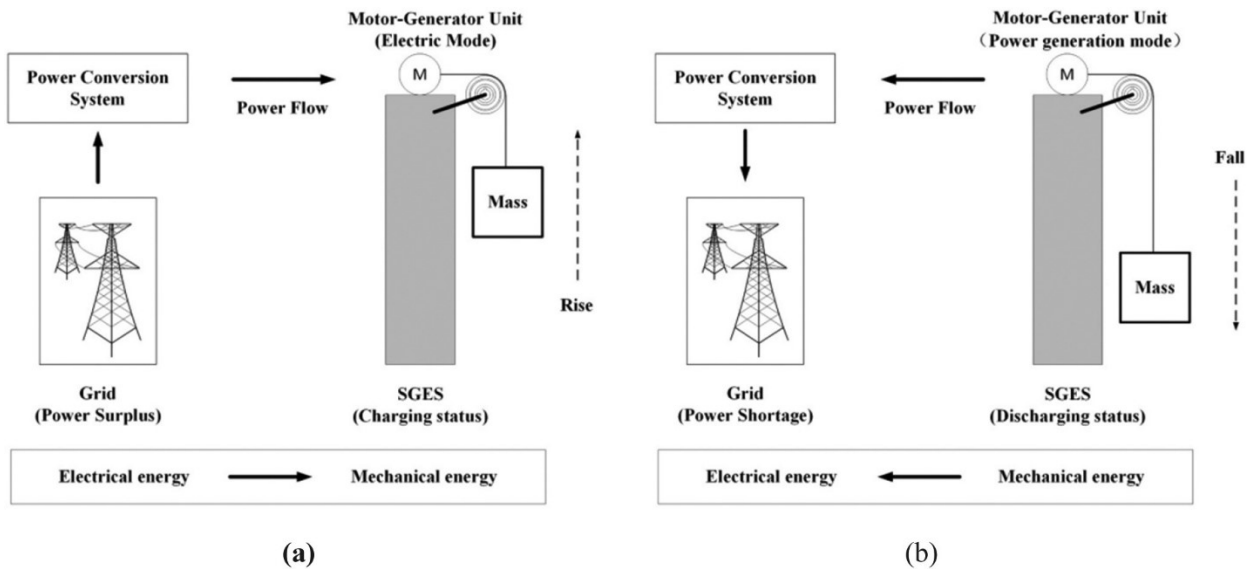


Figure 1.2 Basic operating principle of GES

GES operates in three key phases:

1. **Mechanical lifting:** cranes, winches, or elevator systems elevate a heavy mass to store energy.
2. **Potential energy holding:** once raised, the mass is held stationary, preserving its gravitational potential energy with minimal losses. Support structures and bearing systems are designed to sustain the load over extended periods without significant energy dissipation.
3. **Energy recovery:** On demand, the mass is allowed to descend under controlled conditions, driving generators to produce electricity. Incorporating features like regenerative braking or counterweight systems further improves conversion efficiency and reduces losses during this discharge phase.

GES typically categorize into three structural categories:

- **Tower-based systems:** vertical towers in which heavy weights—often concrete blocks—are lifted, stacked, and then lowered to store and release energy. Tower designs are

compact, making them easy to fit into existing industrial sites with minimal footprint. Its working principle is shown in Figure 2.3. [3]

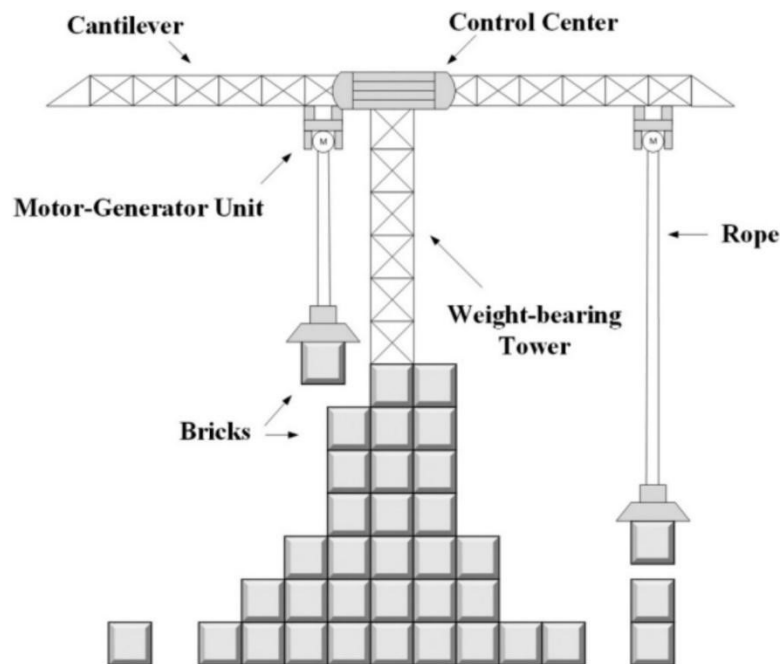


Figure 2.3 Working principle of the tower-based GES

Tower-based gravity storage systems are known for their high round-trip efficiencies often exceeding 80%. By simply adjusting the height of the tower or the mass being lifted, these installations can be designed to a broad range of capacities, from *hundreds of kilowatt-hours up to multiple megawatt-hours*, making them appealing for both localized and grid-scale applications. Moreover, because they rely on inert materials like concrete or steel rather than chemical reactions, they generate no toxic byproducts or hazardous waste during operation. Yet these benefits come at a cost. The towers must be exceptionally robust to bear the loads involved, driving up capital expenditure significantly. Material limits and safety standards currently cap practical tower heights at around 120 meters, which in turn constrains the maximum energy that can be stored per installation. Suitable sites with sufficient vertical clearance—and without

obstacles like air traffic paths or residential neighborhoods are rare, especially in densely populated regions, creating hurdles in land acquisition and permitting.

Beyond these economic and siting challenges, taller towers face amplified structural stresses. Wind forces increase with elevation, seismic events induce greater lateral loads, and material fatigue in cables, rails, and bearings becomes a pressing concern after thousands of cycles. Addressing these issues requires innovation in both materials and design. The adoption of lightweight, high-strength composites—such as carbon-fiber-reinforced polymers—can reduce the load on support structures without sacrificing durability. Aerodynamically optimized tower shapes help deflect wind and damp vibrations, while base-isolation devices or tuned mass dampers can mitigate seismic shocks.

Finally, the longevity of mechanical components is key for cost-effectiveness. Frequent lifting and lowering cycles gradually weaken the materials (winches, ropes, gearboxes) through fatigue as very low rotational speeds and extreme torques are achieved at the GES systems.

- **Shaft-based systems:** masses travel up and down deep shafts—either purpose-drilled or repurposed mine shafts. By using pre-existing underground infrastructure, these setups can significantly cut civil-works costs and limit surface disturbance, making them ideal for areas with a mining legacy. Operating principle is shown in Figure 2.4. [4]

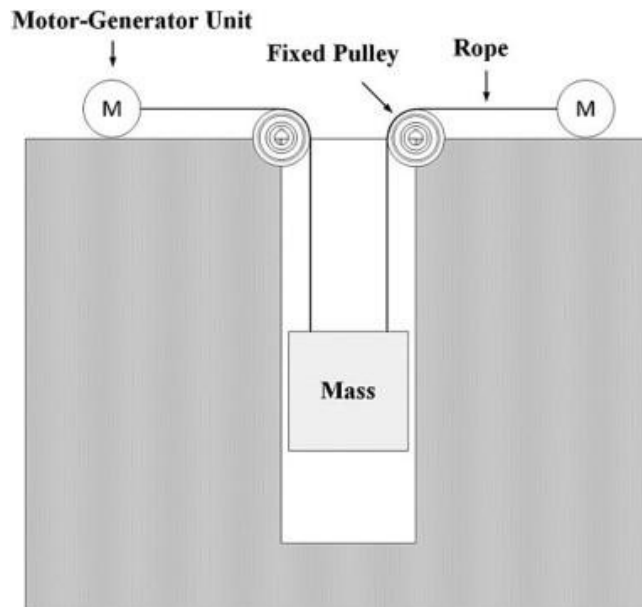


Figure 2.4 Operating principle of the mine shaft GES

Shaft GES systems use deep shafts—often repurposed from decommissioned mines. The reuse of existing mine infrastructure reduces civil-works costs, while the entirely subterranean footprint minimizes land-use conflicts and visual impact, increasing community acceptance in densely developed regions. In addition, the inertia of large mass movements constrains dynamic response: shaft GES cannot ramp power output as rapidly as flywheels or battery systems, limiting its direct use for frequency regulation (FCR). Advanced control strategies powered by predictive analytics can optimize mass-lifting schedules based on forecasted load profiles and electricity costs.

- **Inclined-plane systems:** loads move along sloped tracks or railways, making use of gravity on natural or engineered gradients. Mountainous or hilly terrain is perfect for such installations. Operating principle of inclined plane GES is shown in Figure 2.5. [5]

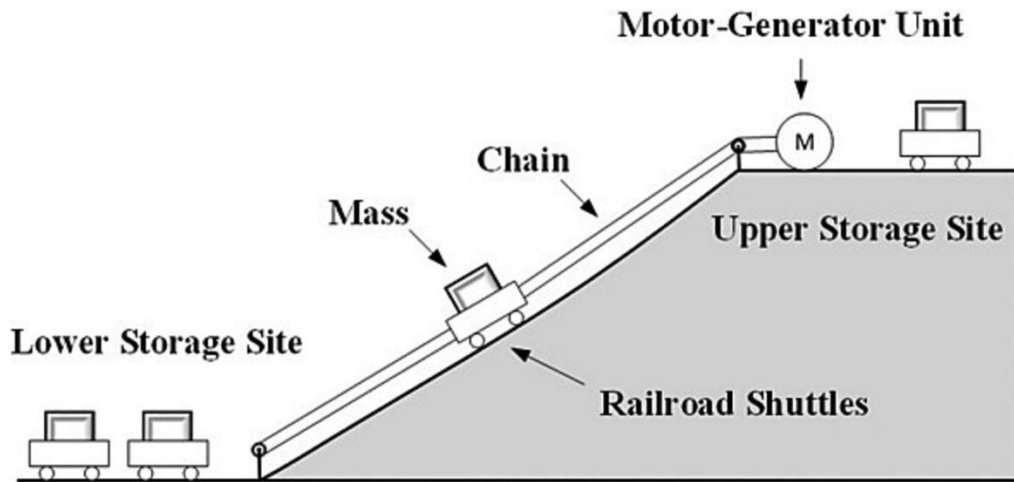


Figure 2.5 Inclined-plane GES - an operating principle

Inclined-plane systems shift heavy masses between two elevations, storing and releasing energy by the use of gravity along an incline rather than vertical lifts. Common technology include rail-mounted mine-cars, cable-cars on tensioned cables, and even wheeled vehicles such as electric trucks, all of which traverse an incline to convert electrical energy into potential energy and back again.

Mechanically, these systems are scaled by the number of carriers in service and the gradient or length of the track (adding more cars or increasing the elevation difference). Because loads move along a slope under controlled conditions, peak structural stresses are lower than in vertical-lift designs. Many inclined-plane installations can (and should) repurpose existing infrastructure—abandoned railways (ARES [6]), mine tramways, utility corridors, or service roads to minimize civil-work costs and environmental impact. Local ballast materials (for example gravel or blasted rock) can often serve as the carried mass.

However, these benefits come with trade-offs. Each carrier requires track, cable, or roadway infrastructure and associated drive and braking equipment—multiplying the number of mechanical interfaces and points of friction. These cumulative losses can drive cycle efficiencies

several percentage points below simpler gravity systems. Steeper slopes and longer track lengths may improve storage capacity but simultaneously raise the risk of runaway loads and need more robust braking systems. In protected landscapes, the visual and ecological impact of extensive track networks and moving masses can meet resistance from stakeholders. Maintenance access along remote inclines often comes with higher operational costs and logistical complexity. Lastly, vehicle-based solutions introduce additional energy-conversion stages—charging the vehicle’s battery and then using its motor for ascent—which reduces the RTE and require significant CAPEX for fleets of specialized vehicles.

2.1.2 GES Technological Maturity – TRL

Tower-Based Systems (TRL 8–9)

Tower gravity installations leverage mature components—permanent-magnet motor-generators, steel frames, and block stacking—most of which are off-the-shelf or adapted from heavy-lift cranes. [7] Energy Vault’s 35 MWh commercial demonstration (EV1CDU) in Switzerland and successive EVx platforms have operated grid-connected for multiple years, meeting FCR requirements and demonstrating $\geq 80\%$ round-trip efficiency, fulfilling TRL 8 criteria. [2]

Shaft-Based Systems (TRL 6–7)

Repurposed mine-shaft systems—such as the Gravitricity prototype in Leith—have validated winch integration, guide-rail performance, and control strategies under real geological conditions but await wider regulatory and safety codification, marking a TRL around 6 to 7. [2] Demonstrations have shown cycle efficiencies of 80–90 % over hundreds of cycles, yet full operational qualification under varying shaft geometries remains outstanding.

Inclined-Plane Systems (TRL 5–7)

Rail-car and cable-car GES prototypes have demonstrated proof-of-concept on test tracks and small mountainside sites, achieving cycle efficiencies of 75–85 % but have not yet integrated into grid service contracts. These systems typically sit at TRL 5 (prototype validation) to TRL 7

(demonstration in relevant environment) depending on the carrier and site-specific validation. [7]
Electric-truck based schemes remain at TRL 5, as full lifecycle and battery-recycling protocols are still under development. [8]

Pathways to TRL 9

To reach TRL 9, gravity storage must:

- **Demonstrate > 10 000 full cycles** with sustained ≥ 80 % efficiency in grid-connected operations.
- **Secure long-term ancillary services contracts** (FCR, long-duration reserves) in multiple markets
- **Codify safety and maintenance standards** via international standards bodies (IEC 62817 for flywheels should be adapted for high-mass systems so there is a single united regulation standard)

2.1.3 Scale and capacity

Gravity-based storage can be engineered from pilot size all the way up to regional-scale reservoirs of energy. The achievable scale depends primarily on the mass that can be moved, the vertical or effective elevation difference, and the number of parallel lines or tracks that can be installed at a given site.

Tower configurations

Commercial tower plants now operate with **4 MW peak power and 35 MWh of storage** by stacking and un-stacking ~35 t concrete blocks over a 120 m lift. [9] Because height is the limiting parameter, capacity is expanded by widening the footprint and adding independent hoist frames—practical up to a few hundred megawatt-hours before land or visual constraints dominate. Block size and motor rating can also be down-scaled for behind-the-meter applications, yielding sub-MW towers (<1 MWh) for micro-grids or industrial campuses.

Shaft-based systems

Repurposed mine shafts support **2–4 MW units with 2–4 MWh** of energy in a single hoist, using 500–750 t masses travelling 600–800m. [10] Where multiple disused shafts exist in parallel, designers can aggregate power modules to tens of megawatts and energy into the **hundreds of megawatt-hours** range. Analytical studies show that a 1 km double-shaft array carrying 1 000 t weights could reach ~50 MWh per pair, scaled linearly with additional shafts.

Inclined-plane systems

Rail-car and cable-car variants exploit long slopes and therefore substitute track length for vertical drop:

- **Rail gravity lines** now under construction are rated **50 MW with 12 GWh** of storage, using 70 t mass-cars running on a 7.2 km grade. [11]
- Cable-car demonstrators on steep alpine faces show 5–20 MW modules and 200–500 MWh per string, expandable by extending line length or duplicating tracks. [12]

Across all formats, capacity scales with the product $m \cdot g \cdot h$ ($= \Delta PE$). Design therefore focuses on maximizing either mass, height, or effective path length (slopes), while duplicating modules to reach grid-level targets.

2.1.4 Efficiency and Performance

GES converts electricity to potential energy with few conversion steps, so round-trip efficiencies are already comparable with lithium-ion batteries and pumped hydro. Commercial tower units now return more than 80 % of the injected energy, mine-shaft prototypes approach 90 %, and well-engineered rail-or truck-based plants reach the high-70 % range. Losses arise mainly from mechanical friction and electrical conversion; they

Table 2.1 Reported RTE by configuration

Configuration	Demonstrated / claimed RTE	Key reference
Tower (block-stack)	80–85 % (EVx platform)	[13]
Mine-shaft hoist	85–90 %	[4]
Hydraulic rock piston	≈ 80 % (Heindl 1–8 GWh cylinders)	[14]
Inclined rail (ARES)	78–82 % over 15 min–24 h duty	[11]
Electric-truck slope	65–80 % (regenerative braking study)	[15]

Greatest sources of losses

1. **Mechanical friction** – rope bending, wheel bearings, guide rails ($\approx 4\text{--}8\%$).
2. **Aerodynamic drag** in tall shafts or tower cells ($\leq 2\%$)
3. **Motor-generator and inverter losses** – modern permanent-magnet drives exceed 97 % per pass, so two-way electrical loss is typically 5–6 %
4. **Stand-by/auxiliaries** – HVAC, PLCs, safety systems ($< 1\%$).

Mitigation techniques

- low-friction polymer or ceramic bearings and rope coatings reduce mechanical drag; efficiency gains of 2 % are reported in shaft prototypes
- high-strength, low-stretch ropes lower elastic losses and allow slower hoist speeds
- soft-switching, large scale 4-quadrant inverters improve electrical efficiency above 98 %
- predictive control keeps winch velocity in the sweet-spot where frictional and electrical losses are minimised

Dynamic performance

- **Ramp rate** – tower and rail systems meet primary frequency-control ($< 30\text{ s}$) with margin [13], [16]
- tower and shaft units remain above 70 % RTE down to 25 % power owing to variable-frequency drives
- **Cycle life** – no fundamental degradation; mechanical components are rated for $> 50\,000$ full cycles (≈ 30 years at four cycles/day) before major overhaul.

- Availability > 95 % with redundant winches and planned maintenance

2.2 Financial Analysis

The financial viability of a gravity storage installation hinges on several key economic metrics: capital expenditure, ongoing operating and maintenance costs, system efficiency, and expected lifespan.

- Capital expenditures are all upfront investments
- Operational expenses include routine maintenance, inspections, and any energy losses that occur during charge–discharge cycles
- System longevity affects how capital costs amortize over time

2.2.1 CAPEX and OPEX Breakdown

Table 2.2 GES CAPEX structure

Work-package	Typical share of total CAPEX	Cost drivers	Notes & recent datapoints
Site preparation & civil works (excavation, foundation pads, tower erection, shaft refurbishment, drainage)	25 – 45 %	rock stability, shaft depth/diameter, tower height	Mine-shaft schemes avoid ~30 % of green-field civil cost by re-using existing galleries [17]
Mass modules (steel cages or concrete blocks, ballast, guide rollers)	15 – 25 %	density of ballast, modularity, local material prices	Heindl's rock-piston: 60–120 US \$/kWh just for the bored cavern and rock plug
Hoisting machinery (electric winches, gearing, drums, ropes/rails)	20 – 30 %	rated power (kW), duty cycle, redundancy	2 MW double-drum hoists for the 2 MWh Czech pilot each cost ~3 M US\$ installed
Power-conversion & controls (PMSM–generator sets, VFDs, PLC/SCADA, protection)	10 – 20 %	grid code, black-start, ancillary-service spec.	ABB–Gravitrinity cooperation targets modular 1–5 MW drive skids [18]
Balance-of-plant & EPC (aux. power, HVAC, fire/life safety, engineering, permitting, owner's costs)	10 – 15 %	regulatory environment, EX-proof rating	Adds ~25 US \$/kWh for mine installations that require ATEX-rated equipment

Indicative turnkey ranges

- Shaft (550 t twin-weight, 750 m travel): **130–180 US \$/kWh** [19]

- Tower (120 m, 35 t block stack): **150–200 US \$/kWh** [20]
- Rail incline (ARES Nevada 372 m, 75 000 t train): **160–220 US \$/kWh** [21]

These figures include construction contingency but exclude network interconnection fees. First-of-a-kind (FOAK) plants tend toward the upper end; nth-of-a-kind costs fall by 15–25 % through modularisation and local sourcing. [22]

Table 2.3 GES OPEX Structure [23]

Cost element	Typical magnitude	Comments & mitigation
Fixed O&M labour and site services	4 – 9 US \$/kW-yr ($\approx$ 1–2 % of CAPEX)	Small crews; remote diagnostics cut staffing by 30 % vs. pumped hydro
Routine inspection & lubrication (ropes, bearings, rails)	0.2 – 0.4 US \$/kWh-yr	IoT tension sensors and self-lubricating bushings extend rope service life beyond 20 years
Major overhaul (winch gearbox, rope replacement)	every 15–20 yr, $\approx$ 8 % of original CAPEX	Scheduled during low-price seasons; condition-based replacement avoids premature swaps
Insurance, permits, land lease	0.1 – 0.3 US \$/kWh-yr	Mine-shaft reuse often offsets lease through avoided closure bonding
Auxiliary power & standby losses	<0.05 % of dispatched energy	No HVAC or parasitic self-discharge; only PLC and brake pumps draw idle power

Across case studies, **total annual OPEX clusters between 1.5 % and 4 % of initial CAPEX**, yielding fixed-charge factors of 45–65 US \$/kW-yr for shaft or tower layouts and $\sim$ 35 US \$/kW-yr for rail systems with fewer moving parts. Variable O&M is negligible (<0.1 US \$/MWh) because there is no fuel and very low cycle-dependent wear, which underpins levelised cost of storage (LCOS) values of **7–15 € ct/kWh** over 30 years—competitive with pumped hydro and compressed-air plants of similar duration. [20] Scale economies as multi-hundred-MWh clusters are rolled out, are expected to push all-in CAPEX below **100 US \$/kWh** by 2030 and keep annual OPEX under **2 % of plant value**, positioning gravity storage as one of the most cost-effective long-duration options for grids with high renewable penetration.

2.2.2 Levelised Cost of Storage (LCOS)

GES is still moving from demonstration to first-of-a-kind commercial plants, so published cost figures span a wide band. Recent peer-reviewed papers, techno-economic models and vendor disclosures make it possible to bracket today's levelised cost of storage and to understand the parameters that drive it. The synthesis below uses the standard LCOS definition (net present value of all costs divided by lifetime delivered energy).

LCOS (\$ kWh⁻¹) is calculated as Eq. 2.3.

$$LCoS \text{ [€/MWh]} = \frac{CapEx \text{ [€]} + OpEx \text{ [€]} - Residual \text{ value [€]}}{Lifetime \text{ [cycles]} * Capacity \text{ [kWh]} * Roundtrip \text{ efficiency [\%]}} \quad \text{Eq. 2.3}$$

Table 2.4 GES LCOS breakdown [19], [24]

Configuration (power / duration)	Reported or modelled CAPEX	Round-trip efficiency	LCOS range*
Tower (300 MW / 12 h) – vendor EPC quotes	120–150 \$ kWh ⁻¹ of energy	80–85 %	60–95 \$ MWh ⁻¹
Underground mine (100 MW / 10 h) – UGES study	2–15 \$ kWh ⁻¹ of capacity (≈40-110 \$ kWh-energy)	80–90 %	40–90 \$ MWh ⁻¹
Linear-machine shaft (10 MW / 3 h pilot)	160–250 \$ kWh ⁻¹	81 %	120–180 \$ MWh ⁻¹
Inclined-plane truck/rail (ARES, 50 MW / 4 h)	60–120 \$ kWh ⁻¹	75–80 %	70–120 \$ MWh ⁻¹

*LCOS bands reflect the base financial scenario, 85 % depth-of-discharge and 330 full cycles yr⁻¹ (≈1 cycle day⁻¹ for 10-h plants).

For context, Lazard's 2024 survey places utility-scale lithium-ion at 140–325 \$ MWh⁻¹ for 10-h service, vanadium redox flow at 165–290 \$ MWh⁻¹ and pumped-storage hydropower at 55–120 \$ MWh⁻¹. [24]

CAPEX dominates LCOS (>75 % in most configurations), so the learning curve is governed by civil works and mature supply chains for winches, cables and power conversion. A ± 25 % swing in capital cost moves LCOS by roughly ± 18 % at 330 cycles yr^{-1} ; halving the cycle rate (seasonal-only use) doubles LCOS because fixed charges are spread over fewer MWh. Increasing round-trip efficiency from 80 % to 88 % trims LCOS ~ 7 %, while extending design life from 35 to 50 years lowers it ~ 10 % under the same discount rate.

2.2.3 Economic Viability in Diverse Contexts

Compared with alternatives such as batteries or pumped hydro, GES excels in providing durable, long-duration capacity with a low environmental footprint and entirely nonhazardous materials. This makes it a particularly green solution for large-scale buffering of intermittent renewables on the grid. Nevertheless, gravity systems face hurdles—identifying suitably tall or deep sites and optimizing conversion efficiency are nontrivial challenges. Moreover, scaling these installations in urban or high-density regions presents both engineering opportunities and integration complexities.

Frequency and reserve services dominate early cash-flow. In Continental Europe the **Frequency Containment Reserve (FCR-N) auction cleared at €25.4 /MW·h for 2024**—worth ~ 90 k€/MW-yr if dispatched continuously. [25] Because mechanical plants have negligible marginal cost, they can bid at \$0/MWh in reserve auctions and still monetise every MWh discharged, producing IRRs > 12 % at 330 cycles / yr even when wholesale prices average $< \$60/\text{MWh}$. [13]

Brown-field mining regions

Converting disused shafts removes 30–70 % of civil CAPEX: published studies of **underground GES in South-Africa, China and Finland point to total installed cost of 40-110 \$/kWh-energy** and LCOS 40–90 \$/MWh at 85 % utilisation.

2.3 Environmental Impact

2.3.1 Lifecycle Impact Assessment

The life cycle assessment (LCA) for Gravity Energy Storage (GES) was conducted using openLCA v2.4.1 and the ecoinvent v3.11 database. The assessment follows the EN15804+A2 standard and ISO 14040/14044 framework. A cradle-to-grave system boundary was used, including raw material extraction, production, use phase, and end-of-life scenarios. The analysis prioritizes the production phase, as it contributes the most to environmental impacts. The functional unit is defined as 1 kWh of electricity throughput over the lifetime of the system.

Inventory data accounted for at least 99% of the mass, energy, and environmental contributions. Foreground systems were modelled using literature sources due to the limited availability of first-hand data. The results were normalized and weighted to provide a comprehensive impact profile, and significance analysis was carried out to identify hotspots within the system.

Key findings include:

- Tower-based GES systems exhibit significant impacts during the construction phase due to the volume of concrete and steel used.
- Legacy mineshaft systems have reduced environmental impacts by repurposing existing infrastructure.
- Operational impacts are minimal due to passive mechanical operation.

Impact categories analyzed include climate change (GWP), resource depletion, particulate matter, water use, and acidification. The GES system performs favorably in terms of carbon footprint compared to battery-based solutions, especially for long-duration applications with high cycle life.

2.3.2 Site-Specific Impacts (e.g., Legacy Mines vs. Urban Areas)

Environmental impacts of GES vary significantly depending on site-specific parameters. Three deployment configurations were assessed:

1. Tower GES (TGES):

- Typically built on undeveloped or peri-urban land.
- High land use intensity and visual impact.
- Generates significant construction-related emissions due to foundation works and structure height.

2. Legacy Mineshaft GES (SGES):

- Reuses abandoned vertical shafts, reducing the need for new construction.
- Minimal surface footprint.
- Avoids additional land degradation but may involve remediation of contaminated sites.

3. Inclined-Plane GES:

- Requires excavation and slope stabilization.
- Intermediate land and material use compared to towers and mineshafts.

Geographic factors, such as proximity to the grid and terrain type, strongly influence environmental feasibility and carbon performance.

2.3.3 Mitigation Strategies

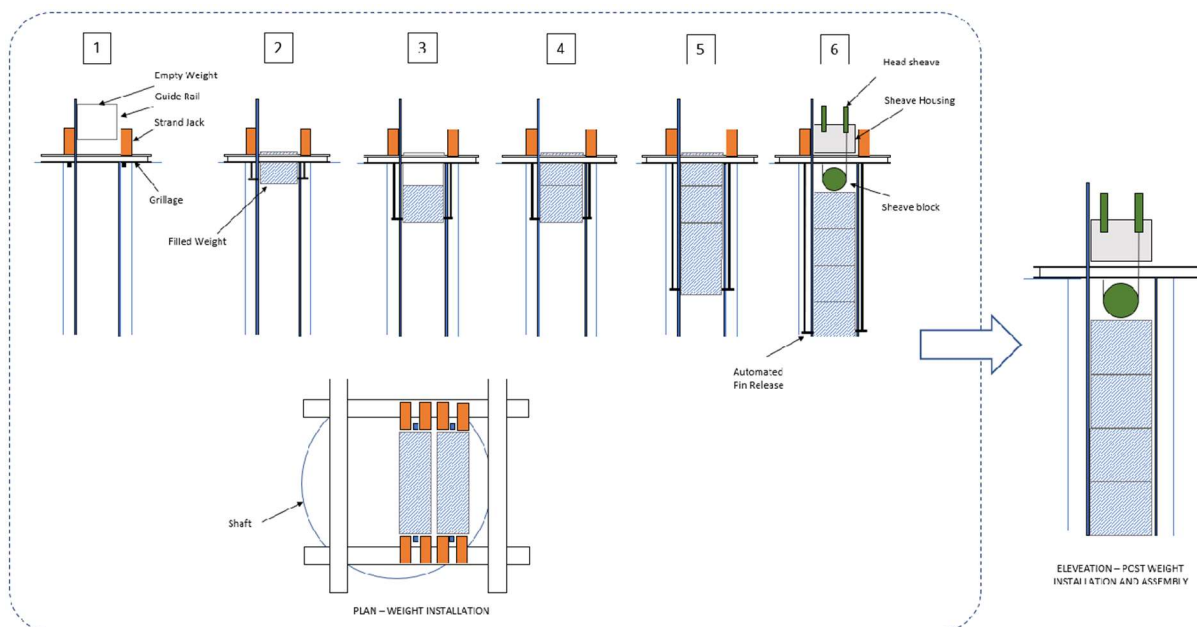
To reduce environmental impacts of GES, the following strategies are recommended:

- **Material Substitution:** Use low-carbon concrete and recycled steel to reduce embodied emissions.
- **Modular Design:** Allows partial disassembly and reuse of components at end-of-life.
- **Local Sourcing:** Reduces transport-related emissions by sourcing construction materials regionally.
- **Synergy with Land Reuse:** Prioritize SGES in regions with legacy mining infrastructure to minimize new land use.
- **Biodiversity Integration:** Incorporate site design that allows for ecosystem restoration or green roofs for tower installations.

The LCA highlights that when deployed in suitable locations and with environmentally conscious design, GES technologies can offer competitive and sustainable alternatives to electrochemical storage systems for long-duration applications.

2.4 Technical Implementation

The schematic drawings below are a specific example of a technical implementation by an unnamed technology provider.



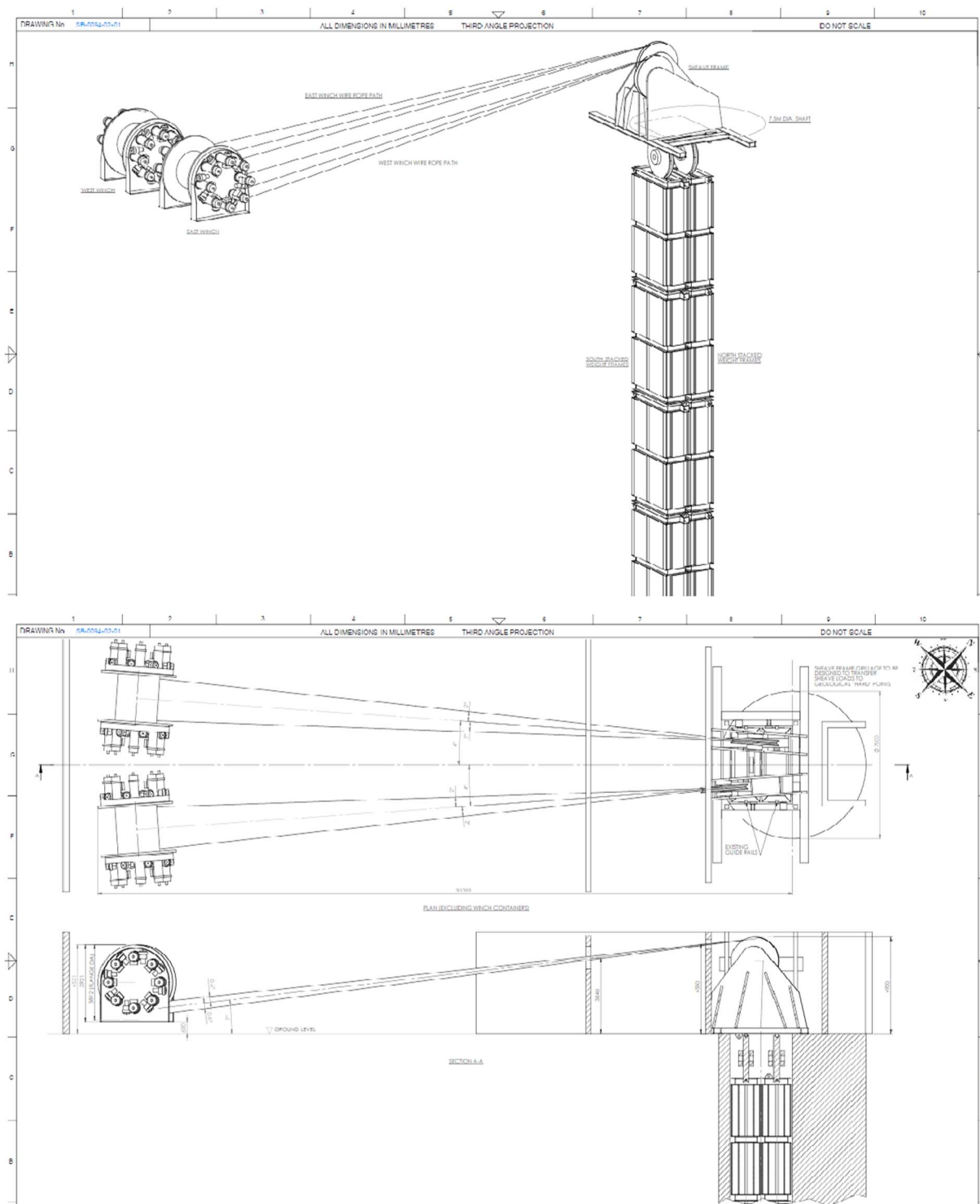


Figure 2.6 Technology implementation of a mine-shaft GES – technical drawings for 4MWh.

2.4.1 Key Design Features

Load subsystem

- **High-density modular weights** – steel-lattice cages filled with iron ore, recycled concrete blocks or locally quarried ballast boost energy density while letting crews adjust mass in small lifts, easing logistics and inspection
- **Segmented assembly** – splitting each weight into 100–150 t modules keeps hoisting loads within common crane or temporary winch ratings, crucial for brown-field shafts and remote tower sites.

Lifting and drive train

- **Bidirectional winches / drum or linear drives** – surface-mounted AC or permanent-magnet machines act as motors when charging and as synchronous generators when discharging; power ratings typically scale 1–20 MW, with inverter packages delivering sub-second response for frequency services. [26]
- **Rope, rail and wheel sets** – compacted-strand steel ropes, hardened rails or rack-and-pinion tracks restrain sway and carry lateral loads, while guide rollers limit wear at speeds $\leq 1 \text{ m s}^{-1}$ to keep side forces within legacy shaft or tower tolerances. [21]
- **Mechanical advantage options** – 2:1 or 4:1 reeving lets designers trade drum torque for rope life and motor size, useful when repurposing older headframes with limited bearing capacity.

Civil and structural works

- **Re-use of existing infrastructure** – decommissioned mine shafts, ventilation raises and industrial headframes cut civil CAPEX by up to 80 % and eliminate green-field permitting.
- **Prefabricated surface pads** – containerised power-conversion skids and bolt-down winch frames minimise on-site concrete and speed up construction to < 12 months for repeat projects. [27]

- **Aerodynamic and seismic detailing** – tapered or clad tower legs plus base-isolation bearings manage wind drag and earthquake forces; the same detailing is being explored for high-rise “gravity battery” façades under design by major skyscraper architects.

Control, safety and monitoring

- **Redundant PLC with grid-forming modes** manages hoist speed, dynamic braking and state-of-charge, while 4-quadrant drives supply synthetic inertia or fast-frequency response within 1.5 s.
- **Condition-based maintenance** – IoT sensors on ropes, bearings and motors feed machine-learning models that predict fatigue, order rope NDT and plan downtime windows.
- **Hazard mitigation** – methane or radon sensors for mine sites, automatic rope-catchers, and fail-safe brakes rated for 150 % of static load are mandated by hoisting codes and mining regulations across the EU and North America.

Modularity and expandability

- **Decoupled power versus energy** – adding extra weights or deeper travel extends energy duration (from 15 min up to 8 h) without altering motor-generator sets; conversely, larger winches lift the same mass faster to raise power.
- **Hybrid co-location** – spare pad area or headframe floors can host batteries, electrolyzers or ultracapacitors, allowing a single interconnection and shared SCADA. [13]

2.4.2 Challenges and Solutions

GES systems share with other large-scale storage technologies a spectrum of risks and challenges that must be rigorously managed to make sure a safe performance and uptime. These risks fall broadly into mechanical, environmental, and operational categories.

Mechanically, the constant cycling of heavy masses imposes fatigue on critical components—steel cables, bearings, rails, winch drums, and motor-generator shafts. Over time, microscopic cracks

propagate under alternating stress, raising the likelihood of sudden failures. To extend service intervals, designers specify high-strength, fatigue-resistant alloys or composite cables (for example aramid-fiber cores). Embedded fiber-optic or strain-gauge sensors along cables and borescope ports in gearboxes feed real-time tension and vibration data to a supervisory control system, to make sure preventative maintenance is done before loads exceed safe margins. Motor-generators, another wear hotspot, face both thermal stresses at high power and mechanical wear on their bearings; switching to water-cooled or oil-cooled permanent-magnet synchronous machines, paired with redundant drive units. This helps to maintain continuous service while one unit undergoes maintenance.

Environmental hazards vary with site conditions. In seismically active regions, sudden ground accelerations can stress tower foundations or rock supports in underground shafts. Therefore viscous dampers, or steel-reinforced shotcrete linings helps decouple structural elements from ground motion. On natural slopes, heavy rainfall may trigger landslides, so earth-retention systems stabilize embankments. Underground cavities risk groundwater infiltration or contamination.

Operational reliability needs minimizing both planned and unplanned downtime. Frictional losses in moving parts reduce round-trip efficiency; using self-lubricating ceramic bearings, low-friction polymer liners, and active regenerative braking can recover a portion of that lost energy.

2.4.3 Scalability and Integration Potential

The scalability and integration potential of GES systems depends on the type of each technology and its design requirements. Understanding these impacts is crucial for identifying strategies to scale and integrate these technologies. Currently, GES systems can be scaled between tens of MWh to several GWh, depending on type of technology and site-specific conditions.

For systems such as tower GES, the environmental footprint is primarily associated with the extensive use of concrete and steel for tower construction. Concrete production contributes significantly to global carbon emissions due to the high energy demands of cement manufacturing. The cement industry is one of the two largest producers of carbon dioxide, creating up to 5 % of worldwide man-made emissions of this gas. Similarly, steel production involves intensive mining and energy use, adding to the carbon footprint. To mitigate these impacts, recycled materials can be incorporated into concrete production. Furthermore, advancements in low-carbon cement technology and the use of modular designs can help minimize material use and associated environmental costs.

Shaft GES systems have a different set of scaling and integration challenges. While these systems reduce surface land use by repurposing abandoned mine shafts, the structural integrity of older mines must be reinforced which is often requiring significant amounts of concrete and steel. Moreover, water intrusion and potential contamination of groundwater pose ecological risks. Waterproof linings and closed-loop water systems can mitigate these issues, while geotechnical surveys and reinforcement techniques ensure that abandoned mines are safely converted for GES use.

Slope-based systems (ARES) typically have a lower construction requirement, as they rely on natural slopes and existing mining or rail infrastructures. However, the visual impact on landscapes and the potential for slope erosion during heavy rainfall or geological instability remain concerns.

Certain GES systems depend heavily on specific geographical features for their deployment and scalability. As it mentioned, Mine shaft GES systems utilize abandoned mine shafts or similar. Globally, the availability of abandoned mines is substantial. The availability of these sites offers

globally versatility and makes the mine shaft GES technology a high scalable system. Structural integrity, as many abandoned mines require reinforcement to safely support SGES operations, high costs of geotechnical surveys and structural modifications, and regulatory and legal barriers on deployment, are all challenges for mine-shaft GES for scaling and deployment. To overcome these challenges, advanced geotechnical assessments using technologies like seismic tomography can help evaluate site suitability. Furthermore, reinforcement techniques, such as using fiber-reinforced concrete, are crucial for strengthening aging mine structures. [4]

2.5 Practical Case Studies

2.5.1 Successful Deployments

Beacon Tower GES Pilot, Germany A demonstration project in rural Bavaria features a 1.2 MWh gravity storage system using a modular steel-and-concrete tower concept. The project demonstrated rapid deployment capabilities and the use of prefabricated materials to reduce construction time and emissions. Although still in the pilot phase, early data suggests high reliability and minimal O&M requirements.

Edmonton Legacy Shaft GES, Canada This installation repurposes an abandoned mine shaft for vertical weight lifting. Operational since 2023, the 5 MWh system provides grid support and frequency regulation. It avoids major land disturbances and demonstrates effective brownfield redevelopment with low lifecycle emissions.

Andes Inclined-Plane GES Concept, Chile In a mountainous mining region, feasibility studies have been completed for an inclined-plane GES system using existing mine ramps. The configuration exploits natural terrain to minimize civil works and reduce environmental disturbance while enabling a storage potential of over 50 MWh. Though not yet constructed, the project highlights the integration of energy storage with post-mining site regeneration.

2.5.2 Lessons Learned

- Repurposing existing structures (e.g., mine shafts) can dramatically reduce both CAPEX and environmental impact.
- Modular, prefabricated designs support faster deployment and reduced on-site emissions.
- Environmental feasibility improves significantly when terrain and structural reuse align with design needs.
- Early stakeholder engagement, particularly in legacy mining regions, helps mitigate regulatory and social barriers.

These case studies confirm that GES systems, when tailored to local conditions and infrastructure reuse opportunities, can offer robust, low-impact energy storage solutions.

2.6 Typical Use Cases of Gravity-Based Energy storage

Gravity-based storage works great at high decoupling capacity of power and energy with good round-trip efficiency and duration capacity, suitable for diverse applications ranging from grid balancing and ancillary services to renewable integration, seasonal and long-duration storage and emergency backup. Below is the list of typical use cases of GES.

1) Grid balancing and ancillary services

GES can inject or absorb power rapidly, making them very suitable for FCR and reserve (mFRR, aFRR) services. By dynamically lifting and dropping masses, they respond within seconds to deviation in system frequency, providing primary and secondary reserves that aid grid stabilization. Energy Vault's G-VAULT™ product line is specifically built to decoupling energy capacity from power rating, providing fast-response grid services at large scale. [13]

2) Renewable energy arbitrage

Irregular sources like wind and solar benefit from the time-shifting aspect of gravity storage. Surplus generation in the middle of the day or in peak wind hours gets stored in potential energy

form; it gets dispatched in the peak evening hours or low-production hours. Mine-shaft gravity storage research demonstrates its potential for bulk integration of renewables in microgrids and stand-alone applications, and Advanced Rail Energy Storage (ARES) demonstrates the potential to utilize off-peak grid electricity to hoist railcars and then generate dispatchable power. [11]

3) Seasonal & long-duration storage

Technologies such as ARES and mine shaft installations can store energy from days to months. Mountain gravity storage research indicates viability for multiday energy shifting in the case of small grids (<20 MW) and as seasonal ability where pumped hydro capability is not possible.

4) Industrial and commercial buildings backup

Heavy industry and data centers require resilience as well as rapid response. Building-integrated gravity systems, like Energy Vault's collaboration with SOM for skyscraper integration, can function as on-site emergency and grid-service resources to reduce diesel genset reliance.

Practical Use Case – Energy Vault in Rudong, China [28]

The 25 MW/100 MWh GES is a 4-hour duration project being built outside of Shanghai in Rudong, Jiangsu Province, China (see Figure 2.7). It balances China's energy grid through the shifting of renewable energy.

It is the world's first commercial grid-scale gravity energy storage system, successfully tested and commissioned by China Tianying (CNTY) on May 4 2024. Licensing agreement with Atlas Renewable for Energy Vault's EVx gravity energy storage system technology was extended from 7.5 to 15 years. The EVx TM system achieves an impressive round-trip efficiency exceeding 80%, with a projected operational lifespan of 35 years.

Despite successful commissioning, the EnergyVault company later in 2024 announced a shift towards electrochemical battery energy storage from GES only, so one could assume that economically the project was not so sound.



Figure 2.7 Rudong Energy Vault Evx 100 MWh commercial unit

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3 Flywheel Energy Storage

3.1 Overview of Flywheel Energy Storage Systems

Flywheel Energy Storage Systems (FESS) store energy in the form of kinetic energy using a rapidly spinning rotor inside a nearly frictionless enclosure. The basic operating principle is straightforward: when there is excess electrical energy, it drives a motor to accelerate the flywheel (a heavy rotating disk or cylinder) to very high speeds, thus converting electrical energy into rotational kinetic energy. When energy is needed again, the motor acts as a generator – the spinning flywheel slows down, and its kinetic energy is converted back into electricity for use. This charge-discharge process can occur very quickly, making flywheels a form of “mechanical battery” that can respond on the order of milliseconds.

A standard Flywheel Energy Storage System (FESS) typically comprises a rotating flywheel, an electric motor/generator with its drive system, bearings, and a protective housing. The flywheel itself acts as the energy storage component by maintaining kinetic energy through rotation. The system operates in three primary modes: charging, standby, and discharging. In the charging phase, the motor drives the flywheel to higher speeds, thereby storing energy. During discharging, the system functions as a generator, converting the flywheel’s rotational energy back into electrical energy to supply power to connected loads.

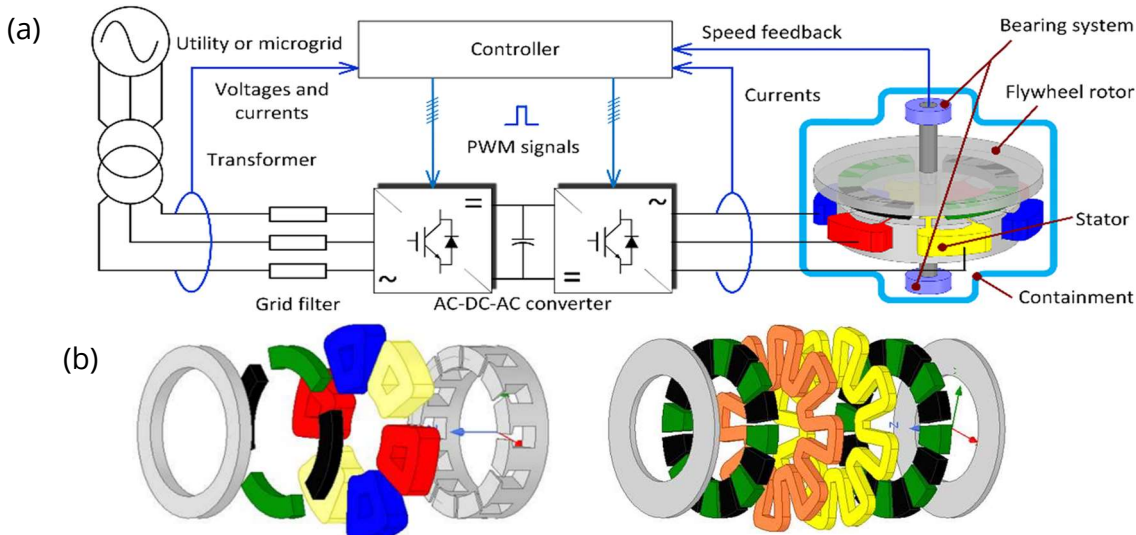


Figure 3.1: (a) A typical FESS with a solid flywheel rotor. A transparent view of the rotor back iron is employed in order to show PMs and stator coils. Two typical AFPM machine topologies, (b) with stator core, (c) without stator core¹

A typical FESS device consists of several key components: a high-strength rotor (the flywheel mass) mounted on a shaft, a combined motor/generator machine, a set of bearings (often magnetic to eliminate friction), and a vacuum enclosure to reduce air drag ² Early-generation flywheels used large steel rotors on mechanical bearings, which limited rotation speed due to friction and material strength. Modern systems use advanced carbon-fiber composite rotors or specialized steel alloys with much higher tensile strength, allowing rotation speeds of 20,000–50,000 RPM (or more) in a vacuum chamber³. Magnetic bearings and vacuum operation minimize energy losses, so the flywheel can spin with very low self-discharge for extended periods (often losing well under 1% of its energy per hour on standby). The state of charge is indicated simply by the rotational speed, unlike electrochemical batteries which degrade and are affected by temperature and depth of discharge ⁴.

Two main design approaches exist: low-speed, high-mass flywheels and high-speed, lightweight flywheels ⁴. Low-speed flywheels (up to ~10,000 RPM) often use heavy steel rotors and sometimes

mechanical or simple magnetic levitation bearings. They are technologically simpler and used in stationary applications where weight is less a concern. High-speed flywheels (20,000–50,000+ RPM) use lighter composite rotors (e.g. carbon fiber) and sophisticated magnetic bearings. These achieve much higher specific energy (energy per unit mass) and power density, at the cost of more complex design and higher material cost ⁴. For instance, a steel flywheel might store on the order of 20–30 Wh/kg, whereas composite flywheels can exceed 100 Wh/kg at very high speeds. In terms of volumetric energy density, designs can range roughly from ~100 up to a few hundred kWh per cubic meter, still generally lower than lithium-ion batteries' energy density, but sufficient for many power-intensive applications. Importantly, increasing the rotor speed has a quadratic effect on stored energy ($\text{energy} \propto \omega^2$), while increasing mass yields linear gains. This means materials science (to allow higher RPM without flywheel rupture) is critical for improving flywheel storage capacity⁴.

In summary, a flywheel storage system rapidly absorbs or releases energy by speeding up or slowing down a spinning mass. Thanks to advances in magnetics and materials, modern FESS can cycle frequently with minimal wear, making them a compelling technology for certain energy storage needs. The next sections will assess the current status of FESS in terms of applications, maturity, scalability, performance, costs, and other key factors.

3.1.1 Maturity and Technological Readiness

Technology Readiness Level (TRL): Flywheel energy storage is generally considered a mature technology. Basic flywheel principles have been known for decades, and modern FESS solutions have reached commercial deployment. In fact, many FESS products are evaluated at TRL 9, indicating systems in actual commercial operation ⁵. According to the International Energy Agency, flywheels are at the highest readiness level (comparable to lithium batteries in maturity) with multiple units operating in real-world environments ⁵. However, it's worth noting that while the

core technology is mature, ongoing innovations (like new magnetic bearing designs, composite materials, or integrated power electronics) continue at lower TRLs in research settings ⁴.

Commercial Availability: There are a growing number of commercial flywheel systems on the market, offered by specialized manufacturers worldwide. In fact, over 20 companies globally have developed or sell FESS technology ⁴. Notable industry players include:

- *Amber Kinetics* (USA) – offers a long-duration flywheel (8 kW/32 kWh per unit) with a **4-hour discharge** capability and a 30-year design life. Amber’s all-steel flywheel is one of the first to provide multi-hour energy storage, boasting >85% efficiency and no capacity fade over time ⁶. They have deployed pilot projects (e.g. a demonstration with Hawaiian Electric) and offer 10-year warranties on their units⁷.
- *Beacon Power* (USA) – a pioneer in grid-scale flywheels, known for the Stephentown and Hazle Township 20 MW plants. Their flywheels (around 25 kWh each) specialize in fast regulation services, with systems in commercial operation since the early 2010s^{8,9}. Beacon’s technology was acquired and continued by other firms after 2018, and their systems remain a benchmark for grid applications.
- *Piller Power Systems / Active Power* (Germany/USA) – provides flywheel UPS systems (often called “PowerBridge”), used in data centers and industrial UPS to deliver ride-through energy for seconds to minutes. These are widely deployed as battery replacements in UPS due to their long life and low maintenance⁸.
- *Stornetic* (Germany) – a European manufacturer offering containerized flywheel solutions (their **EnWheel** flywheel) aimed at renewable integration and industrial applications. For example, Stornetic delivered a flywheel system to EDF in France for a trial on grid support, and has targeted use in wind farms and even railway regenerative braking in the EU.
- *Other emerging players* – e.g., **KineticCore Solutions** (USA startup) developing high-power flywheels for EV charging support¹⁰, **Revterra** (USA) focusing on modular flywheels for commercial buildings, and various research prototypes in China, Japan, and academia pushing the limits of materials and speed.

Today, fully commercial flywheel products are available for purchase, mainly in power ratings from a few kW up to multi-MW (by paralleling units). The number of **installations** worldwide remains modest compared to batteries but is growing. Dozens of large-scale units are in operation for grid services, and hundreds of smaller UPS flywheels are deployed protecting critical facilities. In the

Danube region and Central Europe, adoption has been limited but interest is rising due to the technology's long life and sustainability benefits. As an example of current scale, **Shenzhen Energy Group** in China recently connected a 30 MW flywheel plant (120 units of 250kW each) for grid frequency regulation – currently the world's largest flywheel project⁸. This underscores that flywheels are moving beyond prototype into utility-scale projects.

3.1.2 Scale and Capacity Characteristics

Flywheel systems are **modular by nature**, which gives them flexibility in deployment scale. Each flywheel unit typically provides on the order of kilowatt-hours of energy storage, but multiple units can be installed together to meet higher energy or power requirements.

Table I presents a summary of the performance statistics reported in published studies on FESS. Definitions for key parameters such as depth of discharge, round-trip efficiency, and standby power losses are provided below. Additional details on other performance indicators can be found in reference¹¹

Table 3.1 PUBLISHED METRICS OFFERS STATISTICAL RESULTS FROM MULTIPLE SOURCES

Metric	Value
Power rating (MW)	0.001–10
Specific energy (Wh/kg)	5–200
Specific power (W/kg)	400–30,000
Energy density (kWh/m ³)	0.25–424
Power density (kW/m ³)	40–2,000
Round-trip efficiency (%)	70–96
Calendar life (years)	15–20
Cycle life (cycles)	10,000–100,000
Self-discharge rate (%/day)	24–100

Key points regarding scale and capacity include:

- **Applicable Power Range:** Individual flywheel modules can range from small (a few kW for research or micro applications) up to around 100–250 kW per unit for commercially available high-speed systems⁹. By combining units, effective power installations from tens of kW to tens of MW are achievable. For instance, the 20 MW Beacon Power plant was composed of 200 flywheels each rated ~100 kW. Recently, a 30 MW system in China aggregated 120 flywheels of ~250 kW each⁸. This modularity means flywheels can serve medium enterprise loads or be scaled up to small-grid/community levels.
- **Energy Capacity per Unit:** A single flywheel's energy storage is typically in the single-digit to a few dozen kWh. Many commercial designs fall in the 5–50 kWh range per flywheel. For example, Beacon's units deliver ~25 kWh usable energy each, and Amber Kinetics' product stores 32 kWh. Some high-mass flywheels for long-duration (4+ hour) applications store on the order of 100 kWh, but generally if more energy is needed, additional flywheels are deployed rather than one very large flywheel. Thus, total site storage can be expanded by adding modules, e.g., four Amber flywheels in parallel provide ~128 kWh. *Typical system sizes* for enterprise or district-level storage might involve tens of flywheels delivering a few hundred kWh of energy.
- **Discharge Duration:** Traditionally, flywheels are considered short-duration storage (seconds to minutes). Classic high-power flywheels could discharge their full energy in a matter of minutes (e.g. 15 minutes at rated power, or faster at higher power with less total energy output)⁹. For example, a 25-kWh flywheel providing 100 kW will last 15 minutes, or ~5 minutes if pushed to 150 kW output. However, newer designs have extended discharge times: Amber's 32 kWh unit can supply 8 kW for 4 hours, making it a longer-duration flywheel. Still, relative to many battery systems, flywheels usually cover the short-to-mid duration range – from sub-second response up to a few hours maximum. They are ideal for services that require bursts of power or very frequent cycling rather than multi-day energy shifting. Flywheels are not used for long-term storage over many days (their self-discharge and cost make that impractical), so they fall into the category of short-term to medium-term storage (seconds, minutes, or hours) for grid support.
- **Storage Density:** Flywheels have lower energy density than electrochemical batteries. Specific energy is on the order of 5–50 Wh/kg for most commercial systems (with up to ~150 Wh/kg in cutting-edge designs). This translates to volumetric energy densities roughly in the range of 50–300 kWh per cubic meter of flywheel device, depending on materials and speed (. In practical terms, a flywheel system capable of ~1 MWh might occupy a small building or container array, similar to or somewhat larger than an equivalent battery system. For power-dense applications, flywheels shine – a single flywheel can output hundreds of kW from a device roughly a meter in size – but for energy-dense applications (many hours of supply), a large bank of flywheels would be needed, which can become space-inefficient. It's often noted that if one tries to match the energy of a lithium battery

purely with flywheel mass, the required RPM would exceed material limits by a huge margin^{12,13}. Therefore, today's flywheels are used where power density and cycle life are prioritized over compact energy storage.

- Scalability: Scaling up a flywheel installation is generally straightforward: it means adding more identical modules. This modular approach is highly flexible, allowing installations to be tailored to the required power/energy. There is no strict economy-of-scale requirement – one can start with a few units and expand later. The control systems can coordinate multiple flywheels to act in unison. One limitation is that very large-scale energy needs (hundreds of MWh) would require a very large number of units, which may not be cost-effective compared to alternatives. In practice, flywheels scale well into the low tens of MWh range; beyond that, other storage (like batteries or pumped hydro) might be considered. Nonetheless, for the scale of medium enterprises or small districts, flywheels can be an appropriate solution, especially where short bursts of high power are needed regularly.



Figure 3.2: A large-scale flywheel energy storage facility (30 MW) in Shanxi, China, consisting of 120 modular flywheel units housed in containers (Shenzhen Energy Group, 2024). Such installations demonstrate the ability to scale FESS by aggregating many modules, each contributing a fraction of the total power and energy⁸

In summary, FESS deployments can range from a single small unit for a niche application to dozens of units supporting an electrical grid node. The technology is well-suited for scales up to tens of

MW and durations up to a few hours, which covers many power quality and backup applications. The modular nature means it can adapt to the capacity needs of medium-sized enterprises and communities by adding or removing flywheel modules as needed.

3.1.2 Efficiency and Performance

One of the strong advantages of flywheel storage is its performance in terms of efficiency, response speed, and cycle life:

- **Round-Trip Efficiency:** Flywheels exhibit high round-trip efficiency (the fraction of input energy that can be recovered). Typically, 90–95% of the electrical energy put into a modern flywheel can be retrieved, which is comparable to or even better than most battery systems¹⁴. Common figures cited are around 85–90% efficiency for older or lower-speed designs and up to ~95% for advanced systems with low losses. These efficiencies result from minimal resistive losses in the motor-generator and low friction due to magnetic bearings and vacuum operation. However, note that standby losses (self-discharge) can slightly reduce effective efficiency if energy is stored for longer periods. A high-speed flywheel might lose a small percentage of its energy per hour (e.g. <0.1% per hour in best cases with magnetic levitation and vacuum. For applications where the energy is cycled in and out frequently (multiple times a day), flywheel efficiency remains high. Overall, their energy conversion efficiency is on par with lithium-ion batteries and significantly higher than certain other storage types like compressed air or hydrogen fuel cells.
- **Response Time and Power Performance:** Flywheels provide extremely fast response. They can go from stand-by to full power discharge or charge almost instantaneously (in fractions of a second). This is because the stored energy is purely mechanical and can be modulated by controlling the motor torque very quickly. In grid terms, flywheels can deliver full power in milliseconds, making them ideal for frequency regulation and other ancillary services that require rapid adjustments. The power electronics governing the motor/generator can ramp output up or down faster than typical battery inverters (which may take seconds to minutes to reach full power). Additionally, flywheels can handle high power pulses – they have a high power density, often hundreds to thousands of W per kg, far above batteries¹. This means a properly sized flywheel can absorb or inject huge bursts of power without damage. For example, systems have been demonstrated that supply full power within 4 milliseconds of a control signal, effectively instantaneous for grid purposes¹⁴. This fast

response and high-power capability are a standout performance feature of FESS.

- **Cycle Life and Degradation:** Unlike chemical batteries, flywheels do not suffer from significant degradation with each charge/discharge cycle. The primary wear factors are mechanical (bearing wear or material fatigue), which are relatively minimal in well-designed systems. A flywheel can undergo tens of thousands of cycles with negligible efficiency loss or capacity fade. Data from manufacturers indicates effectively unlimited cycle life within the 20–30 year lifespan – for instance, no daily depth-of-discharge limit is needed and performance on day 1 and day 10,000 cycles is nearly the same ¹⁰. One source notes “*no degradation over time, even with a 30-year life span*” for a modern steel flywheel system ¹⁵. In practical terms, this means flywheels can be charged and discharged multiple times per day (or per hour) without needing replacement, whereas batteries would accumulate wear. The depth of discharge has no impact on lifetime – a full discharge does not harm the flywheel (aside from using up a tiny fraction of bearing lifetime). This makes performance very predictable over the system’s life. Operators also benefit from consistent efficiency; for example, one study found only ~0.14% efficiency reduction per year in a flywheel system, which is negligible. Overall, the lack of capacity fades and high cycle endurance is a major performance benefit, translating to reliable long-term operation.
- **Dynamic Range and Part-Load:** Flywheels can operate efficiently over a wide range of speeds and power outputs. They have no minimum state-of-charge issues – they can be fully “emptied” (zero RPM) without harm and can be left partially charged at any speed. The power output is roughly proportional to the motor torque, which can be controlled smoothly. Unlike some batteries, there is no efficiency penalty for rapid charging or discharging; a flywheel can accept high charge power just as easily as it delivers high discharge power, limited mostly by the motor and power electronics rating. This symmetrical and robust performance makes them very flexible in operation (e.g. switching rapidly between charge and discharge to stabilize frequency).

In summary, FESS offer high efficiency, instantaneous response, and virtually unlimited cycling. They combine the efficiency of batteries with the fast reaction of supercapacitors. A report by the EESI concisely states: “*Flywheels have rapid response times, long life cycles, low maintenance costs, and high energy efficiencies ~90–95%, but energy outputs are small*” ¹⁴. The high performance on the power and efficiency front must be balanced against their limited total energy storage, which defines their suitable applications.

3.2 Financial Analysis

When evaluating cost-effectiveness, it's important to consider the capital cost, operating cost, and levelized cost of flywheel storage relative to alternatives.

Capital Expenditure (CapEx): Flywheel systems tend to have a higher upfront cost per kWh of storage than mass-produced battery packs, but a competitive cost per kW of power for short duration needs. As of recent data, typical **CapEx for flywheels is on the order of €1,000–€3,000 per kWh** of energy capacity⁴. This wide range depends on the design (high-speed composite systems on the higher end, lower-speed steel flywheels on the lower end) and whether the cost includes power electronics and installation. One commercial example, Amber Kinetics, reports roughly ~€1,350 per kWh for their 4-hour flywheel system. In terms of power rating, costs around **€200–€700 per kW** are reported ⁴reflecting that even a small flywheel can deliver high power. By comparison, lithium battery storage might be €300–€500 per kWh for similar scale projects, so on an energy basis flywheels are currently more expensive upfront. However, for applications that are power-intensive but don't need many hours of energy, flywheels can be cost-effective since you purchase less kWh but get high kW capability. Manufacturing cost drivers include the rotor material (e.g. carbon fiber flywheels are expensive to fabricate), precision bearings, and the vacuum containment system. There is also currently less economies of scale in flywheel production compared to batteries, as production volumes are lower. Over time, if production scales up, CapEx may decline for flywheels.

Operational Expenditure (OpEx): Flywheels have relatively **low ongoing costs**. They do not require costly consumables or frequent replacements (no electrolyte top-ups, no battery cell replacements). The main O&M activities are maintaining vacuum pumps, cooling systems for the motor (if any), and periodic inspection of bearings. Some modern flywheels are designed for

maintenance intervals of 10 years or more for major components ¹⁶. One estimate put operational costs at around €0.7 per kW per year – this is quite low, implying that for a 100 kW unit, annual maintenance might be on the order of €70, likely just electricity for standby losses and scheduled checks. Because the flywheel device itself doesn't degrade, you don't have to allocate large reserves for mid-life replacements (unlike a battery where one might need to replace the pack after, say, 10 years). The energy efficiency being high also means minimal cost lost to wasted energy (less electricity needs to be "paid" to losses). Insurance and safety inspections might add some OpEx, but generally, flywheels are often touted as **low maintenance** systems. An additional operational cost consideration is standby power: to keep a flywheel on standby, a small amount of power is needed for vacuum maintenance and possibly heating of the enclosure in cold climates, but these are usually minor. Overall, the **OpEx of flywheels is favorable**, often lower than battery systems which require HVAC and suffer degradation-related expenses.

Levelized Cost of Storage (LCOS): LCOS is a metric that spreads all costs over the total energy throughput over life, yielding a cost per kWh delivered. Thanks to the long life and high efficiency of flywheels, their LCOS can be quite competitive over decades. While exact values depend on assumptions, one analysis for a microgrid application (25-year life, 1 cycle per day) estimated an LCOS of **around \$0.038 per kWh for flywheels, versus \$0.11 per kWh for lithium-ion batteries** in the same scenario ¹⁷

This dramatic difference is because the battery would require several replacements over 25 years and has higher maintenance and efficiency losses, whereas the flywheel's high upfront cost is amortized over 25+ years of daily use. Another source (Storage Lab analysis) found advanced flywheels achieving ~\$100 per MWh (= \$0.10/kWh) levelized cost in certain high-utilization roles, making them among the lowest lifetime cost options for short-duration storage ¹⁸. It's important to note these figures assume the flywheel reaches its full life and is used frequently; if a flywheel

is used only rarely, the cost per use would be higher. But generally, when comparing lifetime costs for frequent cycling, flywheels can be **cost-effective in the long run**, even if the upfront price is higher.

Unlike conventional flywheel technologies, Storage Lab came up with a novel flywheel storage system—Qnetic flywheels designed for stationary, large-scale and multiple-hour discharge applications. Qnetic's approach centers on significantly scaling up the rotor—the core energy-storing component—to dimensions of 5.5 meters in height and 2.5 meters in diameter. This enlarged rotor, constructed from ultra-lightweight composite materials, allows each unit to achieve a storage capacity of 2,000 kWh.

Qnetic highlights that the rotor's design and material optimization significantly enhance energy storage capabilities by combining low weight, high mechanical strength, and high rotational speed. This results in a high energy-to-cost ratio by minimizing material use and reducing mechanical losses, making the system more cost-efficient. The technology is being developed by Qnetic Corporation, with prototype installations expected to begin in 2023 or 2024. The illustration in Figure 3.3 (a) and (b) depicts a conceptual layout of an energy storage facility utilizing multiple Qnetic flywheel units, alongside a comparison of their lifetime costs with other emerging storage technologies

(a)



(b)

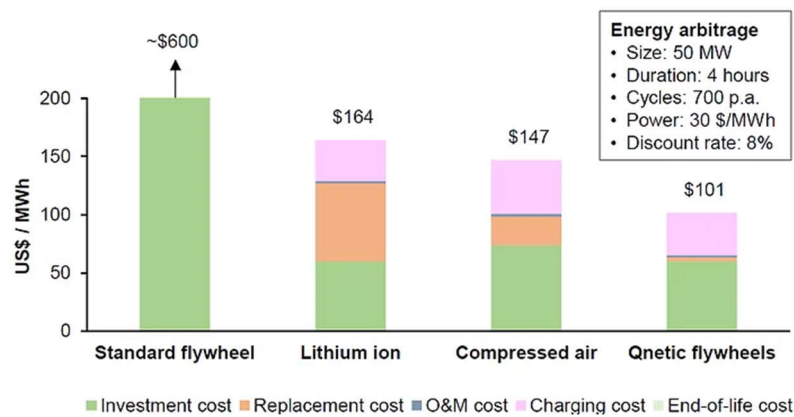


Figure 3.3. (a) depicts a conceptual layout of an energy storage facility utilizing multiple Qnetic flywheel units (b) illustrates the projected Levelized Cost of Storage (LCOS) in a hypothetical 2030 energy arbitrage scenario for four different storage technologies. The top-right text box details the system's operational parameters—such as rated power, discharge duration, expected cycling frequency, input energy price, and discount rate. The chart uses color coding and legends to show the breakdown of each technology's cost components over its lifetime¹⁸

Cost Drivers and Trends: The main cost barrier for flywheels is the manufacturing cost of the high-precision, high-strength components. Carbon fiber rotor fabrication, magnetic bearing

systems, and power electronics all contribute to cost. As research yields better designs (for example, simpler motor-generators or cheaper composite manufacturing techniques) costs may decline. The lack of expensive raw commodities (like lithium, cobalt, etc.) is a benefit – steel and carbon fiber are not scarce, and older flywheels even use recycled materials. In fact, one product is 98% steel by weight, which helps keep material costs manageable and allows recycling at end-of-life ¹⁹. If production volumes rise and standardization improves, the CapEx per unit energy should decrease.

In conclusion, flywheel storage is capital-intensive per kWh but long-lived and low maintenance, which can yield a competitive lifetime cost especially for high cycle applications. For short-duration, high-power needs, they may actually come out cheaper than batteries when considering a 20-year horizon. Each project must be evaluated for its duty cycle: if the application will heavily utilize the flywheel's strengths (lots of cycles, high power, relatively low energy), the economics can be very favorable.

3.3 Environmental Impact

3.3.1 Material Use and Lifecycle Impact

The environmental life cycle assessment (LCA) of Flywheel Energy Storage Systems (FESS) considered two representative configurations: low-speed steel flywheels (LFES) and high-speed composite flywheels (HFES). The assessment followed ISO 14040/44 and EN15804+A2 standards using cradle-to-grave boundaries. Inventory modelling was performed in openLCA v2.4.1 with the ecoinvent v3.11 database.

The functional unit was defined as 1 kWh of delivered energy over the full operational life of the system. Foreground data were derived from published case studies—Beacon Power (HFES) and Temporal Power's Minto project (LFES). The systems were evaluated over a 20-year lifetime with 100,000 full cycles.

Key findings:

- **Steel-based LFES:** The largest environmental contribution arises from the manufacturing of the steel rotor and reinforced concrete housing. High mass requirements lead to elevated GWP and resource depletion scores.
- **Composite-based HFES:** Although lighter, the carbon fiber rotor production has significant impacts, especially in terms of energy use and human toxicity. However, due to improved energy efficiency and lower operational losses, the HFES achieves better impact scores per kWh delivered.
- Use phase impacts are minimal due to low emissions and high roundtrip efficiencies (85–95%).

Impact categories assessed included global warming potential (GWP), acidification, eutrophication, particulate matter formation, and abiotic resource depletion. Compared to battery systems, FESS performs well in circularity and long-term sustainability due to its low degradation and extended cycle life.

3.3.2 Recycling and End-of-Life Considerations

Flywheel systems exhibit high recyclability potential:

- **LFES:** Steel components are fully recyclable. Concrete from containment structures can be crushed and repurposed in secondary construction applications.
- **HFES:** Composite rotors are more challenging to recycle due to the thermoset matrix, though ongoing research explores pyrolysis and mechanical shredding options. Other components such as the vacuum housing, power electronics, and magnetic bearings are largely recoverable.

The long service life and minimal performance degradation of flywheels also support delayed material replacement and reduced waste generation. End-of-life treatment for FESS results in lower environmental burdens compared to most electrochemical battery chemistries, especially those reliant on critical raw materials.

Overall, FESS demonstrates strong circularity potential, particularly in low-speed steel configurations.

3.3.3 Mitigation Strategies

Several measures can further reduce environmental impacts of FESS:

- **Material Substitution:** Using recycled steel and low-impact concrete mixes for LFES housing.
- **Energy-Efficient Manufacturing:** Reducing energy consumption during composite rotor fabrication.
- **Design for Disassembly:** Facilitates easier recovery of key components.
- **Component Standardization:** Encourages reuse and simplifies maintenance logistics.
- **Renewable Energy Supply:** Manufacturing and assembly processes powered by renewable electricity can significantly cut upstream GHG emissions.

When optimized, flywheel systems—especially in hybrid or high-frequency grid support roles—offer environmentally robust storage alternatives, combining low impact per kWh with exceptional durability and end-of-life recyclability.

3.4 Technical Implementation

Safety and Risks

The primary safety concern for Flywheel Energy Storage Systems (FESS) is mechanical failure of the rotor at high speeds²⁰. A disintegrating rotor can cause explosive damage, so robust containment systems (steel or composite enclosures, underground pits) are standard. Real-time monitoring and automatic shutdown protocols further reduce the risk. Proper rotor testing and preventive maintenance are critical.

Over-speed is managed through inverter controls, mechanical brakes, and redundant speed monitoring. Electrical safety protocols similar to high-voltage systems are applied, including grounding and insulation²¹. While power electronics pose typical electrical risks, they are no greater than those of battery systems.

Flywheels store large amounts of kinetic energy—comparable to explosive forces—making containment and access control vital. Magnetic bearings reduce noise and vibration, and imbalances are automatically detected and addressed. Fire risk is very low due to the absence of flammable materials or thermal runaway reactions, unlike batteries.

Materials and Track Record: FESS do not use hazardous chemicals; failures yield only metal or composite debris. Older units occasionally failed, but modern designs have strong safety records with advanced containment and real-time monitoring ²². Manufacturers follow stringent (often proprietary) safety protocols akin to those for industrial machinery.

Maintenance and Operational Requirements

FESS systems are built for minimal upkeep—no chemical refills or frequent component swaps. Maintenance includes vacuum pump checks, bearing inspections, and motor evaluations, often only annually. Magnetic bearings further reduce servicing needs, and some vendors offer 10-year maintenance intervals ²³.

Sensors track vibration, speed, and temperature, enabling condition-based maintenance. The systems are largely autonomous but require trained technicians for emergency handling and safe shutdown. Compared to batteries, flywheels are simpler to operate, with no charge balancing or fire systems required.

Flywheels are modular, skid-mounted, and climate-resilient, requiring no special cooling. They can operate across wide temperature ranges and are suitable for harsh or remote settings. Mounting requires vibration-resistant foundations, and some systems are installed underground for added safety.

FESS can easily integrate with existing energy management systems through inverters and SCADA interfaces²⁴. Their fast response makes them ideal for hybrid setups with batteries or renewables. Downtime for maintenance is minimal, as flywheels can spin back up quickly.

Personnel need training in high-speed mechanical and electrical safety. Retrofitting into existing infrastructure is often straightforward, especially when replacing batteries or adding capacity to solar and UPS systems. Flywheels' modular form factor allows them to fit in constrained spaces.

Flywheels typically last 20–30 years with minimal degradation, even under daily cycling²⁵. They offer hundreds of thousands of charge-discharge cycles, outlasting most batteries. End-of-life is predictable and often linked to mechanical wear rather than capacity loss. Refurbishing can further extend operational life.

Spatial and Site Considerations

FESS units have a small footprint per kW but a larger one per kWh. Units range from appliance-sized to containerized arrays, with installations adaptable to urban, rural, or underground settings. Most designs are vertical, saving floor space and simplifying site integration²⁶.

Flywheels function in hot, cold, or high-altitude environments without the need for air conditioning. Their sealed vacuum enclosures isolate the rotor from external conditions. Installations in seismic areas require secure anchoring, and indoor placement is possible due to zero emissions²⁷.

Modular design allows distributed placement or clustering. No need for fuel or water; only a stable foundation and electrical connection are required. Their rapid charge/discharge ability supports weak grids and stabilizes voltage, improving grid performance.

Flywheels are quiet and visually unobtrusive, often housed in standard containers. There's no towering infrastructure or emissions. With minimal visual or auditory disturbance, community acceptance is usually high, especially with proper safety education.

3.5 Practical Case Studies

3.5.1 Grid Stabilisation Projects

Beacon Power Flywheel Plant, Stephentown, NY (USA) This 20 MW flywheel-based frequency regulation facility utilizes 200 high-speed composite flywheels operating at 16,000 rpm. Installed in 2011, the project demonstrated the feasibility of short-duration high-frequency response in grid

markets. Each flywheel system has an energy capacity of 25 kWh and is housed in an underground vacuum-sealed steel chamber to minimize air resistance and noise. With a 15-minute discharge capability per unit, the plant supports grid frequency regulation without degradation and remains operational with minimal maintenance. Key benefits include near-instantaneous response times (under 1 second), resilience against performance decay, and a proven record of over 100,000 charge/discharge cycles. The system is managed by a proprietary Power Electronics and Control System (PCS) that ensures synchronization with ISO New England's energy market.

Minto Flywheel System, Ontario (Canada) Commissioned in 2014, this low-speed FESS installation comprises 10 steel flywheels (each ~2 MW) used primarily for voltage regulation and short-term backup power. The flywheels are designed as solid steel rotors operating at ~3,000 rpm and magnetically levitated to reduce friction and bearing losses. They are installed in an underground reinforced-concrete vault for safety and thermal stability. The system offers a total storage capacity of 200 kWh, with an average roundtrip efficiency of 85%. It was funded through a public-private partnership involving the Ontario Ministry of Energy and Temporal Power Ltd., and serves as a demonstration of FESS in municipal grid applications with minimal site disturbance and long component lifetimes (>20 years).

3.5.2 Flywheel Use in Transportation Systems

London Underground (UK) In partnership with Ricardo and Artemis Intelligent Power, flywheel energy recovery systems were installed in the braking systems of deep-line trains. These steel-based low-speed flywheels capture regenerative braking energy, which is then reused during train acceleration or fed back into the power rail. This system reduces peak electrical demand by up to 20%, improves train turnaround time, and minimizes electrical infrastructure strain. The units operate in excess of 60,000 cycles per year without noticeable degradation. Additionally, the retrofitting required minimal track or vehicle modification and contributed to lower lifecycle emissions and operating costs for Transport for London.

Kinergy Flywheel Bus Trials (UK) Kinergy's KERS flywheel modules were trialed in multiple public transport fleets from 2012 to 2015. These high-speed composite rotors (rotating at up to 60,000 rpm) were mounted horizontally and used a continuously variable transmission (CVT) to store and release energy from vehicle braking. In practical conditions, the modules reduced fuel consumption by 20–25% and CO₂ emissions proportionally. The trials highlighted engineering challenges, such as managing vibration and rotor containment under dynamic loading. Despite

limited commercial uptake, the results showed technical viability and cost-saving potential, especially for high-stop-density routes like inner-city buses.

These case studies demonstrate the technical and environmental viability of FESS across both stationary and mobile applications. Grid applications benefit from FESS's durability and fast response capabilities, while transport systems leverage their efficiency and regenerative energy potential. Future commercial deployment may be enhanced by integrating hybrid control systems and achieving further cost reductions through modular mass manufacturing.

3.6 Typical Use Cases of Flywheel Energy Storage

Flywheel energy storage is a **versatile technology** with a range of current applications across the power sector and industry. Their unique ability to deliver or absorb power almost instantaneously makes them ideal for short-duration, high-power roles. Compared to other forms of energy storage, particularly chemical batteries, flywheel systems offer significantly higher power density but lower energy density. They are also characterized by extended operational lifespans and efficiency levels that are generally on par with those of batteries. These attributes make flywheel systems especially well-suited for applications involving short-term energy storage.

Flywheel Energy Storage Systems (FESS) have been implemented in various sectors, including uninterruptible power supply (UPS) systems, regenerative braking in racing vehicles, public transit systems, off-road machinery, and port equipment like container cranes and straddle carriers. Additionally, they are increasingly being utilized in grid support applications and have been considered for high intensity uses such as pulse power delivery in electromagnetic launch systems. A summary of the leading FESS manufacturers, particularly those focusing on UPS, braking energy recovery, and grid integration, is presented in Table I

Table 3.2 MAJOR MANUFACTURERS OF FESS AND THEIR APPLICATIONS

Manufacturer	Ratings	Applications
ABB	1,800–3,600 rpm, 100–1,500 kW	Renewable microgrid stabilization ²⁰
Active Power	Max. 10,000 rpm, 225 kW	UPS ²⁸

Beacon Power, LLC	Max. 16,000 rpm, 100 kW	Utility grid ²⁹
Calnetix Technologies, LLC	25,000–35,000 rpm, 125 kW	UPS ³⁰
Williams Hybrid Power	Max. 36,000–45,000 rpm, 150–180 kW	Brake energy recovery for vehicles ³¹
Kinetic Traction Systems	Max. 36,000 rpm, 250–400 kVA	Brake energy recovery, UPS and grid ³²
PowerThru	–	UPS ³³
PUNCH Flybrid	Max. 60,000 rpm, 60 kW	Brake energy recovery for vehicles ³⁴
Ricardo PLC	Max. 44,000 rpm, 100 kW	Brake energy recovery for vehicles ³⁵
Temporal Power	–	Utility grid ³⁶

Some of the prominent use cases and deployment contexts for FESS include:

- Grid Stability and Frequency Regulation:** In electrical grids, maintaining frequency (e.g. 50 or 60 Hz) is crucial. Flywheels can rapidly inject or absorb power within milliseconds to counteract frequency deviations caused by sudden imbalances of supply and demand. For example, if a power plant trips offline, flywheels can immediately release power to keep the grid stable until other resources respond. Their fast response and high cycle life make them well-suited to frequency regulation markets. *Ideal implementations:* high-speed flywheels with magnetic bearings, which offer fast ramping and can withstand continuous cycling^{24,37}.
- Uninterruptible Power Supply (UPS):** Many critical facilities (data centers, hospitals, telecom hubs, industrial processes) use UPS systems to ride through short power outages. Flywheels serve as a reliable, low-maintenance alternative to batteries in UPS systems, providing instantaneous backup power for a few seconds to minutes until diesel generators or backup grids kick in. Flywheel UPS systems are already commercially used in data centers and factories – they react faster than chemical batteries and don't degrade with each discharge. *Typical implementations:* lower-speed, heavy flywheels (often steel rotors) with mechanical bearings, which are cost-effective and can deliver a few minutes of power^{38,39}.
- Renewable Energy Smoothing and Integration:** The variability of wind and solar power can cause rapid fluctuations in output. Flywheels help “smooth” these fluctuations by storing excess energy during brief surges (e.g. a gust of wind or sudden sunshine) and injecting it during dips, thus stabilizing the renewable power output⁴⁰. They are particularly useful for handling short-term oscillations that would otherwise cause wear on batteries or grid equipment. In solar PV farms, flywheels can mitigate the rapid changes caused by

passing clouds and even extend battery life by handling the high-frequency cycling⁴¹. Flywheels have been paired with large solar and wind installations to improve power quality and support grid integration. *Ideal implementations*: high-speed composite flywheels with advanced bearings, offering high efficiency and frequent cycling capability⁴².

- **Power Quality Improvement:** In industrial or commercial settings sensitive to voltage dips or brief disturbances, flywheels can act to stabilize voltage and improve power quality. By injecting power during momentary drops (voltage sag) or absorbing energy during surges, they protect equipment from power transients⁴³. This use is closely related to UPS and grid support functions.
- **Transportation and Kinetic Energy Recovery:** Flywheels have been used as kinetic energy recovery systems (KERS) in transportation – for example, in some buses, race cars, or trains. During braking, kinetic energy can be transferred to spin up a flywheel; upon acceleration, that energy is released, reducing fuel or electricity consumption⁴⁴. While not yet widespread in consumer vehicles (largely due to weight and safety concerns of high-speed rotors), this concept has been demonstrated in Formula 1 racing and rail systems for energy-efficient braking. *Ideal implementations*: compact, high-speed flywheels (often composite rotors) specifically designed for vehicular use, with robust containment for safety.
- **Industrial Machinery and Pulse Power:** In factories, flywheels can provide short bursts of high power to machines that have pulsating loads (such as heavy presses or motors), leveling out the load on the electrical supply⁴⁵. They can also absorb regenerative energy from machinery. This improves efficiency and reduces peak power demands from the grid. Industries like manufacturing, oil & gas, and aerospace use flywheels to manage power spikes and ensure stable supply for sensitive equipment⁴⁶.

Real-world deployments highlight these applications. For instance, in the United States, Beacon Power deployed a 20 MW frequency regulation plant in Stephentown, NY – the first of its kind – using an array of flywheels to help balance the grid⁴⁷. This plant (and a similar 20 MW plant in Pennsylvania) uses dozens of flywheel modules to collectively inject or absorb power on command, demonstrating grid-scale use of FESS. In critical facilities, companies like Piller/Active Power and others have installed flywheel UPS systems to protect against outages, underscoring the technology's maturity in the backup power market. As renewable penetration grows, pilot projects in Europe (e.g. Ireland and Germany) and elsewhere are integrating flywheels for wind and solar smoothing⁴⁸. Flywheels' combination of quick response and long cycle life fill an

important niche between supercapacitors (very fast, very short duration) and batteries (slower response, longer duration).

Overall, FESS technology is already in practical use for niche but important roles. The next sections will evaluate how mature technology is and how it competes with alternatives for broader deployment.

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4 Hydrogen Energy Storage

4.1 Overview of Hydrogen as an Energy Carrier

Hydrogen, with the chemical symbol H (from Hydrogenium), is the simplest and lightest element in the universe. Each hydrogen atom consists of just one proton and one electron. In nature, it's usually found as a diatomic molecule – that is, two hydrogen atoms bonded together to form H₂. Hydrogen is a **colorless**, **odorless**, and **tasteless** gas. Because it's so light, it can escape Earth's atmosphere and drift off into space. According to current measurements, hydrogen makes up about **75% of the mass** and **90% of all atoms** in the observable universe, making it the most abundant element in existence.

Table 4.1 Fundamental parameters of Hydrogen

Density	0,08988 kg/m ³
Specific heat capacity	14 304 J kg ⁻¹ K ⁻¹
Relative atomic mass	1,00794
Lower heating value – LHV	10,8 MJ/m ³ – 119,55 MJ/kg = 33,21 kWh/kg
Higher heating value – HHV	12,748 MJ/m ³ – 141,9 MJ/kg = 39,42 kWh/kg

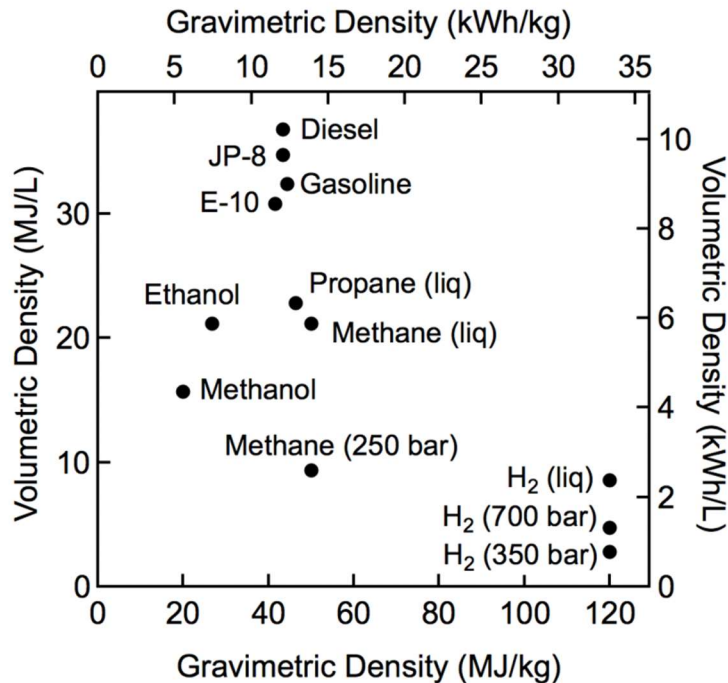


Figure 4.1 Specific volumetric and gravimetric density of several fuels - Source: <https://www.energy.gov/eere/fuelcells/hydrogen-storage>

Today's **Hydrogen:** **Made,** **Not** **Mined**
 Currently, hydrogen is **mostly produced rather than extracted**. While there are a few rare natural deposits around the world where hydrogen can be mined, the vast majority of hydrogen in use today is man-made.

Hydrogen acts as an **energy carrier** – it stores and transports energy but isn't a primary energy source on its own. One of the cleanest ways to produce hydrogen is through **electrolysis of water** using renewable sources, a process that uses electricity to split water (H₂O) into hydrogen (H₂) and oxygen (O₂).

Currently, only app. 4% of hydrogen is produced through electrolysis, while remaining 96% comes from fossil fuels.

When electricity from renewable sources like solar, wind or hydropower is used for electrolysis, the resulting hydrogen is a **green and sustainable fuel** for the future.

4.1.1 Technology overview

One advanced method for storing electrical energy is through the production of hydrogen, which serves as a versatile energy carrier. This approach is commonly referred to as **P2G2P** (Power-to-Gas-to-Power).

Hydrogen is produced by means of electrolysis, where electrical energy is used to split water into hydrogen and oxygen in an electrolyzer. The generated hydrogen is then stored in tanks, either in gaseous, liquid, or chemically bound form, depending on the application and system design. If the oxygen by-product is not utilized, it is safely vented into the atmosphere.

The reconversion of hydrogen into electrical energy is achieved either electrochemically in fuel cells or thermally in combined heat and power (CHP) units, such as piston engines or gas turbines. The storage capacity is constrained only by the physical volume of the storage system, while the duration of energy storage is virtually unlimited.

Both hydrogen production and its conversion back to electricity generate usable heat, which—when recovered—significantly enhances the overall system efficiency.

Low-temperature electrolysis (commercially available electrolyzers)

In cases where a technological waste heat is not available a low-temperature electrolysis is used. Following chapters describes typical properties of low-temperature electrolyzer technologies. Detailed technical parameters and technical requirements are associated with a specific commercial product. Detailed information is usually available after signing NDA documents.

4.1.1.1 AEL – Alkaline Electrolyser

Alkaline Electrolyzer is the oldest method of electrolysis, in which a porous membrane – a diaphragm – is used for separation. The electrolyte is potassium hydroxide (KOH). This technology has its limitations, such as low efficiency and low output pressures depending on the diaphragm material used. The electrolyzer reacts slowly to power changes, and it cannot be easily started up or shut down. The produced hydrogen has to be compressed.

AEL is a mature technology that has achieved low capital costs. It is possible to connect several modules in parallel and scale the output. Electrolysis takes place at temperatures of 40–90°C. It is necessary to avoid high differential pressures to prevent mixing of hydrogen and oxygen. AEL has a relatively long cold start time, around 50 minutes. When connected to fluctuating energy sources, gas purity changes, and at partial load, equipment degradation may also occur.

4.1.1.2 PEM – Polymer Electrolyte Membrane (Proton Exchange Membrane)

A PEM (Proton Exchange Membrane) electrolyzer operates at approximately three times the current density of an alkaline (AEL) electrolyzer and is capable of withstanding short-term power overloads. The hydrogen and oxygen gases produced are effectively separated by the PEM membrane. These systems typically deliver hydrogen at an output pressure of 20–35 bar, with some configurations supporting even higher pressures.

One of the key advantages of PEM electrolyzers is their fast dynamic response to power fluctuations, which makes them highly suitable for coupling with renewable energy sources. However, a major technical drawback lies in the high material demands of the system, as it operates in a strongly acidic environment (pH ~ 14). The membrane is highly sensitive to water purity. Therefore, water treatment is necessary both at startup and continuously during operation, particularly through the recirculation and conditioning of process water.

Compared to alkaline electrolyzers, PEM systems exhibit significantly faster response times to input power changes—on the order of milliseconds. However, current research suggests that repeated system startups and rapid voltage fluctuations may significantly shorten membrane lifetime compared to steady-state operation. [29], [30]

4.1.1.3 AEM – Anion Exchange Membrane

Anion Exchange Membrane (AEM) electrolyzers combine the advantages of both alkaline (AEL) and proton exchange membrane (PEM) electrolyzers. The system uses an anion exchanging membrane to separate hydrogen and oxygen while enabling the electrochemical reaction to occur in an alkaline environment. Thanks to its operation in alkaline conditions, the design of the AEM electrolyzer is less dependent on expensive materials, making it a cost-effective alternative. The membrane allows for higher output pressures compared to traditional AEL electrolyzers. Output pressures of up to 35 bar are achievable, making them comparable to those of PEM systems.

The dynamic response time of AEM electrolyzers to changes in input power is significantly faster than that of alkaline systems—on the order of seconds—although slower than PEM electrolyzers, which typically respond within milliseconds. The company **Enapter** manufactures standardized AEM electrolyzers with a nominal hydrogen production capacity of 0.5 Nm³/h and a power input of 2.4 kW. For larger applications, these units are modularly combined into multi-core systems, with overall capacities commonly scaling up to the megawatt range. [31]

Table 4.2 Comparison of Water Electrolyzer Technologies

Parameter	AEL (Alkaline Electrolyzer)	PEM (Proton Exchange)	AEM (Anion Exchange Membrane)

		Membrane)	
Electrolyte	KOH (30–40%)	Solid acidic membrane (e.g. Nafion)	Solid alkaline membrane
Operating temperature	60–90 °C	50–80 °C	30–60 °C
Reaction time (warm start)	Tens of minutes	Milliseconds	Seconds
Cold start time	>30 minutes	1–5 minutes	5–10 minutes
Cell voltage	1.8–2.4 V	1.8–2.2 V	1.8–2.2 V
Efficiency (LHV)	46–66%	54–63%	57–62%
Electricity system consumption	50.1–72.3 kWh/kg H ₂	53–61.2 kWh/kgH ₂	53,3–57,9 kWh/kg H ₂
Output H ₂ pressure	1–30 bar	Up to 100 bar	1–30 bar
Hydrogen purity	99.5–99.9%	>99.999%	>99.99%
Feed water purity	Demineralized, ~1–5 µS/cm	High-purity water (ASTM Type II/I) ~0.1–1 µS/cm	Demineralized up to ultra-pure
Typical water conductivity	≤5 µS/cm	≤0.1–1 µS/cm	≤1 µS/cm
Electrode materials	Ni, Fe, Co	Pt, Ir	Ni, Co, Mn
Capital costs	Low (~500–1000 €/kW)	High (~1000–1800 €/kW)	Medium (~600–1200 €/kW,)
Operating costs	Low	Higher due to membranes and maintenance	Potentially low
System lifetime	60,000–90,000 h	20,000–60,000 h	~10,000–20,000 h (limited data)
Technology maturity	TRL 9 – commercial	TRL 7-9 – commercial	TRL 7-9 – commercial
Operational flexibility	Low – slow response	High – suitable for variable sources	High – suitable for renewables
Advantage	Long lifetime, cheap electrolyte	High H ₂ purity, pressure, fast response	Low material cost, operational flexibility
Disadvantage	Low flexibility, lower pressure	Expensive materials, water sensitivity	Shorter lifespan, less proven

4.1.1.4 Multi-stack solution

For RES (PV and Wind) and fluctuating sources, a multi-core solution can be used. Multi-cores are assembled from "small" standardized electrolyzers with a power input of about 2.5 kW. This solution allows you to assemble any electrolyzer power. Control is carried out by connecting the power supply of individual electrolyzers. Power management optimizes the operation and utilization of individual stacks. The device allows changing individual electrolyzers/stacks during operation.

Multi-stack AEM technology by Enapter www.enapter.com up to 1 MW.



Figure 4.2 AEM Flex 120 - Source: <https://www.enapter.com/aem-electrolysers/aem-flex-120/>

Multi-stack PEM technology by Leancat www.leancatwe.com up to 0,5 MW.

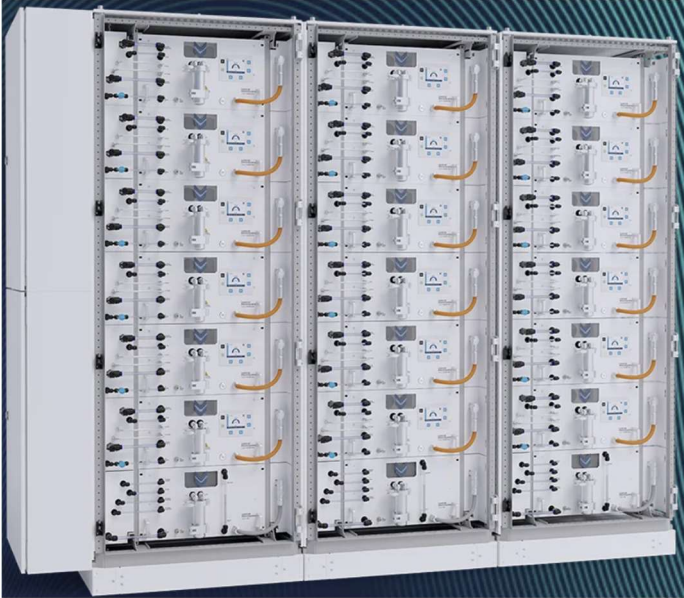


Figure 4.3 - H2gen -Source: <https://leancatwe.com/hydrogen-generators/>

4.1.1.5 Electrolyser technology combination

Co-installment of electrolyzer technologies AEL and PEM was presented in case study for RES and their combinations. The power ratios of the AEL and PEM electrolyzer technologies were selected based on the output characteristics of renewable energy sources and their combinations. [32]

Hydrogen storage

Physical-based

Compressed gas Pressure Storage – Pressure Vessels

Hydrogen storage pressure vessels must be hermetically sealed, and their construction materials must be resistant to hydrogen embrittlement. These vessels are typically classified into two categories: low-pressure (up to 50 bar) and high-pressure (200–700 bar).

Low-pressure vessels are usually welded and offer the advantage of lower manufacturing costs. They can be connected directly to an electrolyzer without requiring a compressor, which simplifies the system and reduces overall costs. However, they require more physical space due to their lower energy density. The gravimetric hydrogen content in pressure vessels typically ranges from 1–2% of the vessel's weight. High-pressure vessels operating at 700 bars can achieve gravimetric hydrogen densities of up to 6%.

There are four classes of pressure vessels Type I – Type IV. For stationary storage is used Type I and Type II.

Table 4.3 Hydrogen Pressure Vessels Classification

Tank Type	Working Pressure	Material	Typical Application		Approximate Cost per kg of Stored H ₂ (EUR)
Type I	up to 300 bar	All-metal construction (steel or aluminum)	Stationary storage, industrial applications		540-720 EUR, pressure 300 bar, from price offer year 2022
Type II	up to 300 bar	Metal vessel	Stationary		

		with partial composite wrap	storage, refueling stations		
Type III	up to 700 bar	Metal liner with full composite wrap	Automotive industry, mobile applications		
Type IV	up to 700 bar	Polymer liner with full composite wrap	Automotive industry, mobile applications		

Note: Prices are approximate and may vary depending on the manufacturer, specifications, and order volume.

Additional Information:

- **Type I** tanks are the least expensive but have higher weight, limiting their use in mobile applications.
- **Type II** tanks offer higher working pressures due to composite wrapping but remain relatively heavy.
- **Type III** and **Type IV** tanks are lighter due to the use of composite materials, making them suitable for the automotive industry, where weight is crucial.



Figure 4.4 High pressure stationary bundles - Source: <https://www.calvera.es/products/hydrogen/>

Compressors

High-pressure storage requires integration of a compression system to reach the desired pressure levels. The use of oil-free compressors is essential to maintain the required hydrogen purity. The required pressures are achieved by using multi-stage compressors, ideally with an intercooler.

Table 4.4 Overview of Oil-Free Hydrogen Compressors (35 bar to 350 bar)

Compressor Type	Flow Rate (Nm ³ /h)	Power Consumption (kW)	CAPEX (€)	OPEX (% of CAPEX/year)	Notes
Diaphragm Compressor	20–100	15–75	300,000–600,000	4–8%	Suitable for hydrogen refueling stations; oil-free compression ensures high purity; robust sealing; capable of high pressures up to 100 MPa; efficiency ranges between 80–

					85%. (mncompressor.com)
Oil-Free Piston Compressor	3–20	2–11	20,000– 50,000	5–8%	Compact design; ideal for small-scale applications; simple maintenance; commonly used in laboratories and small hydrogen systems. (mncompressor.com)
Ionic Liquid Piston Compressor	360–800	90–200	700,000+	4–6%	High efficiency (~70%); fewer moving parts (e.g., Linde's design has only eight); suitable for large-scale industrial applications; capable of compressing hydrogen up to 900 bar in five stages. (transitionaccelerator.ca)
Centrifugal Compressor	500– 1500	150–400	1,000,000 +	5–7%	Best suited for high flow rates; efficiency comparable to piston compressors at high flow rates; requires specialized materials due to hydrogen embrittlement concerns. (mncompressor.com)

Energy consumption of compressors

Compressing hydrogen from a pressure of 35 bar to pressures of 350–700 bar consumes 5–20% of the lower heating value (LHV) energy contained in the hydrogen.

Material-Based Hydrogen Storage – Metal Hydrides

Hydrogen storage in metal hydrides, which are metal-based materials. Hydrogen penetrates the crystalline lattice of the metal due to its small atomic radius. The absorption of hydrogen occurs

as an exothermic reaction, during which heat is released. When hydrogen is released from the material, an endothermic reaction takes place—heat is consumed and must be supplied to the process. The main parameter being monitored is the temperature at which desorption/release of hydrogen from the material occurs. Other important parameters include gravimetric and volumetric capacity, as well as the cost of the hydride. [33], [34], [35]

Metal hydride system need thermal management, cooling during absorption and heating for releasing of hydrogen. Temperatures of cooling and heating are related to used material and energy capacities are related to size of storage. System works with pressures up to 30 bar, which is advantage to pressure storage and brings more safety.

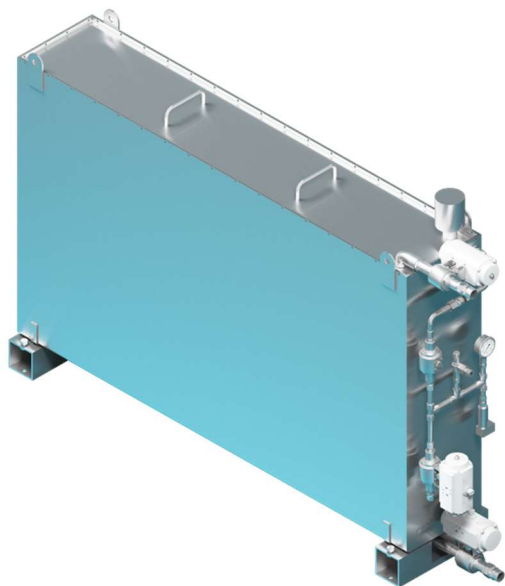


Figure 4.5 - MethHydor - Rack Hydor S 240, Source: <https://methydor.com/wp-content/uploads/2022/05/Rack.png>

Table 4.4 Comparison of Hydrogen Storage Methods

Criterion	Storage of Hydrogen as Compressed Gas	Storage of Hydrogen in Metal Hydrides

Principle	Hydrogen is stored as a gas compressed in a high-strength container. Typically, steel or composite pressure vessels/cylinders.	Hydrogen chemically bonds to a metal alloy, forming a metal hydride. During storage, H_2 is absorbed (exothermic), and during release, it is desorbed (endothermic) by heating the hydride.
Operating Conditions	Low pressure: common industrial welded tanks 10–50 bar. High pressure: special cylinders 200–700 bar (mobility: 350 bar buses, 700 bar cars). Ambient temperature, no cooling required (except during filling) – minimal losses over long-term storage.	Low pressure: typically, up to 30 bar, some hydrides <10 bar. Temperatures slightly above ambient: H_2 is released by heating the tank (e.g., 60–100 °C depending on material), absorption requires cooling to remove reaction heat. Requires thermal management (cooling/heating).
Energy Density (Volumetric)	Compressed gas has low volumetric energy density: at 200 bar ~1 kg H_2 in 112 L, at 700 bar ~1 kg H_2 in 25 L (approx. 40 g H_2 /L). For comparison, liquid H_2 : ~71 g/L.	Metal hydrides have very high volumetric energy density – many hydrides surpass 700 bar gas and even liquid hydrogen. Some metal hydrides achieve >100 g H_2 /L (higher than liquid H_2). This allows more compact storage in terms of volume.
Energy Density (Gravimetric)	Due to the weight of the pressure vessel, usable gravimetric density is ~5–6% (5 kg H_2 per 100 kg of full 700 bar tank). Compressed gas carries little energy relative to tank weight.	Low gravimetric density: metal is heavy, typically <2–3% H_2 by weight (e.g., 100 kg of hydride material contains ~1–3 kg H_2). The whole system can be very heavy. Metal hydrides are more suitable for stationary applications.
Filling/Release Rate	Depends on compressor power – filling large tanks can take tens of minutes to hours. Release (expansion)	Limited by thermal processes: releasing H_2 requires heating the hydride, absorbing requires

	can be fast, but flow is limited by regulators. In general, gas is immediately available for use.	cooling. Rate depends on efficiency of heat exchange. Too fast a release cools the hydride and stops desorption. These systems are typically slower in dynamics than pressure vessels.
Losses and Efficiency	Compressing hydrogen consumes energy (compressor ~5–20% of H ₂ energy content depending on target pressure). No self-discharge if the container is sealed – minor losses possible over long term due to leakage.	Absorption/desorption cycle has thermal losses; if waste heat is used, it can be efficient. Some energy is lost during cooling. Heating for release also requires energy. Overall cycle efficiency can be ~90% (most energy stored in hydrogen, the rest as heat).
Safety	High pressure requires strong containers – risk of mechanical rupture. Modern composite tanks are very robust (tested to multiple of operating pressure). Hydrogen as a gas is light – rises and disperses, but in enclosed spaces can form explosive mixtures.	Lower pressure = higher inherent safety (less risk of container explosion). Hydrogen is bound in solid material – in case of a leak, only slow release occurs. Drawback: hydride tanks must be thermally controlled to avoid overheating during charging or overpressure.
Complexity and Cost	Pressure tank technology is established, simple to operate (just pressure gauges). Costs rise exponentially with desired pressure (700 bar tanks are expensive). For large volumes, existing gas infrastructure (steel tanks, pipelines) or geological storage can be used, lowering cost per stored energy unit.	Metal hydride systems are relatively expensive due to special alloys. Not yet widely manufactured. Require internal heat exchanger, increasing complexity. On the other hand, very space-efficient – advantageous where space is limited. Currently used mostly for small capacities (labs, niche applications). New hydrides (e.g., Mg, NaAlH ₄) and improved

		thermal management may increase adoption.

Hydrogen-to-Power conversion

Fuel cell

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electricity and heat. When hydrogen is used as the fuel, the only by-products are electricity, heat, and water.

The core principle behind fuel cell operation is the electrochemical reaction between a fuel and an oxidizing agent. This process is consistent across all fuel cell types: oxidation takes place at the anode, and reduction occurs at the cathode. While positively charged ions migrate through the electrolyte, electrons travel through an external circuit, generating electric power.

Various types of fuel cells have been developed to suit different applications, utilizing different electrolytes and fuels to optimize performance under specific operating conditions. [36]

4.1.1.6 Polymer Electrolyte Membrane Fuel Cell - PEMFC

PEM fuel cells work with hydrogen. It has low temperature operation and can quickly vary output to fulfil power demands.

Hydrogen and atmospheric oxygen react on a proton exchange membrane (PEM), which separates two electrodes. The reaction is catalyzed by a thin layer of platinum. At the anode, hydrogen splits into electrons and protons. The protons pass through the proton-exchanging membrane to the cathode, where they recombine with oxygen and electrons to form water and heat. The electrons

travel through an external circuit, generating an electric current that performs useful work. The electrical efficiency of the fuel cell can reach up to 60%. [37]

The cells operate at relatively low temperatures of 60–80 °C and can quickly adjust their output to meet changing power demands, making them particularly suitable for automotive applications. They are also suitable for use in stationary power sources.

4.1.1.7 Alkaline Fuel Cell – AFC

Alkaline fuel cells use an alkaline electrolyte, such as potassium hydroxide or an alkaline membrane, which conducts hydroxide ions rather than protons. Alkaline cells were originally used by NASA in space missions and are now finding new applications in portable devices. Their design is closest to that of conventional batteries. The alkaline environment allows the use of common, inexpensive materials. Electrical efficiency approaches 60% at temperatures of 60 – 250 °C. A major disadvantage is their significant sensitivity to carbon dioxide. Even trace amounts of carbon dioxide cause the potassium hydroxide electrolyte to convert into potassium carbonate, a solid that clogs the pores on the cathode. For this reason, alkaline fuel cells are operated with pure hydrogen and pure oxygen. Alternatively, the electrolyte can be cycled and replaced. Alkaline fuel cells have a typical lifespan of about 8,000 hours. For economic viability, a lifetime of 40,000 hours would be necessary. [38], [39], [40]

4.1.1.8 Phosphoric Acid Fuel Cell – PAFC

Phosphoric acid fuel cells operate at temperatures between 170–210 °C. They use a phosphoric acid electrolyte, which conducts positively charged hydrogen ions from the anode to the cathode, held within a porous matrix. The phosphoric acid can be immobilized in polymer membranes. Phosphoric acid adsorbs onto platinum catalysts and can cause corrosion issues. These fuel cells are typically manufactured with power outputs of 400 kW or more. Their electrical efficiency

ranges from 40% to 50%. They are well-suited for applications where their waste heat can be utilized, achieving a cogeneration efficiency of approximately 80%. Examples include hotels, hospitals, office buildings, and grocery stores. These cells are not susceptible to carbon monoxide poisoning, allowing hydrogen to be used directly from steam reforming in combination with air. The service life of the cell exceeds 40,000 hours.

Table 4.5 Comparison of fuel cell technologies [40]

Type	PEM			AFC			PAFC	SOFC
							Phosphoric Acid Fuel Cell	Solid Oxide Fuel Cell
Usage	Portable device	Specialty vehicles	Transportation	Backup power	Military	Space	Distributed generation	Electric utility
Efficiency	40 - 60 %			45 - 60 %			40 - 45 %	50 -60 %
Operating temperature	60 – 85 °C High temperature PEM up to 120 - 220 °C			60 - 220°C			150 – 200 °C	500 - 1000 °C
Start time	1-5 s.			1-10 min			1-10 min	>30 min
Oxidant	Air			O ₂			Air	Air
Lifetime	80 000 h			8 000 h			60 000 h	80 000 h

Hydrogen operated gas engines CHP units

CHP unit with reciprocating internal combustion engine ICE-CHP

Unit uses a conventional reciprocating engine modified for operation with hydrogen. [41] 2G Agenitor [42] produces in electrical output range 115, 170 and 240 kWe. The electrical efficiency of the CHP unit is approximately 42%.

Utilization of waste heat increases overall efficiency of hydrogen conversion. Alternatively, the waste heat has to be dissipated.



Figure 4.6 - CHP unit company 2G - Source: <https://2-g.com/en/products/agenitor>

4.1.1.9 CHP unit with gas turbine GT

4.1.1.10 Hydrogen operated gas turbine

Siemens SGT – 400, gas turbine with package operated with 100 % hydrogen fuel should have 12 MW electrical energy in project -- HYFLEXPOWER. [41], [43]

GE Vernova LM6000VELOX gas turbine can be operated with 100 % hydrogen. [44]

Ansaldo Energia GT 36, as a part of project FLEX4H2, in this project, there was demonstrated on mentioned turbine GT 36 operation with natural gas, blend natural gas- hydrogen and clean hydrogen. [45]

Kawasaki dry-combustion gas turbine GPB17MMX. [46]

The system keeps NO_x emissions levels below Air Pollution. Control act using unique stable hydrogen combustion. Capacity of the unit is 1,8 MW energy.

4.1.1.11 CHP unit with aeroderivative turbine - open-cycle

When a fast response is needed, there are smaller aeroderivative gas turbines their design is based on aircraft engine. This design allows to provide quick start (60 sec.) and a quick response to changes in power.

The electrical efficiency of the CHP unit is approximately 32%, as it is open-cycle turbine and waste heat or combined cycle is not used.

Company CENTRAX produces CXA05-KB7HE [47] with aeroderivative Siemens Energy SGT-A05 gas turbine with capacity 5,8 MWe. [48]



Figure 4.7 - CENTRAX cxa05 - Source: <https://centraxgt.com/products/cxa05/>

4.1.1.12 Combined-cycle gas turbines CCGT

For middle to very high output capacity can be used combined cycle gas turbines CCGT. Hot flue gasses from gas turbine GT are used in heat recovery steam generator HRSG for steam production. In Rankin cycle, the steam then drives a steam turbine, which again produces electricity.

After passing through the turbine, the steam cools, condenses and returns to the HRSG. Electrical efficiency in combined cycle is 50-64 %. GE declares more than 64 %. [49]

4.1.2 Technological Maturity – TRL

Technology maturity of P2G2P project depends on used components.

Hydrogen production TRL

Electrolyzers Technology Readiness Level of electrolyzers depends on the specific manufacturer and product. Commercially available low temperature electrolyzers have TRL 8 - 9.

Hydrogen storage TRL

Compressors, depends on specific manufacturer and type TRL 8 – 9. Low pressure vessels and cylinders class I. have TRL 9.

Hydrogen to power conversion CHP units

CHP Fuel cells low temperature, commercially available TRL 8 – 9.

CHP with reciprocating internal combustion engine TRL 9.

CHP with gas turbine GT, depends on specific manufacturer and type – TRL 8 – 9.

CHP with combined cycle CCGT – TRL 8 – 9.

4.1.3 Scale and capacity

Scale and capacity are from kW to MW. Limited only by installing place and capacity of electrical connection.

4.1.4 Efficiency and performance

4.1.4.1 RTE – Round Trip Efficiency

Energy consumption of electrolysis hydrogen production

Estimated electrical system consumption of a low temperature electrolysis would be 55 – 65 kWh/kg H₂, depends on size of project and efficiency in actual state. [50]

https://mpo.gov.cz/assets/cz/prumysl/strategicke-projekty/2021/8/Vodikova-strategie_CZ_G_2021-26-07.pdf

Energy consumption of compressor pressure storage

Compression of hydrogen would consume 2- 4 kWh/ H₂ depending on output pressure and type of compressor.

https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf

Energy consumption of pressure stored hydrogen

System consumption of electrolysis and pressure storage is 57 – 69 kWh/ kg Hydrogen.

Hydrogens LHV is 33,3 kWh /kg.

Efficiency of produced and stored hydrogen related to LHV is 48,3 – 58,4 %.

CHP unit with **low temperature fuel cell** has declared 90 % complete efficiency; electrical efficiency is up to 53,5 %. [51]

CHP unit with **combustion reciprocating engine**, declared electrical efficiency is 40,2 % [42]

CHP unit with **aeroderivative gas turbine**, declared electrical efficiency is 32,6 % [47]

CHP unit with **combined cycle gas turbine**, declared electrical efficiency 64 % [49]

Table 4.6 Specific electrical energy and RTE for various H₂ CHP technologies

Type of CHP unit	Electrical specific energy	RTE
Low temperature fuel cell CHP	16 kWh _{el} / kg H ₂	23,1 – 28 %
Combustion reciprocating engine CHP	13,4 kWh _{el} / kg H ₂	19,4 – 23,5 %
Aeroderivative gas turbine CHP	10,86 kWh _{el} / kg H ₂	15,7 – 19 %
Combined cycle gas turbine CCGT	21,3 kWh _{el} / kg H ₂	30,9 – 37,4 %

4.2 Financial Analysis

4.2.1 Cost of Electrolysis and Storage Infrastructure

Hydrogen production is a chemical production with all its challenges and limitations. Each project is custom-made according to the specific requirements and goals of the investor (economic/technical). The same project can be implemented in multiple ways. It is defined by priorities, tender and boundary conditions (both financial and technical). The price is significantly dependent on the size of the project. Unit prices of electrolyzers decrease with increasing output.

The project simplifies the use of modularly assembled container solutions.

Capital costs of electrolyzers are not easy to compare, as there are many tailor-made systems with different conditions and capacities. Actual prices for complete AEL electrolyser systems are estimated 1 200 – 1800 €/kWe, PEM systems are about 30 % higher. AEM electrolyzers are between AEL and PEM.

Hydrogen storage CAPEX

From price offer 2022 year.

High pressure stationary bundle - Pressure vessel, type I., 300 bar – 540 – 720 €/kg H₂

4.2.1.1 Fuel cell for stationary applications cost [51]

Micro – CHP – up to 5 kWe

CAPEX – 5 000 €/kW – PEM fuel cell

4.2.1.2 Mid-size CHP – 5 – 50 kWe

CAPEX – 2 500 €/kW – PEM fuel cell

4.2.1.3 Large scale CHP – 51 – 500 kWe

CAPEX – 1 900 €/kW – PEM fuel cell

4.2.1.4 CHP combustion units (piston, turbine)

Price is not available.

4.2.2 Economic Benefits of Green Hydrogen

In actual situation only economic benefit of green hydrogen we can see are subsidies.

For more information on economic analysis of hydrogen technologies, refer to Section 8.3.

4.3 Environmental Impact

Hydrogen energy storage has emerged as a critical component in the transition to sustainable energy systems, offering a versatile solution for balancing renewable energy supply and demand (Turner, 2004; IRENA, 2021). As nations worldwide accelerate their decarbonization efforts, hydrogen's unique properties - including its high energy density (120 MJ/kg, three times that of gasoline) and ability to be produced from diverse energy sources - position it as an essential element of clean energy strategies (IEA, 2021). The global hydrogen market is projected to grow from \$130 billion in 2022 to over \$400 billion by 2030, reflecting its increasing importance in the energy transition (BloombergNEF, 2023).

However, its environmental impact varies dramatically depending on production methods, system design, and operational contexts (Arbabzadeh et al., 2017). While hydrogen combustion produces only water vapor, the full lifecycle environmental footprint ranges from highly beneficial to potentially detrimental based on how the hydrogen is generated, stored, and utilized (Howarth & Jacobson, 2021). This paradox highlights the need for careful analysis of hydrogen's complete environmental profile.

Environmental Benefits of Hydrogen Energy Storage

1. Zero-Emission During Use

When utilized in fuel cells or combustion processes¹, hydrogen produces only water vapor as a byproduct, resulting in no direct greenhouse gas (GHG) emissions at the point of consumption (Turner, 2004). This characteristic makes it particularly valuable for:

- Improving urban air quality by eliminating particulate matter and NO_x emissions

¹ While it doesn't produce CO₂ it does produce NO_x emissions, presenting environmental risks at scale up applications. Several articles support the notion that in some cases, hydrogen combustion can lead to higher NO_x emissions than traditional fossil fuels, especially if not carefully managed.

- Decarbonizing sectors where electrification is challenging
- Serving as a clean alternative to diesel in heavy transport

2. Renewable Energy Integration

Hydrogen storage provides a crucial solution for addressing the intermittency of renewable energy sources (IRENA, 2019). By converting excess renewable electricity into hydrogen during periods of high generation, it:

- Reduces renewable energy curtailment by up to 90% in some grid scenarios
- Enables long-duration energy storage (weeks to months) unmatched by batteries
- Facilitates seasonal balancing of energy supply and demand

3. Hard-to-Abate Sector Decarbonization

Hydrogen shows particular promise in decarbonizing sectors where other solutions fall short (IEA, 2021):

- Industry: Replacing coking coal in steel production (potential 95% CO₂ reduction)
- Transport: Heavy-duty vehicles (300-400 mile range for FCEVs)
- Aviation & Shipping: Potential for zero-emission long-haul transport

Environmental Challenges and Considerations

1. Production Pathway Impacts

The environmental footprint varies dramatically by production method:

- Grey Hydrogen (Fossil Fuel-Based): Produced via steam methane reforming (SMR), emits significant CO₂ unless combined with CCS (carbon capture and storage).
- Blue Hydrogen: Similar to grey but with CCS. Still involves fossil fuels and risks of methane leakage.
- Green Hydrogen: Made via electrolysis powered by renewable energy, with minimal emissions.
- Pink Hydrogen: Pink hydrogen is generated through electrolysis powered by nuclear energy. Nuclear-produced hydrogen can also be referred to as purple hydrogen or red hydrogen. (National Grid, 2023)

In addition, the very high temperatures from nuclear reactors could be used in other hydrogen productions by producing steam for more efficient electrolysis or fossil gas-based steam methane reforming.

Emerging methods like photoelectrochemical water splitting promise near-zero emissions but remain experimental (Hisatomi et al., 2014).

2. Water-Energy Nexus

Electrolysis requires 9-12 liters of ultrapure water per kg of hydrogen (NREL, 2020), posing challenges in:

- Arid regions where water scarcity exists, this could compete with local drinking or agricultural water supplies.
- Ecosystems sensitive to water withdrawals
- Mitigation strategies include using desalinated seawater or advanced water recycling systems. If desalination is used instead, it adds energy consumption and produces brine waste, which has environmental impacts on marine ecosystems.

3. Infrastructure Requirements

Large-scale deployment necessitates:

- New pipeline networks (€80-143 billion investment needed in EU by 2040)
- Specialized storage facilities (salt caverns, cryogenic tanks)
- Materials resistant to hydrogen embrittlement.
- Producing green hydrogen at scale requires massive amounts of renewable electricity. This could lead to land use conflicts (e.g., solar or wind farms affecting biodiversity or agricultural areas). Large renewable projects can also impact ecosystems and local communities, especially if not properly sited.

4. Safety and Leakage Risks

Hydrogen's small molecular size increases leakage risks, which can:

- Contribute to atmospheric ozone formation, it is 4 times more potent as a greenhouse gas as CO₂
- Create explosion hazards (flammability range: 4-75% in air)

Modern detection systems and advanced materials are helping address these challenges (U.S. DOE, 2021).

Building a hydrogen transport and storage infrastructure has its own carbon and material footprint.

Hydrogen is not a greenhouse gas itself, but it is an **indirect greenhouse gas**. It can increase the lifetime of methane (a potent GHG) in the atmosphere by interfering with oxidative reactions.

- **Scientific concern:** Recent research shows that hydrogen leakage—even small amounts—can potentially **amplify global warming** by increasing methane's atmospheric lifespan.
- **Sources of leakage:** Production (e.g., electrolysis), storage, compression, pipelines, refueling stations, and end-use (e.g., fuel cells).

5. Storage & Distribution Options – Ranked by Environmental Risk (and Practicality)

5.1. Compressed Hydrogen Gas (350–700 bar)

Environmental Pros:

- No toxic chemicals or conversion losses.
- Mature technology with growing safety standards (Mdpi, 2021).

Environmental Risks:

- Requires high energy input for compression.
- Leaks contribute to indirect global warming.
- Materials (e.g., carbon fiber tanks) have a manufacturing footprint.

Cost: Medium — expensive to compress and store safely at scale.

5.2. Liquid Hydrogen (cryogenic, -253°C)

Pros:

- Higher energy density by volume than gas.
- Useful for aviation or export.

Risks:

- Very high energy demand for liquefaction (~30–40% of H₂ energy).
- Boil-off losses during storage and transport.
- Leak risks, and cryogenic leaks are harder to detect and manage.

Cost: High — energy-intensive and requires specialized infrastructure.

5.3. Onsite Hydrogen Use / Local Microgrids

Pros:

- Minimizes transport, compression, and storage needs.
- Ideal for industrial clusters, ports, or fleet depots.

Risks:

- Still requires safety protocols, but much lower lifecycle impact.

Cost: Low to Medium — CAPEX for electrolyzers, but fewer logistics costs.

5.4. Hydrogen Pipelines (gaseous transport)

Pros:

- Scalable for industrial clusters.
- Can repurpose existing natural gas pipelines (with retrofit).

Risks:

- Leakage (especially through old or incompatible materials).
- Hydrogen embrittlement of metals.
- Construction footprint (if building new).

Cost: Low to Medium (long-term) — high initial investment, but low operating costs per kg.

5.5. Hydrogen Carriers (Ammonia, LOHCs, Methanol)

Pros:

- Easier to ship internationally.
- Can use existing chemical/fuel infrastructure.

Risks:

- Toxicity (ammonia), flammability, lifecycle emissions.
- Energy penalty for conversion and reconversion (up to 50% loss).

Cost: High — extra process steps add cost and complexity.

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Integrated Assessment Framework

A comprehensive evaluation must consider three key dimensions:

1. Lifecycle emissions - From production to end-use
2. Decarbonization potential - Sector-specific applications
3. Localized effects - Impacts on ecosystems and communities

Recent case studies from projects like HyStock (Netherlands) and NEOM (Saudi Arabia) demonstrate that environmental impacts can be minimized through:

- Strategic siting in industrial zones
- Use of existing geological formations for storage
- Integration with renewable energy clusters

Future Outlook and Recommendations

As the hydrogen economy scales up, key priorities include:

1. Accelerating green hydrogen through renewable energy cost reductions
2. Developing certification systems to ensure environmental integrity
3. Investing in infrastructure that minimizes ecosystem impacts
4. Advancing safety standards for widespread deployment

The following sections will explore these aspects in greater detail, providing policymakers and industry leaders with evidence-based guidance for sustainable hydrogen deployment.

4.3.1 Carbon Footprint of Production Methods

The climate impact of hydrogen energy storage depends entirely on how the hydrogen is produced. Currently, the hydrogen industry resembles a spectrum of environmental performance - at one end, highly polluting production methods that undermine climate goals, and at the other, truly clean solutions that could help decarbonize our energy systems.

The most common production method today is steam methane reforming (SMR) of natural gas, which creates what's known as grey hydrogen. This process emits between 9-12 kg of CO₂ for every kg of hydrogen produced, essentially trading one fossil fuel for another. The environmental impact worsens when considering methane leaks during natural gas extraction - a potent greenhouse gas with 84 times the warming power of CO₂ over 20 years. These emissions occur before the hydrogen even reaches its end use, making grey hydrogen problematic for climate goals.

Blue hydrogen attempts to address this issue by adding carbon capture and storage (CCS) to the SMR process. In theory, this could capture 60-90% of the CO₂ emissions, reducing the carbon footprint to 1-5 kg CO₂ per kg hydrogen. However, real-world performance varies widely. Recent studies show that when accounting for methane leaks and the energy needed to run capture equipment, blue hydrogen's climate benefits may be significantly overstated. The technology remains controversial, with some experts viewing it as a necessary transitional solution, while others argue it perpetuates fossil fuel dependence.

The cleanest option, green hydrogen, is produced through electrolysis powered by renewable electricity. When done properly, the entire process can result in less than 1 kg CO₂ emissions per kg hydrogen - primarily from manufacturing the renewable energy infrastructure and electrolyzers themselves. The water requirements (9-12 liters per kg hydrogen) raise concerns in arid regions, though this pales in comparison to the water used in fossil fuel extraction. Costs remain high but

are falling rapidly as electrolyzer technology improves and renewable energy prices continue to decline.

Electrolyser manufacturing has a negative impact on the environment. Electrolysers (especially PEM types) use critical raw materials like platinum group metals. Mining and refining these materials carry environmental risks, including toxic waste, water use, and biodiversity damage—similar to issues in battery supply chains. Fluorine and fluoropolymers are used for electrolyser production value chain. The advocates for the use of these critical chemical and materials are justifying their use on the economic base, but the scientific concerns, especially about fluorine, apply.

In terms of renewable energy production, the production from photovoltaic panels and wind turbines is mentioned and used. While photovoltaic (PV) technology is vital for renewable energy, its production has negative environmental impacts, including land and water use, resource depletion, and potential pollution from hazardous materials. Additionally, the disposal of old solar panels poses a waste management challenge. Even if the energy production from wind turbines is one of the most environmentally friendly, especially on shore, the most concerning negative environmental impact is connected to material sourcing and manufacturing, however other concerns exist as well.

Emerging production methods show promise but face significant hurdles. Biomass-derived hydrogen can be carbon-neutral or even negative when paired with carbon capture, but sustainable feedstock availability is limited. Photoelectrochemical systems that produce hydrogen directly from sunlight are fascinating scientifically but remain firmly in the lab stage, with major challenges in efficiency and durability.

What's often overlooked in these discussions is the infrastructure required to handle hydrogen. Liquefying hydrogen for transport consumes enormous amounts of energy - typically 30-40% of the hydrogen's own energy content. Pipeline transport requires specially treated steel to prevent hydrogen embrittlement. These "hidden" emissions can significantly impact the overall carbon footprint.

The choice between these production methods isn't just technical - it's economic and political. Grey hydrogen dominates today because it's cheap, using existing natural gas infrastructure. Blue hydrogen proponents argue it's a pragmatic stepping stone. Green hydrogen advocates counter that we should leapfrog directly to renewables, especially as costs continue to fall. Pink hydrogen, produced using nuclear energy to power electrolysis, offers a low-carbon alternative with high reliability. Its proponents argue that nuclear's consistent output can provide a stable, baseload source of clean hydrogen without the intermittency challenges of wind and solar. Supporters see pink hydrogen as a strategic complement to green hydrogen, especially in regions with existing nuclear infrastructure or limited renewable potential. Critics, however, raise concerns about nuclear waste, long lead times, and public opposition, questioning whether investments in pink hydrogen might divert resources from faster-deploying renewable solutions.

Looking ahead, the carbon footprint of hydrogen production will likely decrease through several pathways: more efficient electrolyzers, better renewable energy integration, improved carbon capture rates for blue hydrogen, and potentially breakthroughs in novel production methods. However, realizing hydrogen's full climate potential will require careful lifecycle analysis, robust certification systems, and policies that incentivize truly clean production rather than fossil-fuel derived alternatives with questionable climate benefits.

The environmental promise of hydrogen energy storage can only be realized if we pay as much attention to how we make the hydrogen as we do to how we use it. As the industry scales up, these production method choices will have climate consequences that last for decades.

Comparative Summary

Production Method	Approximate CO ₂ Emissions per kg H ₂	Main Environmental Considerations
Grey	9-12 kg CO ₂	High, fossil fuel-dependent, CO ₂ release
Blue	1-3 kg CO ₂	Lower, CCS implementation risk
Green	Near zero	Dependent on renewable energy source
Pink	Near zero	nuclear waste, long lead times, high-cost investment in nuclear power plants

Conclusions

- Green hydrogen offers the lowest carbon footprint, aligning with sustainability goals.
- Blue hydrogen can significantly reduce emissions but still involves fossil fuels and CCS risks.
- Grey hydrogen has the highest emissions and is less suitable for decarbonization unless CCS is highly effective.
- Pink hydrogen provides a stable, baseload source of clean hydrogen without the intermittency challenges of wind and solar, but is connected with certain concerns.

Always evaluate the specific conditions of hydrogen production systems, regional energy mixes, and lifecycle assessments to accurately assess environmental impacts.

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4.3.2 Role in Decarbonising the Energy Sector

Hydrogen energy storage is emerging as a linchpin in global decarbonization efforts, offering unique solutions where electrification alone falls short. Its ability to bridge the gap between intermittent renewable energy supply and constant energy demand, while decarbonizing stubborn sectors like heavy industry and long-haul transport, makes it indispensable for achieving net-zero targets.

The Renewable Energy Enabler

The intermittent nature of wind and solar power creates fundamental challenges for grid stability. Hydrogen provides an elegant solution by acting as a "renewable energy battery" with unparalleled storage duration. During periods of excess generation - sunny afternoons or windy nights - surplus electricity can power electrolyzers that split water molecules into hydrogen and oxygen. This green hydrogen can then be stored for weeks or even months, addressing renewable energy's most persistent limitation: seasonal variability.

Northern European countries are pioneering this approach. Germany's Energiepark Mainz demonstrates how hydrogen can absorb surplus wind power, with its 6 MW electrolyzer converting enough renewable electricity to power 2,000 fuel cell vehicles annually. Such systems can reduce grid emissions by up to 90% compared to fossil fuel peaking plants, while simultaneously solving renewable curtailment issues.

Transforming Hard-to-Abate Sectors

While batteries excel in light vehicles and short-duration storage, hydrogen shines where electrification struggles:

1. Steel Production

The traditional blast furnace process emits about 1.8 tons of CO₂ per ton of steel. Hydrogen-based direct reduction cuts this by 95%, with commercial plants like HYBRIT in Sweden already operational.

2. Heavy Transport

For long-haul trucking, shipping, and aviation, hydrogen's energy density (120 MJ/kg) outperforms batteries. Fuel cell trucks now achieve 400-mile (643,738km) ranges with 10-minute refueling, while hydrogen-powered ferries ply Scandinavian waters.

3. Chemical Industry

Ammonia production, responsible for 1.8% of global CO₂ emissions, can be decarbonized through green hydrogen-based processes. However, ammonia and other hydrogen carriers and blends (methanol, ethanol, and synthetic hydrocarbons) are increasingly used to make hydrogen more transportable and energy-dense. But each of these introduces its own environmental risks, some of which can be more serious than hydrogen itself.

The Seasonal Storage Advantage

Unlike batteries best suited for hours or days, hydrogen's real potential lies in seasonal storage. Underground salt caverns - like those in the Netherlands' HyStock project - can store hydrogen equivalent to months of energy demand. This proves invaluable in regions with strong seasonal renewable variations, allowing summer solar to power winter heating.

Strategic Deployment Considerations

However, hydrogen isn't a panacea. It is sometimes promoted in applications where direct electrification is more efficient (e.g., light-duty vehicles, home heating). Its relatively low round-trip efficiency (30-50%) makes it poorly suited for short-term storage where batteries (70-90% efficiency) dominate. The key is matching applications to hydrogen's strengths:

Priority Applications:

- Steel and chemical production
- Long-duration grid storage (>50 hours)
- Heavy transport (trucks, ships, planes)

Lower Priority:

- Passenger vehicles (battery superiority)
- Short-term grid balancing

Global Policy Landscape

The global policy landscape for hydrogen development reveals stark contrasts in how major economies are positioning themselves in the emerging hydrogen economy. Europe has staked its future on green hydrogen leadership, committing to massive electrolyzer deployments that align with its aggressive renewable energy targets and industrial decarbonization goals. This ambitious approach reflects both Europe's climate ambitions and its desire for energy independence. Across the Atlantic, the United States has adopted a more pragmatic, technology-neutral stance that

accommodates both green and blue hydrogen pathways, leveraging its abundant natural gas resources while supporting carbon capture innovation. This balanced strategy aims to rapidly scale hydrogen production while managing costs during the transition.

In Asia, we see divergent paths emerging. China, the world's largest hydrogen producer, continues relying on its domestic coal resources while investing in carbon capture to reduce emissions - a practical approach given its energy infrastructure and manufacturing needs. Meanwhile, resource-poor Japan is betting on hydrogen imports and infrastructure development, recognizing its limited renewable potential but seeking to maintain technological leadership in fuel cell applications. These policy differences highlight how national strategies are shaped by unique combinations of resource endowments, industrial structures, and geopolitical considerations.

The varying approaches carry significant implications for global hydrogen trade and technology development. Europe's green hydrogen focus could make it a leader in electrolyzer technology but potentially dependent on imports from sun-rich regions. America's diversified strategy may yield faster scaling but with higher near-term emissions. China's coal-based pathway raises questions about long-term compatibility with climate goals, while Japan's import-reliant model highlights the coming geopolitical shifts in energy trade. As these strategies unfold, they will create competing visions for the hydrogen economy that could either complement or conflict with each other in the race to net-zero emissions.

World regions strategies and targets:

Region	Strategy	2030 Target	Focus Sector
European Union	Green hydrogen leadership	40 GW electrolyzer capacity	Industry, transport
United States	Technology-neutral with CCS	\$9.5B clean hydrogen investment	Industry, power
China	Coal-based hydrogen	100k fuel cell	Transport, chemicals

	with CCS	vehicles	
Japan	Hydrogen import infrastructure	10x cost reduction	Power, mobility

Remaining Challenges

Four critical hurdles must be overcome:

1. Cost Reduction

Green hydrogen needs to fall from \$3-6/kg today to under \$1/kg to compete with fossil alternatives. This requires both cheaper renewables (target: <\$20/MWh) and electrolyzers (target: <\$400/kW).

2. Infrastructure Development

Building a hydrogen economy demands massive investment - the EU alone needs €80-143 billion for pipelines by 2040. Repurposing natural gas infrastructure offers partial solutions.

3. Certification Systems

Robust tracking is essential to prevent "greenwashing" of hydrogen produced from fossil fuels. The EU's certification framework provides a model for ensuring environmental integrity.

4. Environmentally less harmful hydrogen carriers and blends needs to be developed than currently used.

Green hydrogen is essential for decarbonizing hard-to-electrify sectors (e.g., heavy industry, shipping, aviation). But its environmental footprint depends on how and where it's produced, transported, and used. Strong regulations, lifecycle analysis, infrastructure design, and sustainability standards are needed to ensure hydrogen is a truly climate-positive solution.

The Path Forward

The coming decade will be decisive. Pilot projects like Saudi Arabia's NEOM (4 GW solar-powered hydrogen) and Australia's Asian Renewable Energy Hub must scale successfully. Meanwhile, technological breakthroughs in electrolysis efficiency and hydrogen storage materials could dramatically reshape the landscape.

Ultimately, hydrogen's role in decarbonization will be neither universal nor negligible - but strategically deployed, it can solve critical pieces of the net-zero puzzle that other technologies cannot.

4.3.3 Localised Environmental Impacts

The deployment of hydrogen energy storage systems presents a complex interplay between global climate benefits and localized environmental impacts that vary significantly across different production methods and geographical contexts (Reuß et al., 2019; IRENA, 2021). Understanding these site-specific effects is crucial for sustainable implementation.

All areas discussed below can be related to the distribution and use of hydrogen, which is not related to liquefaction or compression of hydrogen but to mixing hydrogen with ammonia, methanol, ethanol, and synthetic hydrocarbons. These substances pose serious risks to land, water and air pollution.

4.3.3.1. Ammonia (NH₃)

Pros:

- Carbon-free hydrogen carrier.
- Easily liquefied under moderate pressure.
- Can be used directly in combustion or fuel cells.

Environmental Risks:

- **Toxicity & Ecosystem Harm:** Ammonia is highly toxic to aquatic life and humans. Leaks or spills can contaminate water sources and kill aquatic species rapidly.
- **NO_x Emissions During Combustion:** Ammonia combustion can release nitrogen oxides (NO_x), which contribute to air pollution and acid rain unless carefully controlled with after-treatment systems.
- **Corrosive Nature:** Handling ammonia requires corrosion-resistant materials, and leaks can result in air and water contamination.
- **Odor Nuisance and Health Risks:** Even low-level exposure can cause respiratory problems. Large-scale use would need strong safety infrastructure.

4.3.3.2. Methanol (CH₃OH) and Ethanol (C₂H₅OH)

These are liquid fuels that can be synthesized using hydrogen and captured CO₂ (e-methanol, e-ethanol) or from biomass.

Pros:

- Easier to store and transport than hydrogen.
- Can use existing fuel infrastructure.
- Burns cleaner than fossil fuels.

Environmental Risks:

- **Toxicity and Flammability:** Methanol is toxic to humans and wildlife, particularly if spilled in waterways. It's also highly flammable.
- **Air Emissions:** Burning alcohols can produce formaldehyde, carbon monoxide, and unburned hydrocarbons—harmful to human health and the environment.
- **Biomass-derived variants may have sustainability issues:** Land use change, monoculture impacts, deforestation, and food vs. fuel debates are real concerns with bio-based production routes.
- **CO₂ Dependency:** Many synthetic alcohols rely on captured CO₂, which can create a carbon lock-in if the source CO₂ is from fossil origins rather than direct air capture.

4.3.3.3. Synthetic Hydrocarbons (e-fuels)

Hydrogen can be used to produce synthetic diesel, gasoline, or jet fuel via processes like Fischer-Tropsch synthesis.

Pros:

- Fully compatible with existing engines and infrastructure.
- Potential carbon-neutral fuels if produced with green H₂ and captured CO₂.

Environmental Risks:

- Combustion Emissions: Still emits CO₂, NO_x, and particulates at the tailpipe—even if net-neutral over the lifecycle.
- Energy Intensive: These fuels are less efficient than using hydrogen or electricity directly, leading to higher upstream energy demand and potentially more land/water use.
- CO₂ Source Matters: If fossil CO₂ is used for synthesis, these fuels risk extending fossil carbon lifespans rather than eliminating them.

Additional Concerns Across All Blends

- Lifecycle Emissions: Without strict carbon accounting, these fuels could look "green" but have hidden emissions across supply chains.
- Toxic Byproducts: Combustion or leakage of carriers can release hazardous substances or persistent pollutants.
- Environmental Justice: Production facilities may be sited near vulnerable communities, raising concerns about local pollution and safety risks.

Key Mitigation Strategies

- Enforce strict handling, storage, and spill protocols.
- Prioritize green hydrogen and sustainable CO₂ sources.

- Invest in combustion control technologies (e.g., SCR systems for NO_x).
- Apply full lifecycle assessments (LCA) before scaling new hydrogen carriers.

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Land Use and Ecological Considerations

Large-scale hydrogen infrastructure requires substantial land area, particularly when integrated with renewable energy generation. A 1-gigawatt green hydrogen plant powered by solar energy may occupy over 50 square kilometers of land, depending on regional insolation levels (Glenk & Reichelstein, 2019). This spatial demand can compete with agricultural land or ecologically sensitive areas, necessitating careful siting strategies.

The Dutch approach to underground hydrogen storage in salt caverns (HyStock project) demonstrates how geological solutions can minimize surface disruption while providing massive storage capacity (Schouten et al., 2023). Similarly, co-locating electrolyzers with offshore wind farms presents an innovative approach to reduce land-use conflicts in coastal regions (IRENA, 2022).

Water Resource Implications

Water consumption remains a critical constraint, particularly in arid regions. Conventional electrolysis requires 9-12 liters of high-purity water per kilogram of hydrogen produced (Nemova et al., 2024), creating potential stress on local water resources. This challenge has driven innovation in alternative water sources:

- Advanced PEM electrolyzers showing improved water efficiency (Carmo et al., 2013)
- Integrated desalination systems in coastal projects like NEOM (Saudi Arabia)
- Atmospheric water harvesting prototypes achieving 5-10 liters/m²/day (Nada et al., 2024)

The water-energy nexus becomes particularly complex when considering that water-scarce regions often have the highest solar potential for green hydrogen production (DOE, 2014). This paradox requires region-specific solutions balancing water conservation with decarbonization goals.

Water Use in Hydrogen Production

Production Method	Water Use (Liters per kg H ₂)	Environmental Considerations
Electrolysis	9–12	High water demand; prioritize sustainable water sources
Steam Reforming	3–5	Lower demand but still considerable; consumption linked to fuel refining

Air Quality and Noise Pollution

Air Emissions: The environmental impact of hydrogen production and usage largely depends on the methods employed in its generation and handling.

Production Emissions:

- Green Hydrogen: Produced via electrolysis using renewable energy (such as wind, solar, or hydropower), it results in no direct greenhouse gas emissions, making it the cleanest option.
- Fossil-Based Hydrogen (Grey/Blue):
 - o Steam Methane Reforming (SMR), the most common method, emits CO₂ and other pollutants (e.g., NO_x, SO₂) unless paired with Carbon Capture and Storage (CCS).
 - o Blue Hydrogen (SMR + CCS) reduces emissions significantly but may still have minor leakage risks.
 - o Coal Gasification (for black/brown hydrogen) is the most carbon-intensive, releasing large amounts of CO₂ and particulate matter.
- Material Handling & Transport:
 - o Compression & Storage: Hydrogen must be compressed for storage and transport, requiring energy-intensive compressors that may emit trace pollutants (e.g., lubricant vapors, particulate matter) and contribute to localized air quality impacts.
 - o Noise Pollution: High-pressure compressors and pumping stations generate significant noise, potentially affecting nearby communities if not properly mitigated with sound barriers or remote siting.
 - o Leakage Risks: Hydrogen is a small, highly diffusive molecule, leading to potential fugitive emissions, which, while not directly harmful, can indirectly affect air quality by increasing ground-level ozone formation.

By transitioning to green hydrogen and implementing best practices in handling and storage, the air quality and noise impacts can be minimized, supporting a cleaner energy.

Air Quality Comparison by Production Type

Production Method	Major Air Emissions	Mitigation Measures
Green Hydrogen	None if using 100% renewable energy	Increase use of renewables, optimize technology
Grey Hydrogen	CO ₂ , CH ₄	CCS integration, efficient process technologies
Blue Hydrogen	Reduced CO ₂ , minor CH ₄ and byproducts	Utilize advanced CCS with high capture rates
Pink Hydrogen	No CO ₂ emissions, it can lead to NO _x emissions	Minimizing NO _x emissions through combustion control or after-treatment is crucial for maximizing the air quality benefits of pink hydrogen.

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Safety and Risk Management

Hydrogen's material properties necessitate rigorous safety protocols. Its wide flammability range (4-75% concentration in air) and tendency to embrittle metals require specialized infrastructure (Hirscher et al., 2020). Modern safety systems incorporate:

- Fiber-optic leak detection networks (Khalil, 2020)
- Composite tank materials resistant to embrittlement (Meda et al., 2023)
- Automated emergency shutdown systems (Georgious et al., 2021)

The 2019 Norwegian refueling station incident demonstrated both the potential risks and the effectiveness of modern safety systems in preventing catastrophic failures (Khalil, 2020). These safety considerations significantly influence regulatory frameworks like the EU's Industrial Emissions Directive.

Community and Socioeconomic Factors

Local impacts extend beyond environmental metrics to broader community considerations. While compressor stations generate noise levels comparable to urban traffic (~75 dB) (Khalil, 2018), hydrogen projects can bring economic benefits:

- Job creation in construction and operations (Felseghi et al., 2019)
- Industrial revitalization opportunities (IEA, 2021)
- New revenue streams for renewable energy producers (Glenk & Reichelstein, 2019)

The German Energiepark Mainz project exemplifies successful community integration through transparent engagement and local benefit sharing (Reuß et al., 2019). Such models prove critical for building social license to operate.

4.4 Technical implementation

4.4.1 Key design Features

Electrolysis and its demands

During electrolysis, the chemical bond between hydrogen and oxygen in water is broken using direct current (DC) electricity. This process is carried out in electrochemical devices known as **electrolyzers**, which operate based on different principles and under various conditions. [30]

The typical system energy consumption of water electrolysis today is around 55–65 kWh per kilogram of hydrogen produced. To produce 1 kilogram of hydrogen, approximately 9 kilograms of process water are needed. This water must be treated and purified according to the specifications of the particular electrolyzer being used.

Different electrolysis systems may have technological losses, including losses from cooling systems.

When reverse osmosis is used to purify water for electrolysis, 15–50% of the input water may be lost during the treatment process, depending on the initial water quality.

4.4.2 Integration with Renewable Energy Sources

Technology selection

The choice of individual technological components is subject to the required technical and economic goal. Each project has different conditions.

Renewable energy sources

For optimal operation of the electrolyzer, it is ideal to minimize fluctuations in its output. This stabilizes hydrogen production under optimal conditions, increases the electrolyzer lifespan, and

improves its utilization. To achieve this goal, different renewable energy sources can be combined, or their output can be stabilized using an appropriately sized battery storage system.

Based on the characteristics of the renewable power source or their combination (surplus energy), it is possible to select a suitable electrolyzer technology, taking into account economic and boundary conditions. For renewable energy sources, a multi-stack solution is a viable option, as well as a combination of electrolyzer technologies such as AEL and PEM, or AEL and AEM. [52]

To achieve 40% utilization of a 1 MW electrolyzer in combination with a photovoltaic system (PV), it is necessary for the PV system to be five times larger. However, this leads to approximately half of the solar-generated energy being surplus, which must be sold—typically during times of PV overproduction, and therefore at low prices. Depending on geographical location, the average annual solar irradiation in Europe ranges between 800–2000 hours per year.

By combining solar and wind energy, the utilization of the electrolyzer can be increased to 60%, with about 20% surplus energy. If hydropower is added to the mix, maximum utilization of the electrolyzer can be achieved.

From an economic perspective, it makes sense to use and store only surplus energy in the form of hydrogen. Combining data on available renewable/surplus energy sources with the energy consumption profile helps determine a suitable technical and business model.

4.4.2.1 Electrolyzer technology and type.

When choosing an electrolyzer technology, it is necessary to take into account the nature of the power supply in combination with the considered battery storage in terms of the size and speed of changes, so that the dynamics of changes correspond to the dynamics of the system.

The correct selection of an electrolyzer in combination with support systems helps to increase the overall system efficiency, utilization and service life of the electrolyzer. Changing the electrolyzer load affects the efficiency of the system / hydrogen production. Repeated system starts and shuts down reduce the overall efficiency and service life of the device. All these parameters together form the economics of the project.

4.4.2.2 Storage technology

4.4.2.3 The selection of hydrogen storage technology must comply with specific technical requirements, including safety, spatial footprint, storage and release rates, as well as system responsiveness.

4.4.2.4 Conversion gas to power – CHP units

The selection of a CHP unit must align with the specific requirements of the application and the overarching project concept. Each technological solution exhibits distinct characteristics, including efficiency, dynamic response, and economic performance. Fuel cells offer CO₂-free operation, making them a clean energy option. Combined heat and power (CHP) units with combustion engines may produce NO_x emissions (Kawasaki offers system, which keeps Nox emissions level below air pollution). [46]

4.5 Practical Case Studies

Hydrogen energy storage has evolved from theoretical potential to real-world implementation, demonstrating its role in balancing renewable energy systems, decarbonizing industries, and enhancing grid stability. These case studies illustrate the technical, economic, and environmental aspects of hydrogen storage, offering valuable insights into its practical applications. While large-scale underground storage and integrated renewable-hydrogen systems highlight hydrogen's

versatility, challenges such as infrastructure costs, efficiency losses, and safety considerations remain. By examining these projects, stakeholders can identify best practices for optimizing hydrogen storage in diverse energy landscapes.

1. H21 Leeds City Gate Project, United Kingdom

One of the most ambitious hydrogen initiatives, the H21 Leeds City Gate Project, explores converting the UK's natural gas grid to hydrogen to achieve deep decarbonization. The project aims to retrofit Leeds' existing gas infrastructure, supplying hydrogen for residential heating and industrial use. By leveraging steam methane reforming (SMR) with carbon capture and storage (CCS), the initiative seeks to minimize emissions while utilizing current pipelines to reduce costs. If successful, this model could be replicated in other cities, significantly cutting CO₂ emissions from heating—a major challenge in urban decarbonization. The project also promises economic benefits, including job creation and positioning the UK as a leader in hydrogen transition.

2. HyDeploy Project, United Kingdom

A more incremental approach is seen in the HyDeploy Project, which tests blending 20% hydrogen with natural gas in existing networks. Conducted at Keele University and a residential community in Northeast England, the project confirms that current gas appliances can safely operate with hydrogen blends without major modifications. This strategy offers a low-disruption pathway to reduce emissions while scaling up hydrogen infrastructure. The success of HyDeploy demonstrates that even partial hydrogen adoption can deliver immediate environmental benefits, paving the way for nationwide implementation.

3. HydroFLEX: Hydrogen-Powered Train, United Kingdom

Transportation is another critical sector where hydrogen storage proves valuable. The HydroFLEX project, led by the University of Birmingham and Porterbrook, retrofitted a conventional train with hydrogen fuel cells, enabling zero-emission rail travel. After successful mainline trials, the project highlights hydrogen's potential to replace diesel on non-electrified routes, offering a cleaner alternative for rail networks. This innovation supports the UK's net-zero goals while demonstrating hydrogen's adaptability in mobility solutions.

4. Australian Renewable Energy Hub (AREH), Australia

Australia's vast renewable resources position it as a key player in the global green hydrogen market. The Australian Renewable Energy Hub (AREH) in Western Australia combines large-scale solar and wind farms to produce hydrogen via electrolysis, targeting export markets in Asia. This project underscores hydrogen's role in international energy trade, providing a sustainable alternative to fossil fuels while boosting regional economic growth through investments and job creation.

5. NEOM Green Hydrogen Project, Saudi Arabia

Saudi Arabia's NEOM Green Hydrogen Project is set to become the world's largest green hydrogen facility, powered entirely by solar and wind energy. Developed in partnership with Air Products and ACWA Power, the project supports the futuristic NEOM city's vision of carbon-neutral living. By integrating hydrogen production with urban planning, Saudi Arabia aims to diversify its economy and establish itself as a leader in the global hydrogen supply chain.

Conclusion

These case studies demonstrate hydrogen energy storage's growing role in the global energy transition, from urban heating and transport to large-scale renewable integration and export

markets. While challenges remain, the progress seen in the UK, Australia, and Saudi Arabia highlights hydrogen's potential to decarbonize multiple sectors while driving economic growth. Continued innovation, policy support, and international collaboration will be essential to scaling these solutions effectively.

4.5.1 Large-Scale Hydrogen Deployment Examples

Hydrogen energy storage at large scales is a cornerstone for decarbonization strategies worldwide, serving applications in industrial processes, power generation, mobility, and export markets. The following case studies showcase notable projects and initiatives that demonstrate the real-world application of hydrogen storage technologies.

Case Study 1: Australian Renewable Energy Hub (AREH), Australia

Overview

- **Location:** Western Australia
- **Objective:** To produce and export renewable hydrogen using vast solar and wind resources.
- **Capacity:** Planned to generate up to 26 GW of renewable energy, producing approximately **1.8 million tonnes of green hydrogen annually**.

Key Features

- Utilizes **large-scale electrolysis** powered exclusively by renewable energy.
- **Export infrastructure:** Hydrogen transported via pipelines or converted into ammonia for shipping.
- **Significance:** Aiming to meet Asian markets' clean fuel demands and position Australia as a global hydrogen exporter.

Impacts

- Supports **climate goals** by providing an export route for green hydrogen.
- Stimulates **local economy** and creates thousands of jobs.

Reference:

- AREH Consortium, Project Overview, May 2025
<https://research.csiro.au/hyresource/australian-renewable-energy-hub/>
- ARENA - Australian Renewable Energy Agency.
<https://arena.gov.au/renewable-energy/hydrogen/>

AREH Project Key Data

Key Parameter	Details
Location	Western Australia
Installed Renewable Capacity	Up to 26 GW
Hydrogen Production Capacity	1.8 million tonnes/year
Main Technology	Electrolysis (Proton Exchange Membrane & Alkaline)
Export Target	Asian markets including Japan, Korea, China

Case Study 2: NEOM Green Hydrogen Project, Saudi Arabia

Overview

- **Location:** NEOM City, Saudi Arabia
- **Objective:** To develop the world's largest green hydrogen plant, producing **up to 650 tonnes per day**.
- **Capacity:** Approx. **4 GW of renewable power** (solar and wind).

Key Features

- Electrolysis powered *entirely* by renewable energy.
- Integrated into Saudi Vision 2030 ambitions for economic diversification.
- Hydrogen exported globally, especially to Europe and Asia.

Impacts

- Decarbonizing Saudi Arabia's economy.
- Facilitating the development of a **net-zero** city.
- Demonstrates high scalability of renewable hydrogen.

Reference:

- NEOM Project (2020). "Green Hydrogen Project Announcement."
<https://acwapower.com/en/projects/neom-green-hydrogen-project/>
<https://nghc.com/#0>
<https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment>

NEOM Hydrogen Project Overview

Parameter	Details
Location	NEOM City, Saudi Arabia
Power Supply	4 GW renewable (solar & wind)
Hydrogen Output	650 tonnes/day (236,000 tonnes/year)

Technology	PEM electrolysis
Export Markets	Europe, Asia

Case Study 3: Hydrogen Valley – North Rhine-Westphalia, Germany

Overview

- **Aim:** Establishing a **regional hydrogen economy** involving production, storage, and utilization.
- **Deployment:** Multiple pilot and large-scale projects integrating hydrogen into industry and power.

Key Features

- Using hydrogen in steel, chemical industries, and mobility.
- Development of **hydrogen storage tanks** and pipelines.
- Formation of **hydrogen alliances** among industry, government, and research centers.

Impacts

- Demonstrates **sector coupling** and infrastructure development.
- Supports **industry decarbonization** and local job creation.

Reference:

- Hydrogen Valley – North Rhine-Westphalia, Germany
<https://h2v.eu/hydrogen-valleys/hydrogen-valley-emsland>
- Ministry of Economic Affairs, Innovation, Digitalization and Energy of the State of North Rhine – Westphalia; Hydrogen Roadmap North Rhine – Westphalia,
https://www.wirtschaft.nrw/sites/default/files/documents/mwide_br_wasserstoff-roadmap-nrw_eng_web.pdf
- Phillip Fest, A Dutch-German Hydrogen Valley – The Netherlands and North Rhine-Westphalia as a Pioneer Region for the European Hydrogen Economy, Challenges and Solutions of Hydrogen Infrastructure, presentation
https://ewir.jura.uni-koeln.de/sites/ewir/user_upload/2023-10-26_FCEEL_Fest.pdf

Regional Hydrogen Deployment Data

Feature	Details
Region	North Rhine-Westphalia, Germany
Hydrogen Production	Large electrolysis units, reforming + CCS
Storage Facilities	Underground salt caverns, pressurized tanks

Key Sectors	Steel, chemicals, mobility
Total Capacity (Project Scale)	Several hundred MW electrolyzers active

Case Study 4: H2Future Project, Austria

Overview

- **Location:** Linz, Austria
- **Objective:** To demonstrate large-scale PEM electrolysis technology for industrial-scale hydrogen production.
- **Capacity:** Initially 1 MW, with plans to expand further to facilitate industrial applications.

Key Features

- **Objective:** To produce green hydrogen using renewable energy and integrate it into industry (e.g., steel and chemical sectors).
- **Partnerships:** Collaborations with voestalpine Steel, Siemens, and other partners.
- **Innovations:** Testing of high-current PEM electrolyzers, facilitating large-scale renewable hydrogen production.

Impacts

- **Decarbonizing industry:** Focused on reducing industrial emissions, especially in steel manufacturing.
- **Technology Validation:** Serving as a blueprint for scaling up hydrogen electrolyzer deployment.

Reference:

- H2FUTURE - Green Hydrogen web page <https://www.h2future-project.eu/en>
- Germán Morales-España et al., Impact of large-scale hydrogen electrification and retrofitting of natural gas infrastructure on the European power system; International Journal of Electrical Power & Energy Systems, Volume 155, Part B, January 2024, 109686
<https://www.sciencedirect.com/science/article/pii/S0142061523007433>

Case Study 5: Dubai Green Hydrogen Innovation Hub, UAE

Overview

- **Objective:** To create a regional hydrogen hub leveraging abundant solar energy to produce green hydrogen and ammonia for domestic use and export.
- **Planned Capacity:** Multiple GW-scale electrolysis, producing several hundred thousand tonnes of hydrogen/year.

Key Features

- Integration of solar farms with electrolysis plants.
- Use of ammonia as hydrogen carrier for efficient export.
- Focus on emphasizing hydrogen's role in sustainable urban development and export.

Impacts

- Supporting Gulf countries' diversification away from oil.
- Exporting green hydrogen globally, especially to Asia and Europe.

Reference:

- Government of Dubai, Green Hydrogen project web page
<https://www.dewa.gov.ae/en/about-us/strategic-initiatives/green-hydrogen-project>
- Green Hydrogen Innovation Centre, web page
<https://isa-ghic.org/countries/uae-1>

Summary Table of Large-Scale Hydrogen Deployment Examples

Project Name	Location	Technology	Capacity/Output	Primary Focus	Official Links
Australian Renewable Energy Hub (AREH)	Western Australia	Electrolysis + Renewable Power	26 GW renewable, 1.8 Mt H ₂ /year	Export markets, renewable energy integration	https://research.csiro.au/hyresource/australian-renewable-energy-hub/
NEOM Green Hydrogen Project	Saudi Arabia	PEM Electrolysis	4 GW renewable, 650 t/day (236 kt/year)	Export and domestic decarbonization	https://acwapower.com/en/projects/neom-green-hydrogen-project/
North Rhine-Westphalia, Germany	Germany	Electrolysis + Sector coupling	Several hundreds MW electrolyzers	Industrial decarbonization, sector coupling	https://h2v.eu/hydrogen-valleys/hydrogen-valley-emsland
H2Future Project, Austria	Austria	PEM Electrolysis	1 MW initial, scalability planned	Industrial hydrogen, technology demonstration	https://www.h2future-project.eu/en
Dubai Green	UAE	Solar +	Multiple GW-	Export,	https://www.dewa.gov.ae

Hydrogen Hub		Electrolysis + Ammonia	scale electrolysis units	urban & industrial use	e/en/about-us/strategic-initiatives/green-hydrogen-project

These case studies emphasize that large-scale hydrogen deployment is ongoing worldwide with diverse applications. They demonstrate how countries leverage abundant renewable resources, innovative technologies, and infrastructure investments to develop hydrogen ecosystems. These projects not only serve as prototypes for future scalable solutions but are crucial in advancing global decarbonization goals.

Region-Specific Insights and Technical Datasheets on Large-Scale Hydrogen Storage Projects

• EUROPE

Key Focus:

- Decarbonization of industry, heavy transport, and power.
- Building cross-border hydrogen infrastructure.
- Major projects: Hydrogen backbone, industrial hubs, and regional pilot sites.

Key Technologies:

1. **Electrolysis Technologies:**
2. **Proton Exchange Membrane (PEM):** High current density, rapid response, suitable for integrating intermittent renewable sources.
3. **Alkaline Electrolyzers:** Mature, cost-effective, suitable for large capacity deployments.
4. **Solid Polymer Electrolyte (SPE):** Emerging, promising high efficiency.

Technical Datasheet: Europe

Item	Specification	Comments
Electrolyzer Capacity	10-1000+ MW per plant	Modular deployment, scaling with renewable availability
Electrolyzer Type	PEM, Alkaline, SOEC (Solid Oxide Electrolyzer)	Choice depends on project scale and grid integration needs
Operating Voltage	1.8–2.2 V per cell	Influences efficiency and operational costs
Current Density	1–4 A/cm ²	Higher current densities improve efficiency but increase cost/complexity

Hydrogen Purity	>99.999%	Critical for fuel cell and industrial applications
Efficiency	60–70% (electrical-to-hydrogen)	Higher efficiencies reduce water and energy usage
Lifecycle & Operating Lifespan	80,000–100,000 hours	Ensures economic viability for large-scale projects

Notable Projects:

- **European Hydrogen Backbone (EHB):** A planned pipeline network of over 100,000 km.
- **Port of Rotterdam Hydrogen Hub:** Using large electrolysis units with surplus wind and solar.

References:

- The European Hydrogen Backbone (EHB) initiative – web page <https://ehb.eu/>
- Hydrogen in Rotterdam – web page <https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/hydrogen-rotterdam>
- Hydrogen Europe <https://hydrogeneurope.eu/>

▪ **ASIA**

Key Focus:

- Export-driven green hydrogen projects, especially in Australia, Middle East, and Southeast Asia.
- Domestic use in Japan, South Korea, and China for industry and mobility.
- Large renewable resource bases: Solar in Middle East, Solar/Wind in Australia.

Key Technologies:

- **Electrolysis:**
 - **PEM Electrolyzers:** Suitable for dynamic renewable sources, high purity.
 - **AEM (Alkaline Exchange Membrane):** Emerging, lower cost, high scalability.
- **Hydrogen Storage:**
 - **Compressed Gas Storage:** High-pressure tanks (~350–700 bar), modular.
 - **Liquid Hydrogen:** Cryogenic tanks for export and long-term storage.
 - **Chemical Storage:** Ammonia or metal hydrides for transportation.

Technical Datasheet: Asia

Item	Specification	Comments
Electrolyzer Capacity	1–10 GW projects in development	Focused on green H ₂ export, especially in Australia and Middle East
Electrolyzer Type	PEM, AEM, Alkaline	AEM gaining interest for lower costs and flexibility
Storage Pressure	350–700 bar (compressed gas)	Modular tanks, suitable for shipboard or pipeline injection
Liquid Hydrogen Storage	Cryogenic tanks (~20 K)	Used for export, ships, and large-scale storage
Cycle Life	10,000–20,000 cycles with high efficiency	Critical for export pipelines and continuous operation

Notable Initiatives:

- **Australian Hydrogen Export Hubs:** Utilizing **large-scale electrolysis** combined with **cryogenic storage**.
- **Middle East (Saudi Arabia, UAE):** Ammonia as hydrogen carrier for export, with large-scale synthesis facilities.

References:

- Commonwealth Scientific and Industrial Research Organisation (CSIRO), Hydrogen Hubs in Australia
<https://research.csiro.au/hyresource/hubs/>
- Australian Government, Department of Climate Change, Energy, the Environment and Water, Building regional hydrogen hubs – web page
<https://www.dcceew.gov.au/energy/hydrogen/building-regional-hydrogen-hubs>

USA

Key Focus:

- Power Sector: Large-scale hydrogen storage as a grid balancing tool, especially with increasing renewable energy.
- Industrial Decarbonization: Replacing fossil-based feedstocks in industries like steel, chemicals, and refining.
- Transportation: Hydrogen refueling stations and fuel cell trucks/ships.
- Export Markets: Developing hydrogen and ammonia export hubs, especially leveraging domestic renewable resources.

Key Technologies:

Critical Technologies and Their Technical Datasheets

A. Electrolysis Technologies

Technology Type	Key Specifications	Advantages	Application Focus	Examples/Projects
PEM (Proton Exchange Membrane)	- Capacity: 1 MW to GW-scale modules - Efficiency: 60–70% - Voltage: 1.8–2.2 V - Operating Temp: 50–80°C	- Rapid response & dynamic operation - High purity H₂ - Modular and scalable	Power-to-Hydrogen, renewable integration	H2@Scale projects; California Hydrogen Program
Alkaline Electrolyzers	- Capacity: Up to 100 MW per plant - Efficiency: 70–80% - Operating Temp: 60–80°C	- Mature, cost-effective - Proven durability	Large centralized green hydrogen production	Northeastern US, industrial hubs
Solid Oxide Electrolyzers (SOEC)	- Capacity: Pilot/demo scale - Higher efficiencies (>80%)	- High efficiency - Can co-electrolyze water/CO₂	Power plants, industrial co-generation	Emerging, pilot projects

B. Hydrogen Storage Technologies

Storage Type	Specification / Features	Capacity Range	Cost & Maturity	Use Cases / Applications
Compressed Gas Storage	- Pressure: 350–700 bar - Material: Steel, composites - Modular	From small tanks (~10 m ³) to large pipelines	Mature, commercial-scale	Fueling stations; industrial supply; pipeline injection
Cryogenic Liquid Hydrogen	- Temperature: ~20 K - Volume: High-density storage	Large-volume storage (100+ tonnes)	Mature but energy-intensive	Export, long-term energy storage
Underground Salt Caverns	- Capacity: TWh scale (~4–10 TWh) - Location: Salt domes, depleted	TWh-scale seasonal storage	Mature (gas storage legacy)	Grid balancing, load shifting

	reservoirs			
Chemical Storage (Ammonia, Hydrides)	- Ammonia: Easy liquefaction at ambient pressure - Hydrides: Compact, safe	Mode- dependent	Emerging, pilot projects	Export, transport, portable applications

Specific Insights & Strategic Focus in the USA

a) Power Sector and Grid Flexibility

- The U.S. emphasizes using underground salt caverns and pressure vessels for seasonal storage.
- Deployment of hydrogen via PEM electrolysis at renewable-rich sites (California, Texas, Midwestern states).
- Projects like H2@Scale aim for multi-gigawatt electrolyzer installations integrated with renewables.

b) Industrial Decarbonization

- Large-scale hydrogen infrastructure supports zero-emission industrial processes, including replacing grey hydrogen in existing facilities.
- Key projects involve carbon capture coupled with electrolysis or blue hydrogen where fossil fuels are used with CCS.

c) Hydrogen Export and Infrastructure Development

- Alaska and Gulf Coast are emerging as key export regions, leveraging existing liquefaction and port infrastructure.
- Projects aim for massive green hydrogen exports (via ammonia or liquefied hydrogen) to Asian markets, driven by abundant renewable resources and existing shipping routes.

d) Key Policy & Market Drivers

- The Bipartisan Infrastructure Law (2021) allocated hundreds of millions USD for hydrogen infrastructure.
- Multiple public-private partnerships facilitate R&D, large-scale pilot projects, and regional hydrogen hubs.
- The DOE's Hydrogen Shot initiative aims to reduce electrolyzer costs by 80% within a decade.

C. Notable Projects in the USA

Project / Initiative	Focus Area	Technology Employed	Capacity / Scale	Location	Remarks
H2@Scale Program	Power, Industry	Electrolysis, pipelines, underground	Multiple MW to GW-scale	Nationwide	Multiple large projects, policy support

		storage			
Texas Salt Caverns	Power grid balancing	Underground salt caverns, compressed H ₂	Several TWh	Texas	Proven for natural gas, expanding for hydrogen
California Hydrogen Network	Fueling, power	PEM electrolysis, compressed gas	>100 stations planned	California	Large regional deployment, renewable emphasis
Alaska LNG & H ₂ Export	Export / Industry	Liquefaction, cryogenic storage	1+ Mt/year capacity	Alaska	Export-oriented projects, renewable + H ₂

Summary Table: USA Key Technologies and Projects

Technology / Focus	Key Parameters / Features	Representative Projects	Capacity / Scale	Remarks
Electrolyzers (PEM, Alkaline, SOEC)	Modular, scalable; high efficiency (>70%)	H2@Scale; HyStor Power	MW to GW-scale	Supporting grid integration and industrial uses
Underground Salt Caverns	Large-scale, seasonal storage	Texas, Utah salt caverns	Several TWh	Proven, expanding for hydrogen
Compressed & Liquefied Storage	High-pressure tanks, cryogenic tanks	California stations, Alaska LNG	10s-1000s t capacity	Widely deployed in fueling & export
Export Infrastructure	LNG-like liquefaction + shipping	Alaska, Gulf Coast	1+ Mt/year	International markets, especially Asia

The USA is leveraging advanced electrolysis, large underground salt caverns, and integrated infrastructure to create a dynamic hydrogen economy. These efforts are aligned with national decarbonization goals, energy resilience, and export ambitions.

Key focus areas include:

- Large-scale green hydrogen production driven by renewable resources.
- Underground salt cavern storage for seasonal balancing.
- Extensive pipeline and export infrastructure for global markets.
- Supporting policies that incentivize capacity building, technological innovation, and private sector investment.

References:

- KV Catalyst, Salt Cavern Storage, web page

<https://www.kvcatalyst.com/blog/salt-caverns>

- Linde, Storing Hydrogen in Underground Salt Caverns, web page
<https://www.linde.com/clean-energy/our-h2-technology/hydrogen-storage>
- Si Huang et al., The Role of Underground Salt Caverns in Renewable Energy Peaking: A Review; Energies 2024, 17, 6005. <https://doi.org/10.3390/en17236005>
https://www.researchgate.net/publication/386229848_The_Role_of_Underground_Salt_Caverns_in_Renewable_Energy_Peaking_A_Review
- Zhen Yang et al., Safety analysis of hydrogen explosion accident in underground hydrogen storage gas injection station, International Journal of Hydrogen Energy, Volume 92, 26 November 2024, Pages 1143-1159
<https://www.sciencedirect.com/science/article/pii/S0360319924044136>
- Jiří Pospíšil et al., Energy demand of liquefaction and regasification of natural gas and the potential of LNG for operative thermal energy storage; Renewable and Sustainable Energy Reviews, Volume 99, January 2019, Pages 1-15
<https://www.sciencedirect.com/science/article/pii/S1364032118306828>
- Alaska LNG – web page, <https://alaska-lng.com/>

Summary Table: Technological and Infrastructure Insights

Region	Key Electrolyzer Technologies	Storage Methods	Major application focus	Notable Projects
EUROPE	PEM, Alkaline, SPE electrolyzers	Pipeline, underground caverns, liquid hydrogen	Power, industry, export, heating	EU Hydrogen Backbone, Port of Rotterdam, HyDeploy
ASIA	PEM, AEM, Alkaline electrolyzers	Compressed, cryogenic, ammonia, metal hydrides	Export, heavy industry, mobility	Australia hydrogen export, Middle East projects
USA	PEM, Alkaline, emerging SOEC tech	Underground salt caverns, high-pressure tanks, liquid hydrogen	Power, mobility, industrial decarbonization	HyScale, H2@Scale, California hydrogen network

Conclusion

The deployment of large-scale hydrogen energy storage is advancing rapidly in Europe, Asia, and the USA, each leveraging unique technological approaches tailored to regional resource availability, infrastructure maturity, and policy incentives.

Technologies like PEM and alkaline electrolyzers dominate due to their proven efficiency and scalability, while storage solutions include **compressed hydrogen, cryogenic liquid storage, and underground caverns**. These projects illustrate a strategic move toward a **hydrogen economy** capable of supporting emissions reductions across multiple sectors globally.

4.5.2 Challenges and Best Practices

Despite the progress demonstrated by these case studies, hydrogen energy storage faces significant challenges that must be addressed to achieve widespread adoption. One of the most pressing issues is system efficiency. Hydrogen storage involves multiple energy conversions—electricity to hydrogen via electrolysis, compression or liquefaction for storage, and reconversion

to electricity or heat—each incurring energy losses. Studies by Glenk and Reichelstein (2019) estimate that the round-trip efficiency of hydrogen storage systems ranges from 30% to 50%, significantly lower than batteries (70–90%) or pumped hydro (70–80%). Improving electrolyzer and fuel cell efficiencies, as well as exploring alternative storage methods such as liquid organic hydrogen carriers (LOHCs), could mitigate these losses.

Infrastructure costs represent another major barrier. The construction of hydrogen storage facilities, pipelines, and refueling stations requires substantial capital, often deterring private investment. For example, the European Hydrogen Backbone initiative estimates that developing a continent-wide hydrogen pipeline network could cost €80–143 billion by 2040 (Hydrogen Europe, 2021). Public-private partnerships and phased deployment strategies, as seen in the HyStock and Energiepark Mainz projects, are critical to distributing financial risks and accelerating infrastructure rollout.

Safety and regulatory frameworks also pose challenges. Hydrogen's high flammability and low ignition energy necessitate stringent safety protocols for storage and transportation. The 2019 explosion at a hydrogen refueling station in Norway highlighted these risks, prompting revisions to international safety standards (Khalil, 2020). Best practices include using advanced leak-detection systems, reinforced storage tanks, and remote monitoring technologies. Regulatory harmonization, such as the EU's Hydrogen Strategy's certification system for renewable hydrogen, is equally important to ensure consistency in safety and environmental standards across borders.

From an environmental perspective, the water footprint of hydrogen production remains a concern, particularly in arid regions. Proton exchange membrane (PEM) electrolyzers require ultra-pure water, with estimates suggesting 9–12 liters per kilogram of hydrogen produced (Carmo et al., 2013). Projects in water-stressed areas, such as the NEOM Green Hydrogen Project in Saudi

Arabia, address this by using desalination plants powered by renewables, though this adds to system complexity and cost.

Best practices emerging from these challenges include:

- Co-locating hydrogen production with renewable energy sources to minimize transmission losses and reduce costs. The FH2R model, which integrates solar and wind power directly with electrolyzers, exemplifies this approach.
- Prioritizing geological storage (e.g., salt caverns, depleted gas fields) for large-scale deployments, as demonstrated by HyStock, to leverage existing infrastructure and reduce land-use conflicts.
- Adopting modular and scalable designs to accommodate technological advancements and fluctuating demand. The Energiepark Mainz's phased expansion, which grew from a 1 MW pilot to a 6 MW system, illustrates the benefits of incremental scaling.

Major Challenges in Hydrogen Energy Storage

Challenge	Description	Impact
High Capital and Operating Costs	Cost of high-pressure tanks, cryogenic systems, underground caverns, materials, and infrastructure	Limits economic viability, especially for green hydrogen
Material Compatibility & Durability	Hydrogen embrittlement of metals, degradation of membranes and seals over time	Reduces lifespan and increases maintenance costs
Leakage and Flammability Risks	Small molecule size leads to permeation, and leaks can cause safety risks	Safety hazards, environmental concerns, hydrogen loss
Energy Losses and Efficiency Degradation	Boil-off in cryogenic storage, permeation through materials, compression losses	Reduced storage efficiency, increased operational costs
Environmental Impact of Material Extraction	Mining, processing steel, composites, membranes	Environmental footprint and supply chain concerns
Space and Land Use	Large physical footprint of tanks, caverns, and pipeline infrastructure	Constraints in urban and land-limited environments
Regulatory and Standardization Gaps	Lack of universally adopted standards for safety, design, and certification	Delays deployment, increases costs

Challenges in Detail

1. Economic and Cost Challenges

- High capital expenditure: Construction of high-pressure tanks, cryogenic systems, underground caverns, and pipeline networks involves significant initial investments.
- Operational costs: Maintenance, material replacement, and energy losses reduce overall economic competitiveness.

2. Material Compatibility & Safety Challenges

- Hydrogen embrittlement: Hydrogen can weaken metals such as steels used in tanks and pipelines, leading to cracks and failure.
- Seal and membrane degradation: Over time, permeation and environmental factors degrade seals, affecting safety and efficiency.

3. Leakage & Flammability Risks

- Leak potential: Hydrogen's small molecular size causes permeation through materials, leading to leaks.
- Flammability: Leaked hydrogen can form explosive mixtures with air; ongoing safety monitoring required.

4. Energy Losses

- **Cryogenic boil-off:** Hydrogen stored as a cryogenic liquid continually vaporizes without active containment, leading to energy losses.
- **Permeation & leakage:** Lipid permeation decreases overall efficiency.
- **Compression losses:** Compressing hydrogen for storage introduces energy costs and handling complexities.

5. Environmental and Material Supply Chain Concerns

- Mining for steel and composites involves environmental impacts.
- Supply chain risks: Dependence on scarce resources and materials (e.g., rare metals for membranes and catalysts) can have environmental footprints.

6. Space and Land Use

- Large tanks and underground caverns require significant space.
- Pipelines and infrastructure may be difficult to deploy in densely populated urban areas or sensitive ecosystems.
- **Best Practice:** Use existing natural or geological formations for underground storage and develop modular, scalable infrastructure.

7. Regulatory & Standardization Gaps

- Lack of universal safety and design standards causes delays, increased costs, and interoperability issues.

- Common standards are critical for public acceptance, market growth, and international trade.
- Best Practice: Adoption of international standards (e.g., ISO/TC 197) and Certification protocols for tanks, pipelines, and safety systems.

Best Practices in Hydrogen Energy Storage

Best Practice	Description	Application Examples
Use Proven Underground Salt Caverns	Large capacity, low cost, proven technology	Texas, Utah, Louisiana salt cavern facilities
Material Testing & Material Compatibility	Regular testing and advanced materials to prevent embrittlement	Use of advanced alloys, coatings, and composites
Implement Advanced Safety Systems	Leak detection, pressure monitoring, automated shutdown	Fiber optic sensors, gas detectors
Modular and Scalable System Design	Phased deployment, flexibility in capacity	Modular tank systems, phased pipeline expansion
Integrated Storage & Infrastructure Planning	coupled pipelines, refueling stations, and storage; safety & efficiency	Cross-sector planning, GIS mapping

Summary & Recommendations

Aspect	Key Insight
Economic Viability	Reduce costs via process optimization, materials innovation, and scale
Material Durability & Safety	Use high-performance materials; continuous monitoring
Safety Systems	Leverage latest sensing, automation, safety standards
Environmental & Material Footprint	Minimize resource extraction, optimize supply chain
Infrastructure Deployment	Modular design, public-private cooperation, standardization

Conclusion

Hydrogen energy storage, while critical for a sustainable future, must overcome significant technical, safety, and environmental challenges. By adopting best practices such as underground cavern use, advanced materials, integrated planning, and rigorous safety standards, stakeholders can optimize costs, enhance safety, and minimize environmental impacts.

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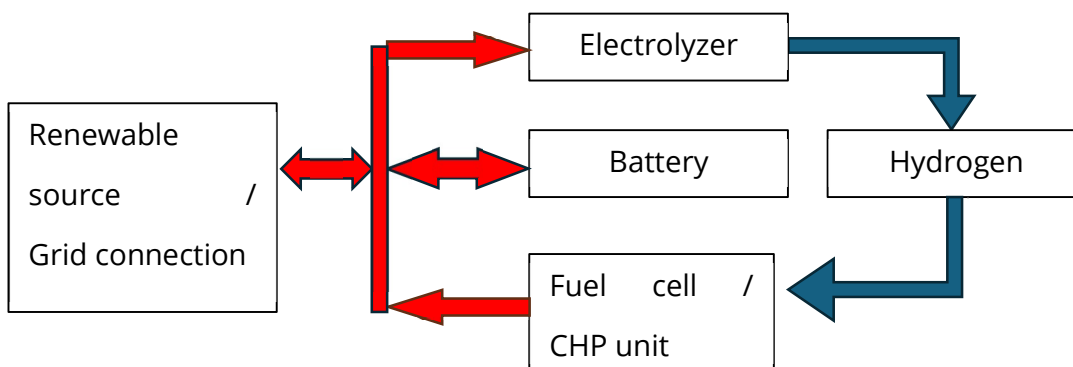
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4.6 Typical Use cases of Hydrogen Energy Storage



System Overview and Power Management

The block diagram illustrates the integration of an electrolyzer with an electrical power source, where the power supply to the electrolyzer is stabilized using a battery system. The hydrogen

generated by the electrolyzer is stored in a dedicated storage unit. Electricity can then be produced from the stored hydrogen using either a fuel cell or a combined heat and power (CHP) unit. The output voltage from the fuel cell or CHP unit is also stabilized via a battery.

Incorporating a battery into a hydrogen energy storage system provides several key benefits. Most notably, the battery ensures the stabilization of the power supply to the electrolyzer. This stabilization primarily serves to reconcile the mismatch between the variable characteristics of the power source and the specific operational requirements of the electrolyzer.

A properly designed power stabilization system directly affects the efficiency of the electrolyzer, the purity of the hydrogen produced, the overall utilization rate of the system, and the longevity of the installed equipment.

4.6.1 Power Balance Service Source

The system is permanently connected to the electrical distribution grid and may also be supplied by renewable energy sources (RES). During periods of electricity surplus, the system produces and stores hydrogen via electrolysis. When electrical power is needed, the stored hydrogen is converted back to electricity using a combined heat and power (CHP) unit. Fuel cell, combustion engine, gas turbine, aeroderivative turbine, or a combined-cycle gas turbine (CCGT) all supplemented as needed eg. by batteries. Utilization of waste heat from these processes increases the overall system efficiency and improves the project's economic viability.

4.6.2 System with high self-sufficiency – P2H2P (Power to Hydrogen to Power)

The system is connected to renewable energy sources such as photovoltaic panels, wind turbines, or possibly a hydroelectric power plant.

It produces and stores hydrogen from surplus renewable energy (e.g. in summer season) for use during times of demand (e.g. in winter season). The amount of electricity and hydrogen produced is sufficient to cover significant part of annual electricity consumption. Based on the specific

energy sources and their combination, the nature of the power supply can be determined, which allows for the selection of the suitable electrolysis technology. Utilization of waste heat from processes hydrogen production and power production increase the overall system efficiency and improves the project's economic viability. For seasonal storage accumulation a large amount of hydrogen needs to be stored. With low number of operating cycles, hydrogen storage becomes the most expensive part of the project.

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5 Vanadium Redox Flow Batteries (VRFBs)

5.1 Overview of VRFB Technology

VRFBs are a type of rechargeable flow battery that stores energy in liquid electrolytes held in external tanks and converts it to electricity via an electrochemical cell. Vanadium ions in different oxidation states serve as charge carriers in both the positive and negative electrolytes, eliminating cross-contamination issues since the same element is used on both sides ⁴⁹. During charging, vanadium ions in one tank are oxidized (releasing electrons) while those in the other tank are reduced (accepting electrons), and the process reverses during discharge. An ion-selective membrane between the half-cells allows ion transport to maintain the charge balance, while preventing the mixing of electrolytes. A key distinguishing feature of VRFBs is the decoupling of power and energy capacity: the stack (number and size of cells) determines the power (kW or MW rating), whereas the tank volume and electrolyte concentration determine the energy capacity (kWh) ⁵⁰. This means a VRFB can be scaled by expanding the electrolyte tanks for more energy without changing the stack, or adding more cells for higher power, providing exceptional flexibility in design ⁵¹. VRFB systems typically include pumps to circulate the electrolyte and power conditioning units (inverters) to interface with the electric grid. The response of VRFBs is rapid – they can ramp up output in seconds or less – and they exhibit low self-discharge since the electrolytes can sit in tanks for extended periods with minimal losses ⁵¹.

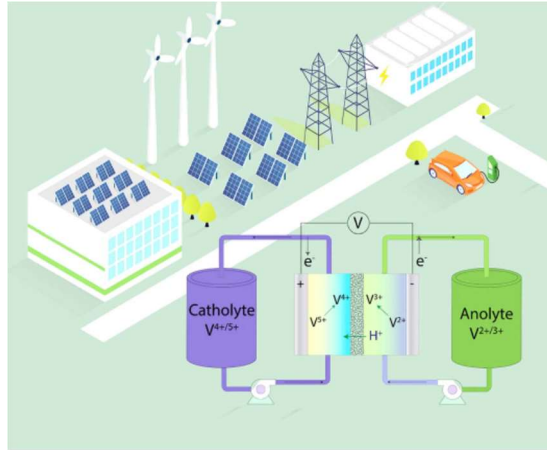


Figure 5.1 : Schematic of a Vanadium Redox Flow Battery (VRFB) system, showing two electrolyte tanks (anolyte and catholyte) connected via pumps to a central stack of electrochemical cells separated by an ion-selective membrane⁵²

Flow batteries (RFBs) store electricity in two separate electrolyte tanks that contain redox couples. A battery system that uses a lithium-ion or lead–acid battery uses chemical reactions involving the electrodes' intercalation, alloying, conversion. Recent decades have seen the development of several RFB chemistries, but the all-vanadium redox flow battery (VRFB) stands out as one of the most advanced RFBs due to its low capital cost, high-energy efficiency (EE), and ability to prevent electrolyte cross-contamination. The thermodynamic shows that an open circuit voltage (VOC) of VRFB is 1.25 V. As shown in Fig. 1, the catholyte and anolyte of this system are V^{4+}/V^{5+} and V^{2+}/V^{3+} dissolved in sulphuric acid, respectively, separated by ion exchange membranes and electrodes with carbon fabric materials.

5.1.1 TRL and maturity of VRFBs

VRFB technology has advanced from laboratory concept to full-scale deployments over the past decades. As of 2025, VRFBs are generally considered to be at a **high TRL (around 7–9)** – meaning pilot demonstrations and early commercial systems are in operation, though widespread adoption is still emerging⁵³. The basic principles were proven in the 1980s by Maria Skyllas-Kazacos's team

in Australia, and continuous improvements since 2010 have led to significant gains in performance and durability⁵⁴. Today, VRFBs meet many criteria for large-scale storage: they are **safe, long-lasting, and efficient**, as noted by researchers, and are seen as one of the most promising technologies for stationary storage⁵⁵. Dozens of demonstration projects worldwide have validated VRFB operations from kW-scale up to multi-MW scale. In fact, VRFBs have already been *commercialized* for years and by 2021 accounted for roughly **4% of the world's installed electrochemical storage capacity (excluding pumped hydro)**⁵⁶. This market share, while small, is growing as VRFBs move from prototypes to bankable products.

The scientists in the reference⁵⁵ tested a bunch of different combinations of new ideas to improve these batteries. They then picked the top 10% of those combinations—the ones that made the batteries cheapest to run by the year 2030. It is seen from the chart that #1: Novel active electrolytes are the special liquids inside the battery that store energy and every top-performing plan included better, more powerful electrolyte. At #2 & #3: Manufacturing at scale and speeding up discovery making batteries cheaper by improving how they're made, and quickly testing new materials, are also big priorities. Middle tier ideas like better system packaging, using recycled materials (secondary sourcing), and boosting power performance play a strong role too. Lower on the list are things like supply chain analytics or domestic recycling are still useful, but they showed up less often in the most cost-effective solutions.

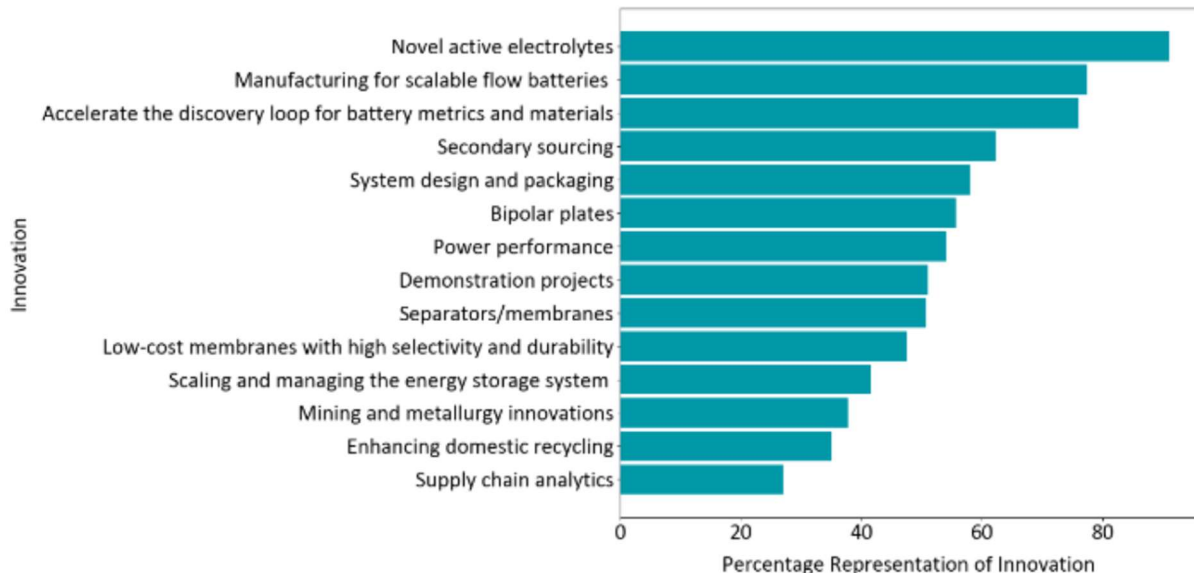


Figure 5.2: The share of innovations in top performing innovation portfolios for long duration flow batteries. Top performing portfolios are the top 10% of portfolios that reduce the projected 2030 levelized cost of storage⁵⁵

Overall, the core VRFB technology (electrochemistry and stack design) is **proven and mature**, with systems operating in real-world settings for over a decade⁵⁷. The focus is now on scaling up manufacturing and deployment, which suggests that with supportive policies, VRFBs can quickly progress to the highest readiness levels for broad commercial use. In some regions, continued pilot projects and knowledge-sharing (like the Hungarian VRFB project and regional research initiatives)⁵⁸ are recommended to elevate familiarity and readiness. These efforts can help local stakeholders move from seeing VRFBs as experimental to viewing them as a viable alternative for medium-sized energy storage installations.

5.1.2 Scale and Capacity

VRFB systems are intrinsically scalable, capable of serving a wide range of deployment sizes – but in practice they are most suitable for medium to large-scale installations. The technology can technically be built at kilowatt scale (and indeed, some kW-scale VRFB units for research or small

microgrids exist ⁵⁹, yet the economics and physical footprint favor larger deployments. Typical current VRFB products are in the 100 kW to multi-MW power range, with energy capacities from a few hundred kWh into the tens or hundreds of MWh. For example, commercial containerized VRFB units might be rated around 250 kW/1 MWh per module, and multiple modules can be linked for higher capacity. The *modularity* of VRFBs allows scaling up by adding more stacks and tanks in parallel. This makes them attractive for medium-sized enterprises or small districts that need more storage than a few home batteries but cannot implement massive pumped-hydro or other large infrastructure. A VRFB can grow with the demand: if an industrial park initially installs a 2 MWh (e.g. 500 kW with 4 h) battery for peak shaving, it could later double the energy capacity to 4 MWh by simply expanding the electrolyte tanks and adding cells, rather than replacing the whole system⁶⁰.

The deployment sweet spot for VRFBs tends to be in projects on the order of *several hundred kW up to tens of MW*, especially where discharge durations of 4–10 hours are needed. This aligns well with needs like community energy storage, renewable firming for villages or campuses, and industrial backup for multi-hour outages. Small businesses or residential settings (kilowatt-scale, short duration) are generally not targeted by VRFBs because the overhead of pumps and tanks is not justified for very small energy quantities – in those cases, solid batteries like Li-ion or other chemistries dominate. On the upper end, utility-scale VRFB farms of >100 MW are conceivable and are being piloted (e.g. China's large projects), but building many large stacks in parallel requires substantial investment and space⁶¹

Energy & Power Density (Storage Density)

One trade-off with VRFBs is their relatively **low energy density** compared to mainstream battery technologies. The energy density of a VRFB is on the order of 20 – 35 Wh per liter of electrolyte (or roughly 10 – 30 Wh per kg) ⁶². This is an order of magnitude lower than lithium-ion batteries, which

can exceed 200 Wh/kg. In practical terms, VRFBs require **more physical space** (and weight) to store a given amount of energy. A complete VRFB system includes not only the electrolyte volume but also tanks, pumps, and stack hardware. For example, a 1 MW/4 MWh VRFB installation can occupy several standard shipping containers (in one instance, 10 containers were used – 8 for battery stacks and electrolyte, and 2 for power conditioning)⁶³. As a result, VRFBs have a larger footprint per MWh: they are usually sited outdoors or in dedicated battery buildings where space is available. In dense urban environments or where footprint is at a premium, this can be a limitation.

The **power density** (W per kg or per m³) of VRFBs is also lower than that of lithium-ion systems; typical VRFB designs deliver about 50 W/kg ⁶¹. VRFBs support very high energy capacities, often between 10² and 10⁷Wh, significantly surpassing most traditional batteries, especially in long-duration storage applications exceeding 4–6 hours as seen in the chart below. Though RFBs typically involve higher upfront capital costs per kW and kWh—positioning them in the upper-right quadrant of cost-performance charts—they provide notable engineering advantages: enhanced safety due to non-flammable electrolytes, efficient thermal management via liquid circulation, modular construction for streamlined manufacturing, and simplified maintenance through straightforward electrolyte rebalancing. VRFBs, in particular, also offer fast response times, minimal self-discharge, long life cycles, room-temperature operation, and high round-trip efficiency, making them ideal for large-scale, long-duration energy storage despite lower energy and power densities compared to lithium-ion batteries.

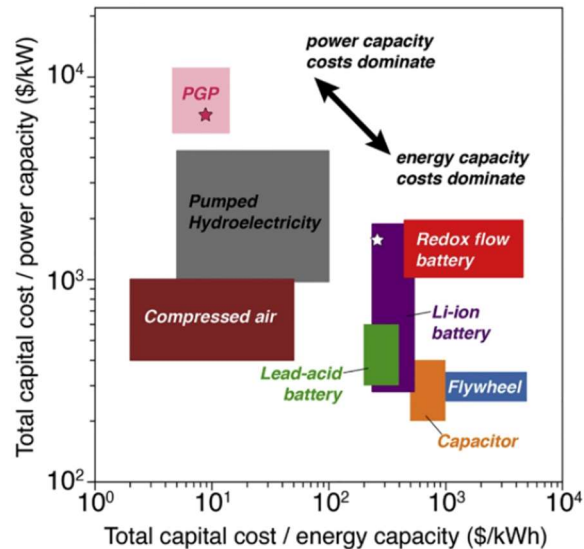


Figure 5.3. Long- and short-duration energy storage technology capital costs by capacities⁶⁴

Discharge Duration and Applications by Timescale

VRFBs excel at providing **medium-duration energy storage**, typically in the range of **4 to 12 hours** of discharge at rated power, and they can be engineered for even longer durations if needed. This makes them well-suited for daily cycling applications. By increasing the volume of electrolyte, a VRFB can store more hours of energy; theoretically, very long discharge times (24+ hours) are possible, though costs scale roughly linearly with energy capacity. In current practice, most VRFB projects aim for the 4–10 hour window, which addresses use cases like load shifting (storing energy during low demand and releasing during peak demand in the evening or night) and ensuring solar PV output can meet evening loads. This is in contrast to **high-power, short-duration technologies** such as flywheels or supercapacitors (which handle seconds to minutes) and **very long-duration storage** like hydrogen or thermal storage (which target multi-day or

seasonal storage). VRFBs fill an important niche: **multi-hour storage for daily cycles**, crucial for moving toward grids dominated by renewables.

Because VRFBs can sustain output for many hours, they can cover an entire night of solar downtime or a prolonged grid support event. For example, a 8-hour VRFB could charge from excess wind at night and discharge through the morning peak, or charge from solar at midday and discharge until midnight. In contrast, lithium-ion batteries are often deployed for 1–4 hour durations due to economic optimal points, and are less cost-effective beyond 4 hours. VRFBs have been identified as a leading option for **longer discharge** needs because their incremental cost for additional hours is mainly the cost of electrolyte and tank, which can be cheaper than adding multiple lithium battery packs to achieve the same duration⁶⁵. Additionally, VRFBs can be cycled at partial discharge; they don't need a full charge/discharge cycle to be effective, allowing them to also supply shorter bursts of power if required. Their **response time** is fast enough (often sub-second to ramp) that they can participate in frequency regulation or spinning reserve markets, although they may not be as agile as, say, supercapacitors for sub-second spikes.

To categorize:

- *Short-term (seconds–minutes)*: VRFBs can provide power for grid stability (voltage/frequency support) in this regime, but it uses only a tiny fraction of their capacity⁶⁶.
- *Medium-term (hours)*: This is where VRFBs shine – e.g., peak shaving for a factory for 6 hours or storing wind energy overnight to deliver in the morning⁶⁷. Most current VRFB installations operate in this domain.
- *Long-term (days+)*: While technically possible by scaling tank size, using VRFBs for multi-day storage becomes capital-intensive due to the large volume of vanadium electrolyte required. Competing solutions like hydrogen might be more economic for seasonal storage. That said, VRFBs could be part of microgrid solutions to ride through one or two days of bad weather if designed appropriately, but this is not yet common⁶⁸.

For the Project region's energy needs, which often involve daily balancing (e.g., shifting solar generation into evening, or reducing peak imports on the grid each night), VRFBs' discharge duration aligns well. They could help **small districts or cities manage a high solar PV penetration** by capturing daytime excess and delivering it over the subsequent hours, or help an industrial site avoid drawing power during the expensive peak hours by discharging a VRFB. This medium-duration capability also complements the region's existing storage: pumped hydro handles multi-day or seasonal fluctuations in some countries, while VRFBs could cover the intra-day balancing more effectively than short-duration battery banks. In summary, VRFBs are most advantageous when **continuous power output is needed for many hours** – a scenario increasingly common as we push toward higher renewable energy fractions.

Efficiency and Performance

The **round-trip energy efficiency (RTE)** of VRFB systems – the ratio of energy out to energy in over a full charge/discharge cycle – typically ranges from about **70% up to 85%** under normal operating conditions ⁶⁹. This means that for every 1 kWh of electricity used to charge the battery, about 0.70–0.85 kWh can be retrieved during discharge, with the remainder lost as heat, pumping work, and other losses. The efficiency can vary depending on the design and operating regime: higher power operation may incur more resistive losses in the stack, and running pumps continuously for circulation imposes a fixed overhead that affects efficiency more for small systems or low discharge rates. Modern VRFB designs tend toward the upper part of this range (80–85% RTE) by using advanced membranes and optimizing flow rates ⁷⁰. Even so, VRFB efficiency is generally a bit lower than that of lithium-ion batteries, which often achieve 90–95% in similar conditions ⁷¹. This efficiency gap means VRFBs may lose slightly more energy over each cycle, which can influence economic calculations, especially for daily cycling.

It's worth noting that VRFB efficiency does **not degrade significantly over time** – a VRFB that starts at 80% RTE will likely remain near that level for most of its life, whereas some other batteries might see efficiency drop as internal resistance rises with age. Engineering efforts are ongoing to improve VRFB efficiency, such as better electrode materials to reduce losses and intelligent pump control. For instance, some systems can dynamically adjust the pumping power or even temporarily halt circulation when the battery is idle to reduce parasitic losses, thereby improving the effective RTE for slower cycles ⁷². Additionally, when a VRFB is at full charge and idle, it can be left in a standby state with minimal self-discharge – any slow crossover of vanadium ions that might self-discharge the system can often be reversed by rebalancing, and clever designs drain electrolytes out of the stack when not in use to prevent unwanted reactions ⁷³.

In practical operation, an efficiency of ~75% means that some excess generation is needed to “cover” the losses. For a grid storage application in the Project's region, this loss is comparable to or a bit higher than other storage options, but it must be balanced against VRFB's advantages in duration and life.

Using low-cost surplus renewable energy to charge VRFBs can mitigate concerns about round-trip losses, since the alternative might be curtailing that surplus (wasting 100% of it). Nonetheless, for applications like bulk energy time-shifting, the slightly lower efficiency is a factor: more input energy is required for the same output, potentially affecting economics if energy is expensive. Many analyses, including a 2024 US DOE report, project that improvements in **electrolytes and stack design could boost flow battery efficiencies and drive down costs, making the lower RTE less of an issue by 2030** ⁷⁴. In summary, while VRFBs may not be the absolute most efficient battery, they offer respectable efficiency in the 70–85% range, which is adequate for most grid and industrial uses, especially given their other benefits and long service life (which allows many cycles to amortize the initial energy cost).

Response Time and Performance Characteristics

VRFBs exhibit **fast response times**, making them capable of providing dynamic grid services. The electrochemical reactions in the cell stack are not slow – the battery can go from standby to full output in milliseconds to a few seconds, limited mostly by the power electronics and the time to ramp the pumps to full flow. In practice, a VRFB can respond to a control signal almost instantaneously on the electrical side, since electrons flow as soon as a load is connected, and the ionic reaction in the cells begins immediately. This means VRFBs can handle **rapid load fluctuations** and participate in frequency regulation or other ancillary services that require quick power adjustments⁶⁰. Tests and deployments have shown that VRFBs can track changing loads and switch from charge to discharge (and vice versa) without delay or damage – an advantage over some batteries that need a “rest” period or that degrade if switched too often. For example, a VRFB can go from charging at full rate to discharging at full rate essentially as fast as flipping the power electronics, since the chemical process is fully reversible and can be driven in either direction on demand ⁷⁵. This flexibility was demonstrated in the Oxford Superhub project, where the VRFB handles rapid shifts in power to support the grid alongside a lithium battery ⁶⁷.

One performance characteristic where VRFBs truly excel is the ability to **sustain their output and capacity over an unlimited number of cycles** without significant degradation. From an operational perspective, this means a VRFB can be charged and discharged multiple times per day, deep cycled to 0% state of charge and back, without needing recovery periods or suffering the wear that a lithium battery would. VRFBs can also idle at any state of charge for extended periods. For instance, leaving a VRFB completely discharged causes no harm (whereas some chemistries might deteriorate if left empty), and leaving it full just requires occasional trickle charge to counter minor self-discharge. Additionally, VRFBs operate at near-ambient temperatures (typically 10–40 °C), and performance is stable across this range – they don’t have the steep efficiency drop or

safety concerns at high temperatures that lithium-ion batteries have ⁶⁰. In hot summers of the Project's region, a VRFB might need cooling to keep electrolyte below ~40 °C (to avoid vanadium precipitation), but within normal conditions the output and response remain consistent.

One minor latency factor is the mechanical aspect: the pumps must be running to supply electrolyte to the stack. If a VRFB system were completely off with pumps stopped, there would be a short delay (maybe on the order of seconds) to restart flow. In most grid applications, though, VRFBs are kept in a ready state with the circulation on low, so this delay is negligible. The **ramp rate** of VRFB is essentially only limited by the inverter – they can ramp at hundreds of kW per second or faster, comparable to other electrochemical storage. For grid code purposes, VRFBs can qualify for fast frequency response markets. For example, the VRFB in Hungary is expected to perform grid balancing which entails responding within seconds to frequency deviations ⁵⁸.

In summary, VRFBs combine fast electrical response with a unique endurance under continual cycling. The Project's region grid operators could utilize VRFBs not only for long-duration energy shifting but also for **stabilization services** (voltage support, fast reserve) without requiring separate systems. This multi-function capability – sometimes termed **stacked services** – improves the value proposition: one VRFB installation can contribute to several aspects of grid performance simultaneously. VRFBs essentially behave like a stable, controllable power source or sink that operators can ramp up or down quickly, with the only limitation being that the total energy is finite (until recharged). As long as the application is within that energy budget, VRFBs can provide a very high level of performance and reliability due to their robust chemistry and design.

5.2 Financial Analysis

Capital Expenditure (CapEx)

The upfront **capital cost** of VRFB systems has historically been relatively high, but it is on a downward trend as the technology matures and production scales up. CapEx for VRFBs is

commonly expressed per unit of energy capacity (€/kWh or \$/kWh) or power (€/kW) depending on context. As of the early 2020s, typical costs for a utility-scale VRFB (including tanks, stacks, power electronics, etc.) were on the order of **€300–€600 per kWh** of energy capacity for multi-hour systems. For example, a 2021 estimate for a large 100 MW, 10-hour VRFB system put costs around **€350 per kWh** (which would be €3.5 million per MW for a 10h system) ⁷⁶. This translates to roughly \$400 per kWh, significantly higher than lithium-ion battery pack costs at that time. However, because VRFB cost scales with energy more than power, longer duration systems are where they become more competitive on a per kWh basis. Research indicates that at 8–10 hours duration, VRFB CapEx can become quite reasonable – a recent techno-economic assessment projected future capital costs **down to ~€260 per kWh for a 10-hour system** as manufacturing techniques improve ⁷⁷. Indeed, by leveraging economies of scale (large electrolyte volumes, automation in stack assembly) and cheaper vanadium sourcing, manufacturers aim to cut VRFB costs dramatically in the mid-2020s.

It's also informative to look at cost per kW (power capacity). VRFBs typically might cost on the order of \$2000–\$3000 per kW installed ⁶⁰ for a 4–6h system, due to the significant cost of the cell stacks and balance-of-plant. This is higher than lithium-ion for short durations, but for long durations the cost per kW of VRFB becomes more favorable because adding more hours only incurs electrolyte and tank costs, not additional power equipment. For instance, doubling the energy from 4h to 8h might only increase total cost by ~30–40%. The **CapEx gap** between VRFBs and more established batteries is closing: the U.S. Department of Energy projects that with advancements, flow batteries' total system cost could reduce by ~66% by 2030 ⁶⁶. They cite novel electrolytes and scalable manufacturing as key enablers, potentially bringing flow battery costs in line with the DOE target of \$100/kWh for energy storage.

Operational Expenditure (OpEx)

The **operational and maintenance costs** of VRFB systems are generally moderate, especially considering their long lifespan. Key components of OpEx include: energy costs to run auxiliary systems (pumps, control systems, thermal management), routine maintenance of mechanical parts (pump replacements, seal checks, flow battery stack refurbishments), and any electrolyte management (periodic electrolyte rebalance or conditioning). A study from 2021 estimated O&M costs for VRFB around **€10–€20 per kWh of capacity per year** – though this metric can be hard to generalize, it suggests that for a 1 MWh system one might spend on the order of €10k–€20k annually in upkeep. In percentage terms, if the CapEx is €350/kWh, then €14/kWh-year is 4% of CapEx per year, which is a bit higher than some conventional power equipment but not unreasonable. Much of that cost can be attributed to fixed checks and staffing rather than the battery consuming costly reagents (since fuel is just electricity).

One advantage of VRFBs is the **low maintenance frequency** of the electrochemical core. The stacks have no moving solid parts (aside from flow through them), and degradation is minimal, so they do not require frequent replacement (some vendors claim 10+ years before any stack refurbishment). Maintenance is more focused on the **pumps and plumbing**: pumps may need overhaul or replacement perhaps every few years depending on usage, valves and pipes should be inspected for leaks or corrosion (the electrolyte is typically acidic, so all system materials are corrosion-resistant but still need monitoring). These are relatively standard industrial maintenance tasks. Because VRFBs operate at ambient conditions, there's no need for complex HVAC systems like those required to cool large lithium-ion banks – only simple cooling (radiators) for the electrolyte in hot weather, which lowers operational complexity and cost. A stable VRFB chemistry also means **no expensive battery management electronics** to balance cells (like in Li-ion packs each module needs a BMS). The state-of-charge of a VRFB can be determined by electrolyte measurements and doesn't drift significantly, simplifying operation.

Levelized Cost of Storage (LCOS)

When evaluating cost-effectiveness, it is crucial to consider the **levelized cost of storage (LCOS)** – the total lifecycle cost per unit of energy delivered. LCOS accounts for CapEx, OpEx, lifespan, efficiency, and throughput. VRFBs, thanks to their long life and high cycle capability, can achieve a competitive LCOS even if upfront costs are higher. As of 2024, estimates put the current LCOS for flow batteries around **\$0.16 per kWh** (16 US cents per kWh delivered)⁷⁴, assuming typical cycling and a 20-year life. This value is already in the same ballpark as lithium-ion storage for long-duration use, and is projected to improve markedly.

Table 5.1 provides a detailed breakdown of the capital costs associated with different redox flow battery (RFB) technologies across two key grid storage applications: solar energy integration and demand charge management. Notably, aqueous-based RFBs such as VRFB, Zn-Br₂, and Zn-Fe(CN)₆ demonstrate substantially lower capital costs in comparison to their non-aqueous counterparts like TEMPO-based systems. For instance, under a 2 MW, 6 h energy-to-power (E/P) scenario, the total cost ranges from \$168.40 per kWh (DHPS-Fe(CN)₆) to \$517.84 per kWh (Vi-TEMPO). Similarly, in the case of a 10 MW, 11 h E/P application, DHPS-Fe(CN)₆ again emerges as the most economical option at \$114.81 per kWh, while Li-TEMPO reaches \$864.73 per kWh.

This table below compares the capital cost breakdown of various redox flow battery (RFB) chemistries across two key grid storage applications: solar energy integration (2 MW, 6 h) and demand charge management (10 MW, 11 h). Among the technologies, **DHPS-Fe(CN)₆** consistently offers the lowest total cost—\$168.40/kWh for solar and \$114.81/kWh for demand charge management—due to its low cell stack and balance-of-plant expenses. **VRFBs** also show strong cost competitiveness, particularly in longer-duration applications, with a total cost of \$172.77/kWh in the 11 h case. In contrast, **Vi-TEMPO** and **Li-TEMPO**, both non-aqueous systems, have

significantly higher costs, driven mainly by expensive electrolytes and stacks, reaching up to \$864.73/kWh in the Li-TEMPO demand management scenario. Overall, aqueous-based RFBs like DHPS-Fe(CN)₆ and VRFB stand out as the most economical choices for long-duration grid storage.

Table 5.1. A comparison of the capital costs of RFBs for different grid storage applications⁶⁴

Application	RFB	Cell stacks (\$/kW·h)	Electrolyte (\$/kW·h)	Balance of plant (\$/kW·h)	Battery management system (\$/kW·h)	Total cost (\$/kW·h)
Solar energy integration (2 MW, 6 h E/P = 6)	VRFB	156.14	75.22	18.99	1.51	251.86
	Zn-Br ₂	246.5	159.1	27.47	2.64	435.72
	Zn-Fe(CN) ₆	369.75	13.74	26.08	3.96	413.55
	Vi-TEMPO	327.91	121.22	65.53	3.16	517.84
	DHPS-Fe(CN) ₆	100.89	46.77	19.75	0.97	168.4
	Li-TEMPO	430.25	410.07	19.79	4.61	864.73
Demand charge management (10 MW, 11 h E/P = 11)	VRFB	85.17	75.22	11.55	0.82	172.77
	Zn-Br ₂	134.45	159.1	15.34	1.44	310.34
	Zn-Fe(CN) ₆	201.68	13.74	17.93	2.16	235.52
	DHPS-Fe(CN) ₆	55.03	46.77	12.47	0.53	114.81
	Li-TEMPO	430.25	410.07	19.79	4.61	864.73
	VRFB	85.17	75.22	11.55	0.82	172.77

These results underscore the economic viability of aqueous RFBs, particularly as the E/P ratio increases, which correlates with reduced power-specific cost components. However, even the most cost-effective technologies still exceed the U.S. Department of Energy's (DoE) long-term target of \$100 per kWh, highlighting the need for continued innovation and cost reduction efforts within the RFB sector. The U.S. DOE report referenced by Flow Batteries Europe suggests that with

continued innovation, flow battery LCOS could drop to **\$0.052 per kWh** by 2030⁷⁴. Such a drop – roughly a two-thirds reduction – would make VRFBs one of the most cost-effective solutions for energy storage on a per-cycle energy basis, potentially beating out lithium-ion for any application beyond a few hours in duration.

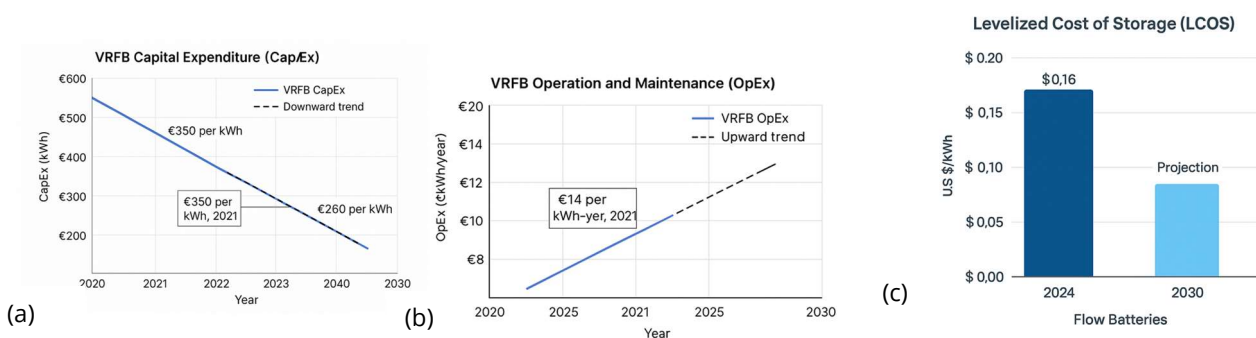


Figure 5.4 (a) Capital Expenditure (CapEx) versus time (b) Operational Expenditure (OpEx) versus year (c) Bar chart of Levelized Cost of Storage (LCOS)- was generated using artificial intelligence (AI) tools and subsequently verified for accuracy and validity by the authors.

5.3 Environmental Impact

The VFB system can be split into the four main modules:

- stack,
- electrolyte,
- foundation, and
- support.

The four groups are illustrated in Figure 2. The first group is the stack, which includes all electrochemical cell components.

The module “energy storage” comprises vanadium electrolyte and the storage tanks.

The module “support” covers all components needed for the balance of plant.
The last group is the “foundation”.

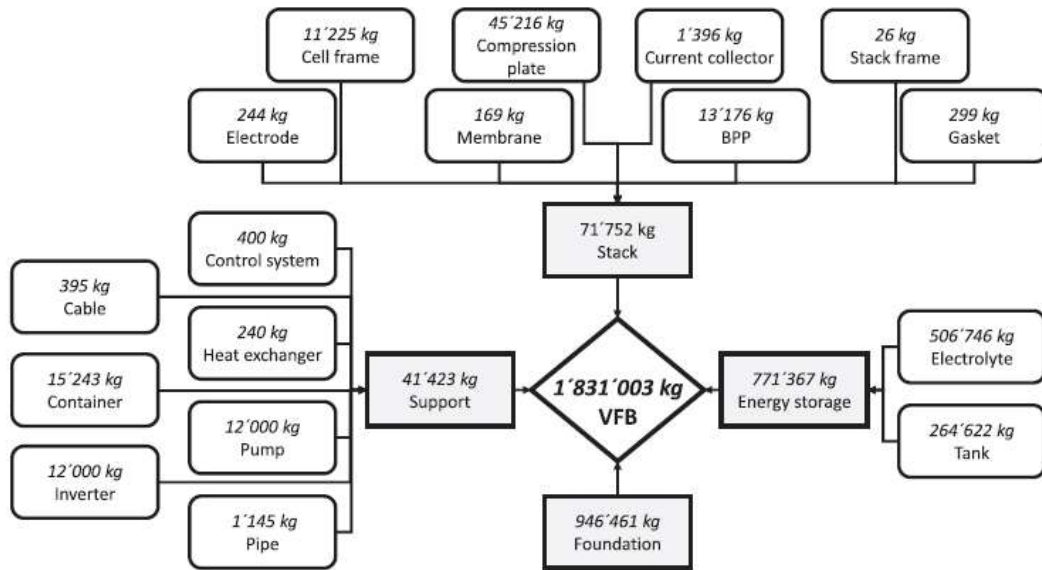


FIGURE 2 Main components of a 1 MW – 8 MWh vanadium flow battery with mass balance

The LCI in Figure 2 (more details in S1) is based on a **nominal power of 1 MW and a nominal capacity of 8 MWh**. This capacity is realized by 375.4 m³ of vanadium electrolyte with a vanadium concentration of 1.6 mol L⁻¹ and a total sulfate concentration of 4 mol L⁻¹ (Martin et al., 2020; Skyllas-Kazacos et al., 2016). The cycle life refers to a lifetime of 20 years and an overall system efficiency of 70% is assumed. The most important technical key parameters are shown in Table 1.

TABLE 1 Technical stack data

Parameter	Quantity	Unit
Number of stacks	10	
Cells	60	Cells per stack
Active membrane area	0.72	m ²
Vanadium concentration	1.6	mol L ⁻¹
Open-circuit voltage	1.42	V
System efficiency	70	%
Target current density	2.00	kA m ⁻²
Specific volume flow	466	L (h ⁻¹ m ⁻²)
Total volume flow	20 148	L h ⁻¹
Nominal power density	2.60	kW m ⁻²
Nominal output stack	112.32	kW

Primary data and particular information on technical and electrochemical set up of VFB originate from the joint research project Re3dOx funded by the German Federal Ministry for Economic Affairs and Climate Action (03ET6156F). Primary data on vanadium mining production are based on the Mapochs mine in South Africa. The technical system design is based on preliminary works (Minke & Ledesma, 2019; Minke & Turek, 2015; Minke et al., 2017) and described in detail in the SI.

In our previous work (Minke & Ledesma, 2019) on maintenance within the life cycle of VFB, we differentiate between three different possible scenarios. The present study refers to the “maintenance scenario.” In this model, the pumps, the inverters, and the complete stacks need to be replaced after 10 years. The electrolyte does not have to be changed in the 20 years of the system lifetime; an internal rebalancing is sufficient for this period (Schafner et al., 2021). The mass balance of all components based on this maintenance scenario is listed in Figure 2. The total weight of the battery is 1 831 004 kg, resulting in a reference flow of 0.01144 kg (kWh)⁻¹.

5.1.1 System description

In Figure S1-2 the components for the production of a VFB are shown.

All data base on ecoinvent v3.6, cut-off allocation. "Market for processes" have mostly been used. Exceptions can be taken from the excel file (attached). Due to privacy of ecoinvent, the balance sheets cannot be reproduced in full. In particular, the manufacturing steps have been adjusted. The explanations and process names of the balances given here can be found in the paper or the S1. The processes were also adapted to the respective location. First, the values of the figures are provided. The Attribution 4.0 International (CC BY 4.0) license from Creative Commons has been selected.

For transparency these parts were divided into main elements.

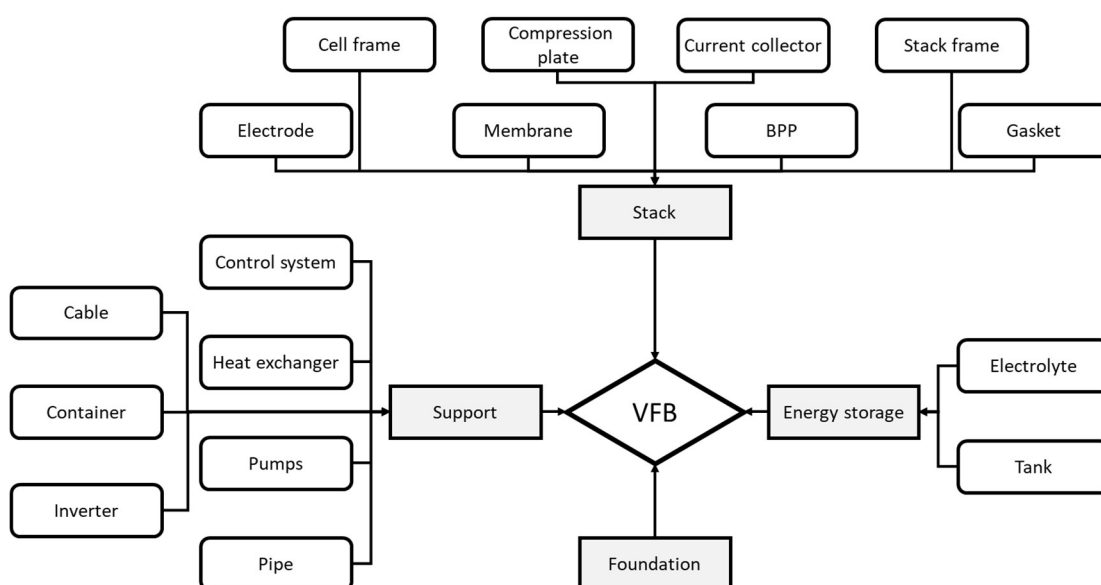


Figure S1-2: Main components of a Vanadium Flow Battery

The main groups are support, foundation, electrolyte and stack. Each main group is divided into several individual components. The different parts of the VFB and their sub parts are explained in the following section. Since section 3.2 angular rectangles are used for products and rounded

rectangles with a grey background symbolize a process. The processes are illustrated in different ways, because of a lack in the literature many processes in this model base on simulation results, modifiedecoinvent data or extrapolated laboratory observations. These processes are marked in the following section with quotes. The transport datasets are not illustrated. The modification, especially of significant processes, are explained in this section. The complete balances are listed in the Supporting Information S2. In Table S1-1 the mass balance of the VFB is illustrated. In this calculation. The mass balance from the table refers to the complete input needed to produce the VFB. Consequently, material losses are also included.

Table S1-1: Mass balance of the vanadium flow battery

Input			Output		
Material	Quantity	Unit	Material	Quantity	Unit
Electrolyte	506 ´ 746	kg	VFB	1 ´ 831 ´ 004	kg
Tank	264 ´ 622	kg			
Compression plate	45 ´ 216	kg			
Cell frame in Stack	11 ´ 225	kg			
Bipolar plate	13 ´ 176	kg			
Data cable	124	kg			
Current collector	1 ´ 396	kg			
Pipes	1 ´ 145	kg			
Control cabinet	400	kg			
Foundation	946 ´ 461	kg			
Aluminum	271	kg			

cable		
Heat exchanger	240	kg
Electrode	244	kg
Membrane	169	kg
Gasket	299	kg
Pump	12 ´ 000	kg
Stack frame	26	kg
Inverter	12 ´ 000	kg
Container	15 ´ 243	kg

Figure S1-3 illustrates the percentages by weight of the stack components. In Figure S1-3 (a), the manufacturing losses are also balanced, so this value reflects the balanced input in the model. Whereas the weight in Figure S1-3 (b) refer only to the installed components. This balance is particularly important for the foundation. A distinction between the two balances will become increasingly important in the future, as it will be necessary to distinguish between production

losses and material contaminated with electrolytes for potential recycling.

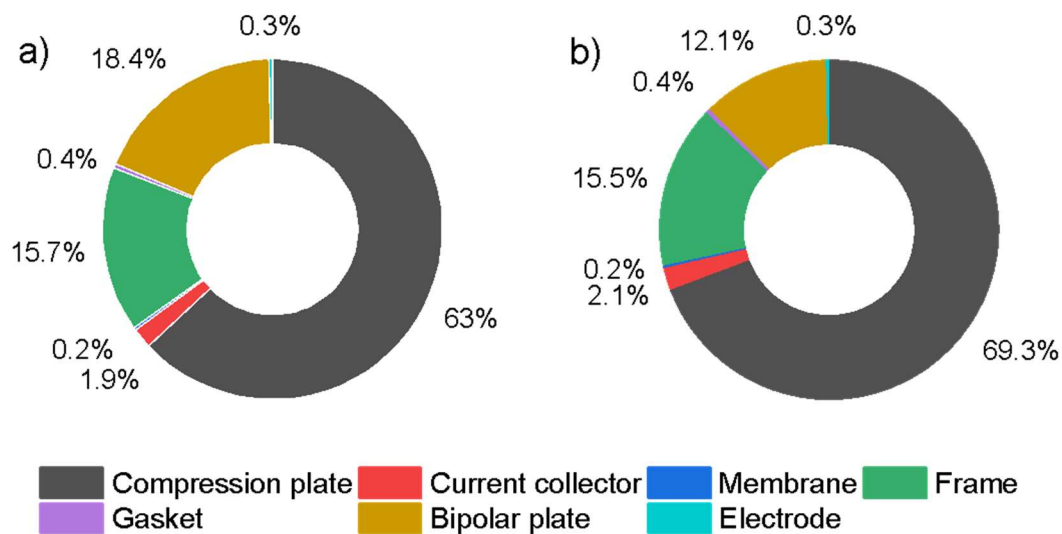


Figure S1-3: The different percentages by weight of the stack components are shown. In figure a), the manufacturing losses are also balanced, and figure b) refers to the system weight

5.1.1.1 Energy storage

5.1.1.1.1 Tank

The tank consists of two main components, in these tanks the negative or rather positive electrolyte is stored. The first component is the reinforced concrete (Figure S1-4), which guarantees the shape and stability. The other component is a separate polypropylene (PP) tank inside the actual reinforced concrete tank. The support structure in the air gap between the

reinforced concrete and PP, is not considered in the model. The volume of one tank holds to 235 m³ for a capacity of 8 MWh, since a maximum tank filling of 80% is permitted. In total, a volume of 470 m³ is required for both tanks. In the process of tank production, a ratio of 2 wt% was used for the PP used and the reinforced concrete accordingly accounted for 98 wt% of the tank. This ratio was calculated using the densities and volumes of PP and reinforced concrete. The process chain was defined by the data set “sand-lime brick production [DE]”. The data set can be used not only for sand-lime brick production, but is also suitable for the production of reinforced concrete (European Aluminium Association, 2008). For this purpose, the upstream chain must be modified. The required steel only consists of primary steel, although this is against the regulations of the cut-off approach. However, the accounting of only primary steel is defined in the data set “market for fiber-reinforced concrete, steel [BR]”. Consequently, this data set is only modified to the geographical restriction.

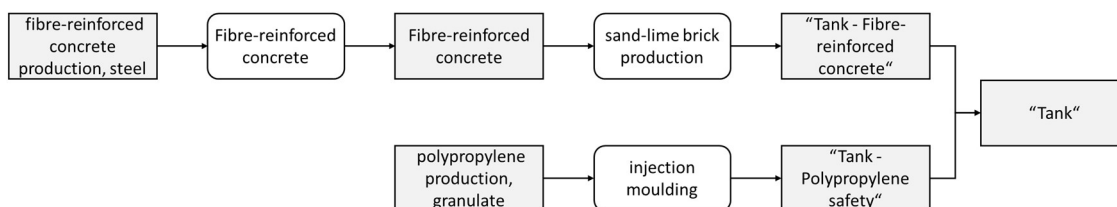


Figure S1-4: Schematic representation of the manufacturing process of the reinforced concrete tank.

5.1.1.1.2 Electrolyte

In the life cycle assessment by Weber et al. (2018) a high potential influence of the electrolyte on the impact indicators was identified. For this reason, the focus of the work was placed on electrolyte production. In the following section, all calculations and balances are therefore shown and explained transparent. In addition, the data are adapted to the latest technical restrictions of a VFB on an industrial scale.

The vanadium is a main component of the electrolyte of the VFB. The problems in mapping this process result from the lack of data in the field of ore mining and especially the representation of the vanadium pentoxide. For the first time, the representation of vanadium is modelled to a large extent using primary data.

In this section, the focus is on steel production, because vanadium pentoxide is a by-product of this process (R. Li et al., 2018). The vanadium pentoxide is also called vanadium (V) oxide in the literature and is the most important vanadium compound (Ternes, 2013). Due to the insufficient data available, the assumptions and values are subject to a particularly high degree of uncertainty compared to the data sets of the other components. Accordingly, individual process steps from section 3.2.1.1 up to and including 3.2.1.9 are explained, documented and validated in detail. In addition, all energy and mass balances are presented in the Supporting Information S2. All processes of the presentation of vanadium are adapted to the geographical restrictions, this includes the local energy mix as well as the transport data records. In general, each sub-process is adapted individually to the given circumstances.

5.1.1.1.3 Vanadium and location

Vanadium can be bound in various minerals. It depends on the source, how the further representation of vanadium has to proceed. It can be extracted both as a main and a by-product. In the model the extraction is modelled by a titanomagnetite, which is a starting material in steel production. Vanadium is extracted as a by-product during steel production. About 80% of the world's mined vanadium originates from the processing of magnetite (W. Song, K. Li, Q. Zheng, H Li). It is estimated that 80% of the vanadium is used in steel making, with only a small percentage used for VFB (Marbler, 2017). The Mapoch Mine in South Africa, where titanomagnetite is mined, is taken as the reference mine. South Africa is considered one of the largest vanadium producers

along with China and Russia, which ensures the representativeness of the results (P. Taylor et al., 2021). The mine was acquired in 2017 by Evraz Highveld Steel and Vanadium Ltd. (formerly to the Chinese company International Resources Limited in 2017 and currently no more vanadium is mined at this site (Roskill, 2017). However, Evraz Highveld Steel and Vanadium Ltd. staff and external scientists have carried out detailed work and studies (Bushveld Minerals; Cardarelli, 2008; Dunne et al., 2019; Evraz Highveld Steel and Vanadium Limited, 2018; W. S. Steinberg, 2008; W.S. Steinberg & W. Geyser; X.C. Goso et al., 2016) describing the representation of the vanadium pentoxide from the time of production, which makes the site particularly suitable based on the sound data available.

5.1.1.1.4 Mining of the ore

The mining of the ore and the processes for the other material for the heating process are shown in Figure S1-5. In the first process step of the ore process, the titanomagnetite is extracted with the bound vanadium. The extraction process in the Mapoch mine is modelled by the data set “iron mine operation, crude ore, 46% Fe [GLO]”, which takes into account all relevant aspects that have to be taken into account during the extraction process (Classen et al., 2009). Both effects on the ecological systems and specific energy consumption are considered (Althaus & Classen, 2005). The process was adapted to the restrictions and the modified energy and mass balance is documented. On the other hand, “ilmenite - magnetite mine operation [GLO]” would also be a suitable data set, but there is a contradiction in the referenced values (A. Korneliussen, S. A. McEnroe, L. P. Nilsson, H. Schiellerup, H. Gautneb, G.B. Meyer, L.R. Størseth, 2000) and the data actually used in input and output (Classen et al., 2009). However, one of the most important points when selecting the process is that the data set used refers to an open-cast mining process. An underground mining process, on the other hand, would entail much higher potential

environmental impacts and is therefore less suitable in comparison. In general, the Titanomagnetite is mined close to the surface due to the low costs, which is why the reference model also assumes open pit mining (Bushveld Minerals). Despite all adjustments, the modelling of a mining process of a life cycle assessment is subject to a high degree of uncertainty, as the current data situation is not sufficient for precise modelling. The potential environmental damage is highly dependent on the location and soil composition of the mining process (Awuah-Offei & Adekpedjou, 2011).

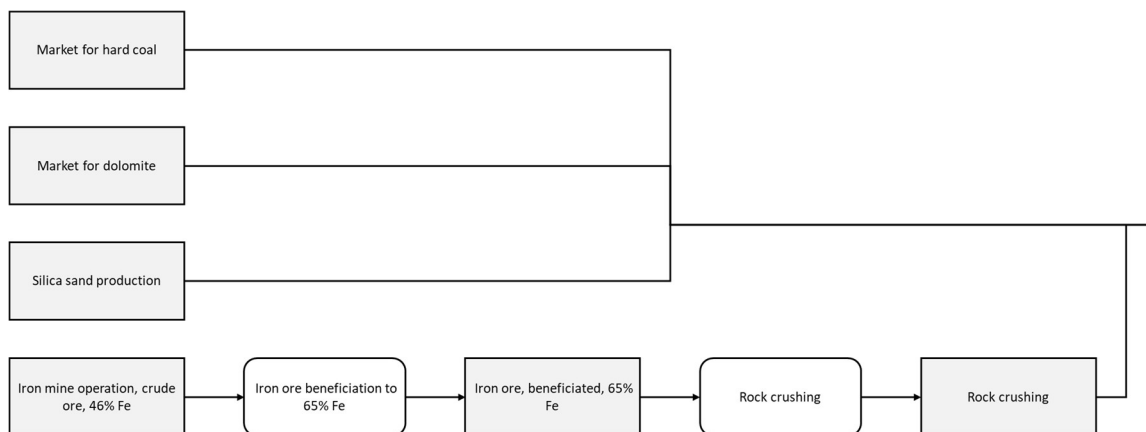


Figure S1-5: Schematic representation of a manufacturing process of the oven material for the preheating process. All processes base on ecoinvent data.

5.1.1.1.5 Transport to the slag bath

On site, the extracted material is roughly classified, separated and processed. The modified data set “iron ore beneficiation to 65% Fe [RoW]” models this pre-treatment of the ore (Classen et al., 2009). After beneficiation, the material is transported from the Mapochs mine to the open slag

bath in eMalahleni (formerly Witbank) for further processing (Cardarelli, 2008; Evraz Highveld Steel and Vanadium Limited). It should be noted that the mine is not in Mapoch, but is located in Roossenkall 90 kilometers away (Google LLC: Google Maps, 2020). The transport is carried out via public railways and a specially constructed rail system (Creamer Media, 2020). Accordingly, the transport route is only by rail and the rest of the transport can be neglected. The transport costs were calculated on the basis of the 250 km railway line in conjunction with theecoinvent data sheet (Bushveld Minerals; R. Frischknecht et al., 2007). The length of the railway line was estimated on the basis of maps (Google LLC: Google Maps). The balance is documented in Supporting Information S2.

5.1.1.1.6 Open slag bath

In order to be able to process the magnetite in the blast furnace, the ores must be homogeneous from a physical and chemical point of view (Hiersig, 1995). In the following process, the fine ores are made into pieces, since only a small part of the ore can be processed directly. The modified process is based on the data set “rock crushing [RoW]” (Kellenberger D., Althaus H-J, Jungbluth N, Künniger T, 2007).

Due to the high titanium content of the ores from the mine, they have to be processed in a further process in comparison to other mined titanium magnetite. For this purpose, as described in Figure S1-6, the magnetite is mixed with coal, silicon and dolomite and preheated at 1140°C in one of the 60-meter-long rotary furnaces. To reduce the iron oxide in the iron, an excess of carbon from the coal is necessary (P. R. Taylor et al., 2006). The preheated material is then transported into the open slag furnace. Normally, the material is further processed in an electric arc furnace, but due to the high titanium content of the ore, the company has continuously converted all electric arc furnaces into open slag baths since 2005.

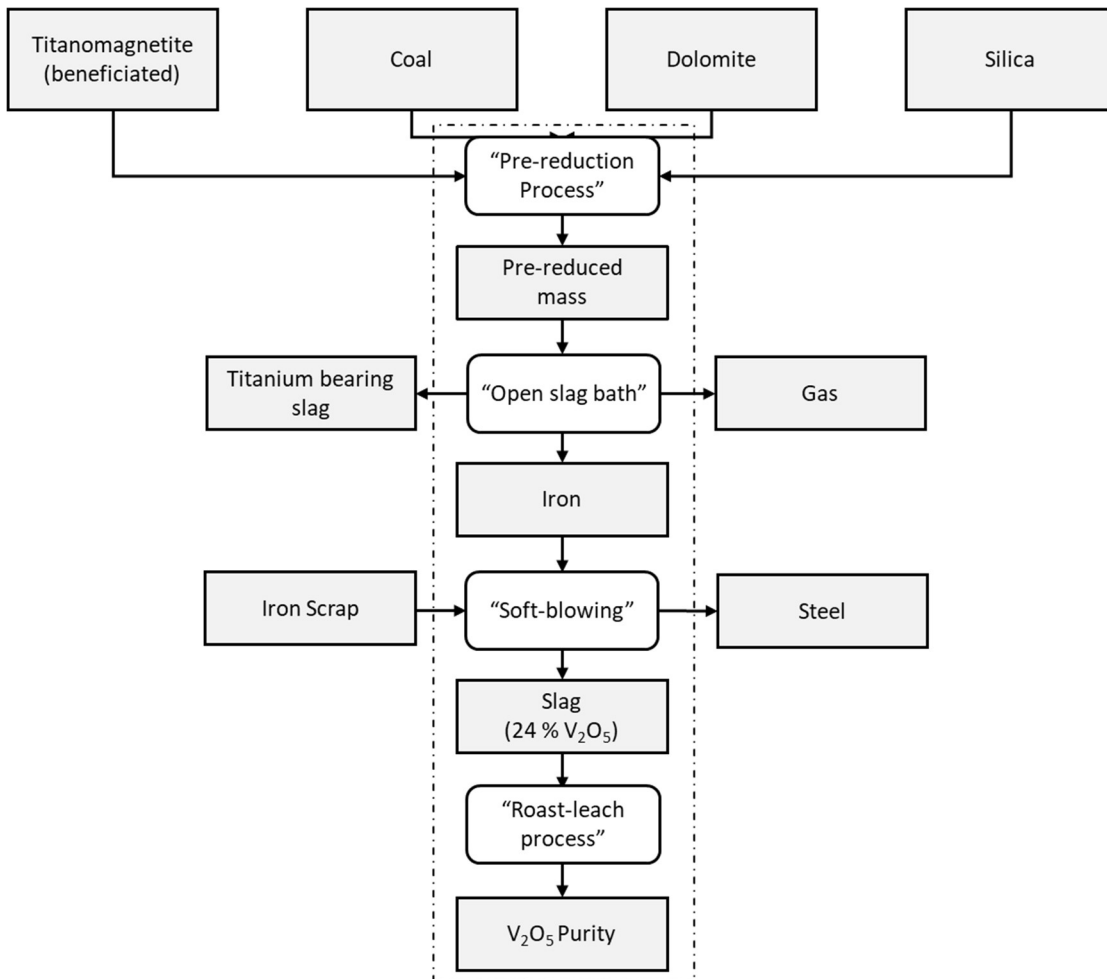


Figure S1-6: The schematic extraction of the vanadium pentoxide. The data are based on processes of Evraz Highveld Steel and Vanadium Ltd. All processes in the box base on primary data

These are also described below as open slag furnaces or ovens. The main difference is that in the open slag furnace, the arc of the electrodes is generated via the furnace contents. In contrast, in the electric arc process, the electrodes are immersed in the furnace contents (W. S. Steinberg, 2008). The changed process results in different mass and energy balances, and the immersion also results in a higher percentage of vanadium being recovered. It should be noted that the mass balances in the furnace are adapted to the iron ore from the Mapoch mine. The preheating and

the actual melting process have been summarized in the mass balance as only the summed energy consumption of the two heating processes is known. Starting from 1 t of iron ore, 548 kg of iron can be produced at a temperature of 1350°C and as a byproduct 448 kg of titanium slag is extracted at a temperature of 1440°C. In addition, 345 Nm³ of gas is produced, which, like titanium slag, is not considered further (W. S. Steinberg, 2008). The release of these substances is schematically illustrated in Figure S1-6. The iron is the relevant product for the formation of vanadium and is further treated in the steelworks in the next step. The regeneration of the iron is modelled with the data from the process “steel production, converter, unalloyed [RoW]”. The literature refers to “soft” blowing, but this process is not further specified (W.S. Steinberg & W. Geyser). The balance sheet is modelled slightly for the sake of clarity, as all data have been adjusted to the reference level of the input of iron from the upstream sub-process. This adjustment is not necessary, but serves the transparency of the entire process chain, since the inputs are still based on the original one kilogram of ore. Vanadium slag is also added to the process outputs. In the next step, the slag with a vanadium pentoxide content of 24 wt% still needs to be further processed in order to be used for the production of the electrolyte.

5.1.1.1.7 Processing of the vanadium slag

In general, there are different processes how the vanadium slag can be processed. The process steps depend on the composition of the slag but also on the location or country in which it is processed. In the present model, the slag is processed in South Africa, which is why the variables and the transport distances refer to the country South Africa. In South Africa are existing different methods to extract the Vanadium, the Highveld process gained acceptance in the industry (Cardarelli, 2018). The exact energy and mass balances are documented in the Supporting Information S2. First, the slag is crushed to ensure optimum further processing (*Ullmann's*

Encyclopedia of Industrial Chemistry, 2000). The crushing of the slag was simulated on the basis of the “rock crushing [RoW]” process data. This is followed by the roast-leach process. This process can be simplified and divided into four main parts, the roasting, leaching, precipitation and calcination process. This sequence and the processes are illustrated in Figure S1-7. In general, the processes can be carried out on the basis of different chemical compounds, but in the following section only one process is discussed (Nkosi et al., 2017). For the roasting process the process with sodium carbonate is used in the following application case. The titanomagnetite from Evraz Highveld Steel and Vanadium Ltd. at was also treated with this process and furthermore it is the most commonly used method because of a comparatively low required temperature (Nkosi et al., 2017). At the same time, ecological requirements can also be met. The required temperature is between 800-1200°C, so that the sodium carbonate can be converted into sodium metavanadate (Gilligan & Nikoloski, 2020; Nkosi et al., 2017). This chemical compound is water-soluble at a neutral pH (Nkosi et al., 2017)

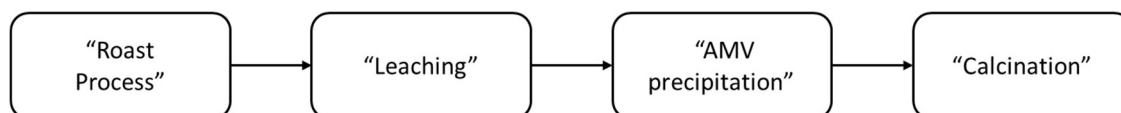


Figure S1-7: Schematic representation of the roasting and leaching process

Therefore, in the next step, the vanadium is dissolved in the sodium metavanadate with water as a leaching agent. Water is the most commonly used solvent compared to sulfuric acid due to the cost and efficiency of dissolution (Nkosi et al., 2017). In the following step, ammonium metavanadate is formed by adding ammonium sulfate. Subsequent calcination allows the extraction of vanadium pentoxide with a purity of about 97.5-99.5 wt% (Cardarelli, 2018; Nkosi et al., 2017; X.C. Goso et al., 2016). Other degrees of purity for the final product are given in the literature. However, the degree of purity in the literature is partly in contrast to the required energies. According to this, less energy is required for a higher degree of purity for the same

starting product. Consequently, the energy requirement can only be calculated based on assumptions. Decisive for the cumulated energy demand are mainly roasting and calcination, because in the ammonium metavanadate (AMV) precipitation the material is treated at a very low temperature of 50-100°C for several hours (Nkosi et al., 2017; X.C. Goso et al., 2016).

The calculation was made on the basis of the documented balances, the energy input was estimated on the basis of assumptions and calculations, since there are no meaningful data for this material. However, the resulting purity of 97.5 wt% of the VP is not sufficient for the use in VFB, so the VP must be treated again (X.C. Goso et al., 2016). However, this additional energy input cannot be accounted for or calculated using the literature. Consequently, only the purity of 97.5% was assumed, which does not correspond to the GfE standard (Martin et al., 2020). This step cannot be considered in more detail at this time, specifically for this starting material. The energy balances of the roasting-alkaline processes were calculated on the basis of the process “sinter production, iron [IN]” and then adapted to the boundary conditions. The modified sintering data set describes the phases of the Roast Leach process very precisely, as the thermal treatment and the intermediate stages are very similar, especially with regard to the temperature intervals (Rausch, 1964).

In theecoinvent data set the two temperature zones from 1150 to 1250°C and from 900 to 1000°C are defined. In the literature are different conversions about the heat with the same starting material. A temperature of approx. 850-1200°C is referenced in the Roast process (Cardarelli, 2018; Jena et al., 1995; Nkosi et al., 2017; X.C. Goso et al., 2016). The vanadium must be roasted at a higher temperature than other slags (Gilligan & Nikoloski, 2020). A more distinct maximum vanadium extraction at 1200°C is described (Nkosi et al., 2017). Accordingly, the value of 850°C can be neglected and thus the data set correctly reflects this value. In contrast, a slightly lower value of (300-690°C) is defined in the literature for the lower temperature zone. However, this factor is compensated by the longer holding times in the roast leach Process. By means of

calculation, a slightly higher value for the energy requirement was calculated for the comparison to the requirement in industry, the main reason is the heat and energy recovery. With the heat and energy recovery, the energy requirement is thus slightly higher than the actual requirement in industry.

5.1.1.1.8 Composition and production electrolyte

The electrolyte bases on a 1.6 M vanadium concentration. as well as a total 4 M concentration of sulfate (Martin et al., 2020; Skyllas-Kazacos et al., 2016). The electrolyte composition is designed for the location Germany, in a warmer country the sulfate concentration can be up to 5 M (Skyllas-Kazacos et al., 2016). The final completion of the electrolyte is at the factory, therefore the electrolyte has not to be classified and transported as a dangerous good, which has to be noticed for the balance. The energy consumption for the electrolyte treatment needs $0.0962 \text{ kWh L}^{-1}$ and it is based on the potential difference of the initial states of vanadium V 5 and V 3.5. Whereas the pumping capacity of the electrolyte can be neglected as it represents less than 1% and cannot be quantified.

Using the parameters from Table S1-2, the electrolyte volume of 375.2 m^3 was calculated.

Table S1-2: Design and technical parameter of the vanadium flow battery

Capacity	8 MWh
Vanadium concentration	1.6 mol L^{-1}
Open circuit voltage	1.42 V
Depth of discharge energy (DoDe)	70%
Practical energy density	21.3 kWh/m^3

Spec. volume	46.9 m ³ /MWh
PE Electrolyte volume	187.6 m ³
NE Electrolyte volume	187.6 m ³

A total of 55.554,3 kg of vanadium pentoxide was required for the required quantity of electrolyte and 3.580.122,6 kg of steel was produced during the soft-blowing process.

5.1.1.1.9 Validation of the resulting vanadium pentoxide amount

The task of this section is to prove that although the vanadium pentoxide content of 1.65 wt% of the ore is correct, the resulting amount is significantly lower than this percentage (Steinberg & Pistorius, 2009). Accordingly, it is explained here in detail how much vanadium pentoxide can actually be recovered from 1 kg of ore, since this value is often misinterpreted. Particularly since not only the efficiency, but also the titanium content in the ore, which is particularly high in this case, has an influence on the representation of the vanadium. The validation of the calculation is done with the help of the Figure S1-6, this was extended by relevant components (Figure S1-8). On the one hand, the masses of the inputs were entered, but also the percent efficiencies of the processes. The black percentage value refers to the loss of the respective process, whereas the red value illustrates the percentage cumulative loss of vanadium. The composition of the roughly processed ore from the Mapoch Mine is illustrated in Table S1-2. A vanadium pentoxide content of 1.65 wt% is assumed (Steinberg & Pistorius, 2009). The various percentages in the mined material may also vary slightly in different reports and over the years. For this reason, data from the company or external employees are mainly used in the following.

Table S1-3: Percentage composition of ore from Mapoch Mine (Steinberg & Pistorius, 2009).

Fe_{total}	FeO	Fe₂O₃	CaO	SiO₂	MgO	Al₂O₃	V₂O₅	TiO₂	MnO	Cr₂O₃
56	16.5	60	0.08	2	1.4	4.8	1.65	12.7	0.3	0.4

The ore is reduced in a furnace, as described above. In the preheating furnace, the material to be heated consists of 59 wt% ore, 27 wt% coal, 13 wt% dolomite and 0.01 wt% silicon (Evraz Highveld Steel and Vanadium Limited, 2018). Two products relevant to the process result from the open slag furnace. First, 1 kg of ore results in 0.448 kg of titanium slag, which contains 0.9 wt% vanadium pentoxide, but also about 36 wt% titanium oxide. The slag is crushed and some of the magnetic particles are reintegrated into the process and reused as flux (Steinberg & Pistorius, 2009). Due to the high titanium content in the slag, the vanadium pentoxide in particular cannot be extracted (Dunne et al., 2019). Even the extraction of the titanium is not economically feasible because of the low oxides such as the TiO₂ and the CaTiO₄ (Marbler, 2017). A possible process for the extraction of the vanadium has been discussed, with which it is possible to recover up to 27 wt% of the vanadium pentoxide of the titanium slag (M. Lekobotja et al., 2017).

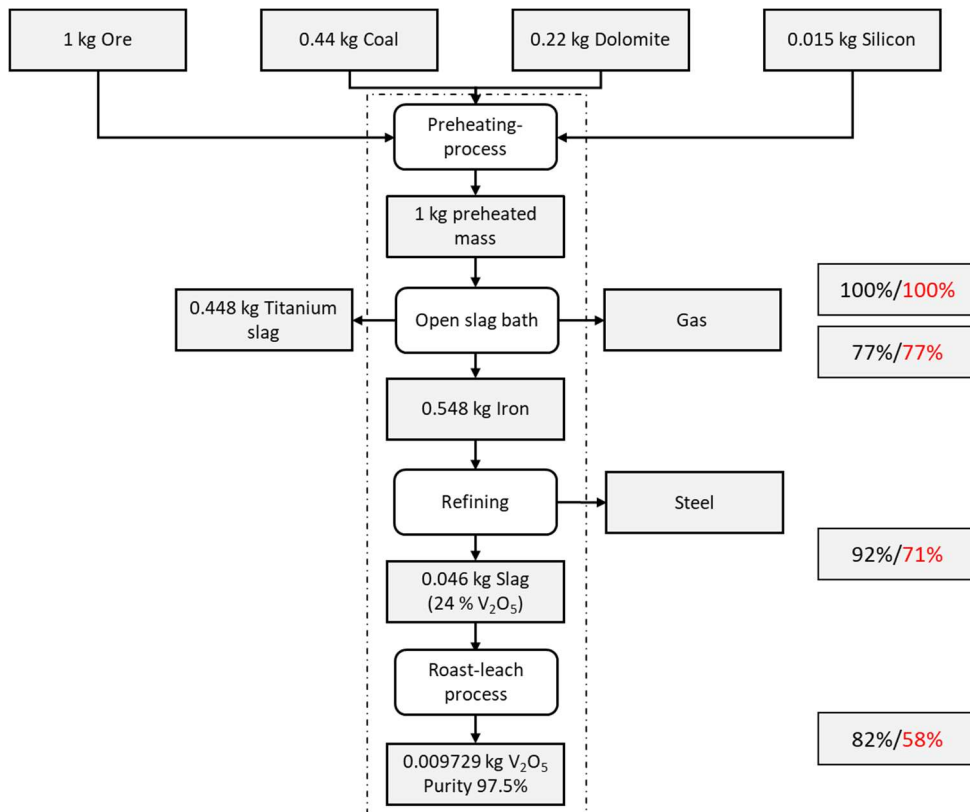


Figure S1-8: Schematic representation of the vanadium representation. This includes the mass data based on own calculations. The percentages indicate the efficiency in the extraction of vanadium, where the black percentages refer to the respective process and the cumulative efficiency of the extraction of vanadium is indicated by the red numbers.

However, this process has not yet been applied commercially. In addition, it is questionable whether it makes economic sense at all. The economic aspect also depends on the highly fluctuating vanadium price. In addition to the high loss of vanadium in the slag, there are additional losses in the further processing of the vanadium. On the other hand, the second product obtained is 0.548 kg of iron, the chemical composition of which is broken down in Table S1-4.

Table S1-4: Chemical composition of the iron after the furnace in wt%.

Ti	Fe	Si	Mn	V	Cr	C
0.2	94.5	0.2	0.2	1.29	0.34	3.2

As the purity of the VP increases and the impurities are removed, the amount of vanadium pentoxide obtained decreases. However, the efficiency of X.C. Goso et al. (2016) can still be assumed. Figure S1-8 shows the individual processes and also the efficiency of the steps. In the calculation it must be taken into account that the losses refer to the vanadium and not to the vanadium pentoxide.

In the next step, the material is separated by “soft” blowing to recover the vanadium slag. The loss of vanadium in the blowing process is between 8 and 10 wt% (Nkosi et al., 2017; Steinberg & Pistorius, 2009; X.C. Goso et al., 2016). In the following, an efficiency of 92% is assumed, so that the vanadium content in total is only about 1.19 wt% vanadium. However, “soft” blowing does not extract vanadium pentoxide, but vanadium (III) oxide. The reaction is shown in equations 1.-3. (W.S. Steinberg & W. Geyser).



However, in the chemical mass composition in Table S1-5, vanadium pentoxide is assumed in a simplified way and, accordingly, the mass fractions of the other elements in the calculation were adjusted to the mass ratios. The vanadium fraction is used to determine the amount of vanadium (III) oxide. As shown in Figure 8, the efficiency of 92% is first assumed and calculated with the vanadium before the amount of vanadium(III) oxide is determined based on the stoichiometry (X.C. Goso et al., 2016).

Table S1-5: Chemical composition vanadium slag in wt% (X.C. Goso et al., 2016).

MgO	Al₂O₃	SiO₂	CaO	TiO₂	V₂O₅	Cr₂O₃	MnO	FeO
4	5	15	5	9	24	5	3	29
Mg	Al	Si	Ca	Ti	V	Cr	Mn	Fe
2.4	2.6	7	3.6	5.4	13.4	3.4	2.3	22.5

Figure S1-9 illustrates the calculation. In order to quantify the weight of the vanadium slag, the composition of the slag first had to be defined. Since there is no information in the literature on the weight of vanadium, based on the chemical composition of the vanadium slag, the efficiency and the chemical composition of the iron, the resulting weight is calculated. Starting from 0.548 kg of iron with a vanadium content of 0.0119 wt% after refining, results in 0.007 kg of vanadium. This is the starting point in Figure S1-9. The efficiency refers only to the pure vanadium and not to the vanadium (III) oxide or vanadium pentoxide. Accordingly, the same amount of 0.0065 kg vanadium results in both cases (step 1).

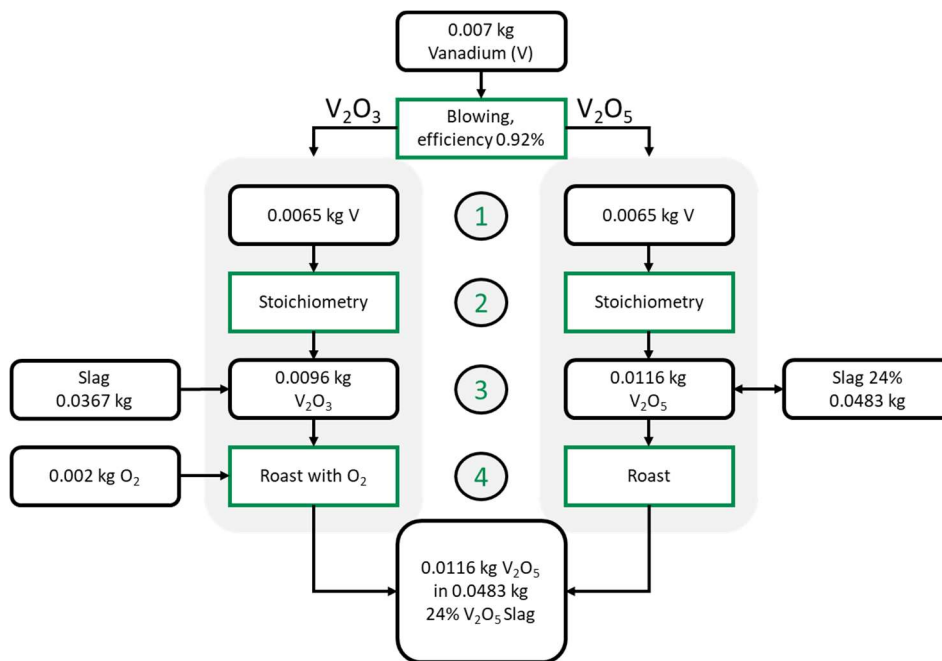


Figure S1-9: Vanadium pentoxide extraction with mass indication

Based on the law of constant proportions, the quantity for the vanadium slag can be determined in the second step for the case of vanadium(III) oxide and the vanadium pentoxide. The vanadium(III) oxide has a weight of 0.0096 kg, whereas the vanadium pentoxide weighs 0.0116 kg because of the additional oxygen particles. The weight of the total 24 wt% vanadium pentoxide slag is calculated to be 0.0483 kg. In the third step, it was also mapped that the weight of the slag is initially composed of the weight of the impurities of 0.0367 kg and the weight of the vanadium(III) oxide of 0.0096 kg. Only by adding oxygen to the vanadium(III) oxide is the actual weight of the slag reached, with a vanadium pentoxide content of 24 wt%, which corresponds to 0.0483 kg, as can be seen in Figure S1-9. Consequently, the first reaction step must be carried out with the addition of oxygen. Accordingly, oxygen is added in Equation 4. The weight of the additional oxygen is calculated based on the chemical composition of the reaction. Using the molar mass, a mass fraction of oxygen before the reaction of 11 wt% has been calculated. The composition as well as the mass of impurities in the slag remain unchanged after the reaction.



Considering the vanadium(III) oxide instead of the vanadium pentoxide makes quantification difficult (Gilligan & Nikoloski, 2020). However, for proper technical consideration, the reaction must be represented in this manner. Regardless of whether vanadium(III) oxide or vanadium pentoxide is considered, 0.01557 kg of sodium metavanadate results. The mass fractions of the impurities in the slag remain the same. This is followed by the leaching process, in which the iron and titanium components are separated from the slag with a solvent (X.C. Goso et al., 2016). The reaction is shown in equation 5, where 0.0149 kg of H_2VO_4 is formed with the addition of the solvent water (Gilligan & Nikoloski, 2020). Only the amount of water can be accounted for by the reaction equation, in reality the water requirement will most likely be higher.



However, due to the 86% efficiency in the leaching process, only 0.01284 kg of H_2VO_4 results, because the loss of 14 wt% refers only to the vanadium, for this reason it must be considered in isolation for this calculation (X.C. Goso et al., 2016). This corresponds to a vanadium content of 0.0559 kg and, accordingly, a loss of 0.0021 kg of vanadium from 1 kg of iron. The slag is reduced by about half to 0.0184 kg due to the precipitation of titanium and iron particles. The amount is given by the chemical composition from Table S1-5 and the actual weight of the slag of 0.0484 kg. Due to the subsequent reaction of ammonium and H_2VO_4 , in addition to water, ammonium metavanadates are formed. The reaction of this process step is broken down in equation 6, it is the most common process used in the industry (Gilligan & Nikoloski, 2020).



In this process step, a loss of 5 wt% of the vanadium is assumed, resulting in a quantity of 0.0123 kg of ammonium metavanadate. The vanadium slag is calculated from Table S1-5 in conjunction with Table S1-6, which gives the chemical composition of the vanadium pentoxide (X.C. Goso et al., 2016).

Table S1-6: Chemical composition of vanadium pentoxide in wt%.

Al₂O₃	SiO₂	CaO	V₂O₅	Cr₂O₃
1	0.52	0.23	97.5	0.41

In the table is the composition of vanadium pentoxide from the laboratory. Based on the composition in Table S1-6, the impurities that cannot be removed in the vanadium pentoxide were calculated. Also, based on this, the composition as well as the mass of the slag that was removed after this process can be calculated. The exact composition in the slag can be obtained from the mass ratio in the Supporting Information S2, as each chemical element is listed individually for traceability. Finally, in the last step, the vanadium pentoxide is obtained, which has the chemical composition shown in Table S1-6. The 100 wt% pure vanadium pentoxide resulting from the entire process chain has a weight of 0.00945 kg. In the final step, the vanadium is recovered from the calcination process without loss. The reaction is given in equation 7.



5.1.1.1.10 Validation of the energy balance

Since the energy balance of the slag bath process does not result from the existing data sets, the procedure is first explained to ensure a transparent life cycle assessment. The energy balance is based on an average of three furnaces at the plant, each recorded over a six-month period between 2005 and 2007. As a result of the recordings, an energy consumption of 1.64 kWh for one kilogram of iron is calculated for the average of the open slag furnaces (W.S. Steinberg & W. Geyser). In the model, this corresponds to an energy demand of 0.9 kWh to produce 0.55 kg of iron. In a report (W. S. Steinberg, 2008), which dates from the same period and was also written by Steinberg, the consumption is described as requiring 20-30% more energy (W. S. Steinberg, 2008). On the basis of possible optimization potentials, which were also described in the reports, the lower energy consumption of 1.64 kWh (kg iron)⁻¹ is assumed. To what extent the optimizations were implemented in a later period and what energy savings would result by new processes were not documented in the literature. The gas from the furnace process could be quantified as 345 Nm³ (t iron)⁻¹, but was not considered in the energy balance. Consequently, a decreasing trend can be assumed, which is why the lower energy demand is assumed. The energy demand related to the output and input quantities in the model is described by the black numbers in Figure S1-10. In addition, the effective electricity consumption of the individual processes for one kilogram of steel was broken down by the red figures (Figure S1-10). In the case of refining, the resulting steel quantity was defined by the process "steel production, converter, unalloyed [RoW]" and adjusted to the ratio of the input. Predominantly through the input of 0.55 kg iron and 0.13 kg ferrous scrap, in combination with an energy demand of 0.013 kWh, 0.61 kg steel is produced. The cumulative electricity consumption of 1.59 kWh (kg steel)⁻¹ and the sub-processes must be calculated as a function of the output. Due to the production of the steel in combination with the scrap, the energy consumption for one kilogram of iron is higher than for one kilogram of steel. For clarity, the input "iron scrap" was added to Figure S1-10 to explain the one kilogram of steel produced from only 0.9 kg of iron. The extraction of the ore is thus included in the calculation for steel production, but the extraction or production of the other materials relevant to the process (coal, dolomite, etc.)

has not been taken into account. In any case, the processes not considered have no significant influence on the amount of energy required.

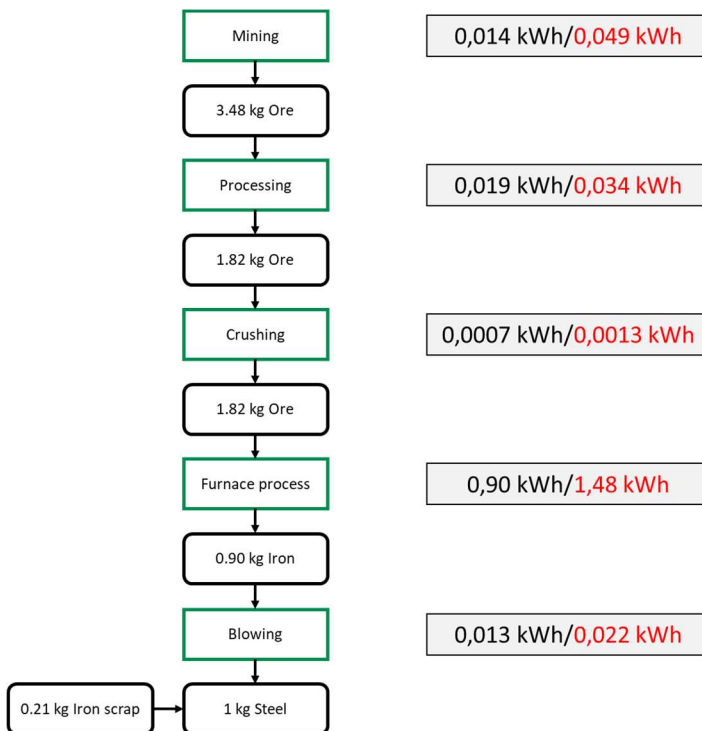


Figure S1-10: Schematic representation of steel production. Mass and energy balances are based on our own calculations. The energy balance was calculated in relation to output. The black figures show the energy requirements used in the model, each of which relates to the quantity of output in the model. The red figures indicate the electricity requirement of the respective process for one kilogram of steel.

In the life cycle assessments (Das & Kandpal, 1997; Hu et al., 2006; Renzulli et al., 2016; Sakamoto & Tonooka, 2000), which serve as a comparison in the section below, it is not clearly defined how the balance for steel production is made up. Furthermore, there is no clear statement as to whether it is primary energy or direct energy. Primary energy in this context refers to the complete energy requirement of all processes necessary for the production of a VFB, for example the energy

required to "produce" energy. Direct energy, on the other hand, refers only to the energy consumed by the respective processes for the VFB. However, in another report (Pardo et al., 2015), a distinction was made between direct and primary energy. Based on these data, it can be assumed that direct energy was used in the life cycle assessments (Das & Kandpal, 1997; Hu et al., 2006; Renzulli et al., 2016; Sakamoto & Tonooka, 2000). The same applies to CO₂ emissions, which refer to direct emissions and do not refer to full emissions of CO₂eq (Pardo et al., 2015). To guarantee a valid comparison, only the energy supply of the individual process steps may be considered.

The validation of the steel production results is based on the life cycle assessments already mentioned above (Das & Kandpal, 1997; Hu et al., 2006; Renzulli et al., 2016; Sakamoto & Tonooka, 2000). Decisive for the potential impact on the environment are, in particular, the location and the type of furnace used in steel production (Renzulli et al., 2016). Both aspects cannot be sufficiently considered because the furnace is a conversion and there is no well-founded and comprehensible information on emissions in steel production in South Africa. This uncertainty must be taken into account when validating the process.

The modern electric arc furnace emits between 0.59- 1.18 kg CO₂eq (kg steel)⁻¹ while requiring 0.8- 1.44 kWh (kg steel)⁻¹. However, the values must be put in context, as normally in electric arc furnace mainly steel is produced from steel scrap. For the Linz-Donawitz process, various life cycle assessments result in values between 1.97- 2.46 CO₂eq (kg steel)⁻¹, with the maximum value of 2.46 CO₂eq related to the Poland site. Energy consumption varies between 2.2- 3.5 kWh (kg steel)⁻¹ (Das & Kandpal, 1997; Hu et al., 2006; Renzulli et al., 2016; Sakamoto & Tonooka, 2000). The calculated value of 1.59 kWh (kg steel)⁻¹ is between these two values of the electric arc furnace and the Linz-Donawitz process.

Considering the process as a pure steelmaking process results in a value of $3.3 \text{ CO}_2\text{eq (kg steel)}^{-1}$ due to the conservative approach and the lack of balancing of the VP. This allows us to validate our primary data, but it becomes clear that considering only the steelmaking process is not sufficient. The paper has already discussed the relevance of processing the ore with coal. Accordingly, for the validation of the data set, a similar ore at a similar location has to be compared. For this purpose, the value of Chen et al. (2015) was used in the paper, which is very close to our value with $2.84 \text{ CO}_2\text{eq (kg steel)}^{-1}$. The value of $2.84 \text{ CO}_2\text{eq (kg steel)}^{-1}$ is used for the validation of the data set.

5.1.1.1.11 Electrolyte production

Based on these calculated and validated balances, the electrolyte production process was balanced and presented. The simplified processes are shown in Figure S1-11. The production refers only to primary electrolyte. Additional processes and parameters are included in the Supporting Information S2, these have already been explained in the S1 but are not illustrated in the figure for clarity.

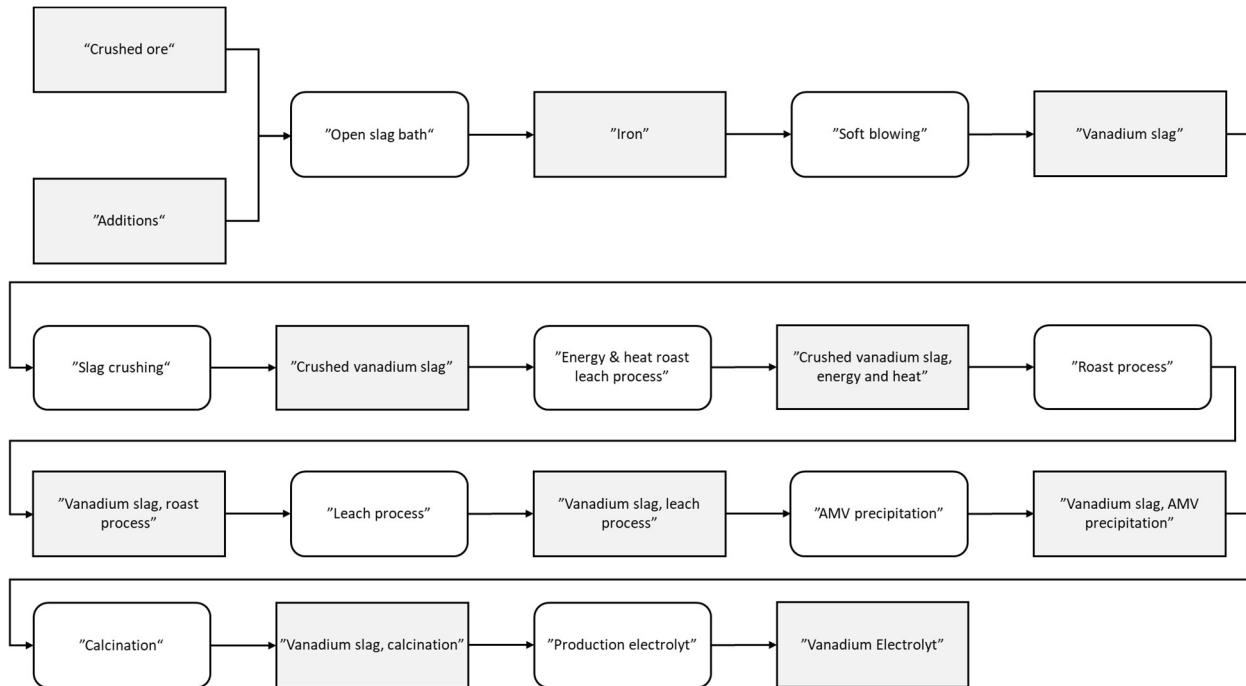


Figure S1-11: Production of vanadium electrolyte after mining the ore. For the sake of clarity, not all processes have been shown.

5.1.1.2 Support

5.1.1.2.1 Container

For the calculation of the containers the dimensions of the stacks were calculated. A safety factor of 10% was added to the stack thickness for protruding screw elements or cabling. Based on a standard length of a container of 6 meters, the required number was determined. A total of 7 containers are required for the stacks. The containers are made of steel and a coated wood.

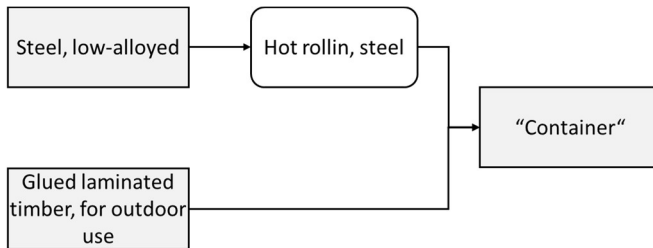


Figure S1-12: Simplified illustration of the processes for manufacturing the containers.

5.1.1.2.2 Control unit

The literature does not list all individual components for a control unit of the VFB. Accordingly, first a list of all relevant components was made, then it became clear that besides the control cabinet, the industrial computers has the second largest mass share. Whereas the control cabinet dominates the mass balances, because the industrial computer weighs only about 7 kg of the 400 kg of the system. In the design, a SIMATIC PCS 7-BOX was used as an example, which is sufficient for the requirements of the 8 MWh battery. Other individual subcomponents, such as a distributed I/O unit, have a very small share. The mass balances of the control unit can be described most accurately on the basis of the composition of the control cabinet. The 400 kg control unit is thus defined with the help of the data set "control cabinet production, heat and power co-generation unit, 160kW electrical [RER]". The data set was determined using the mass balances and modified according to the requirements.

In the literature, the data for a lithium battery (LIB) are taken over, but even these mass balances and individual components are not broken down concretely and cannot be traced. However, the energy balances and the mass balances from the LIB are also comparable with the data from the VFB. The data set of the LIB comprises considerably fewer materials.

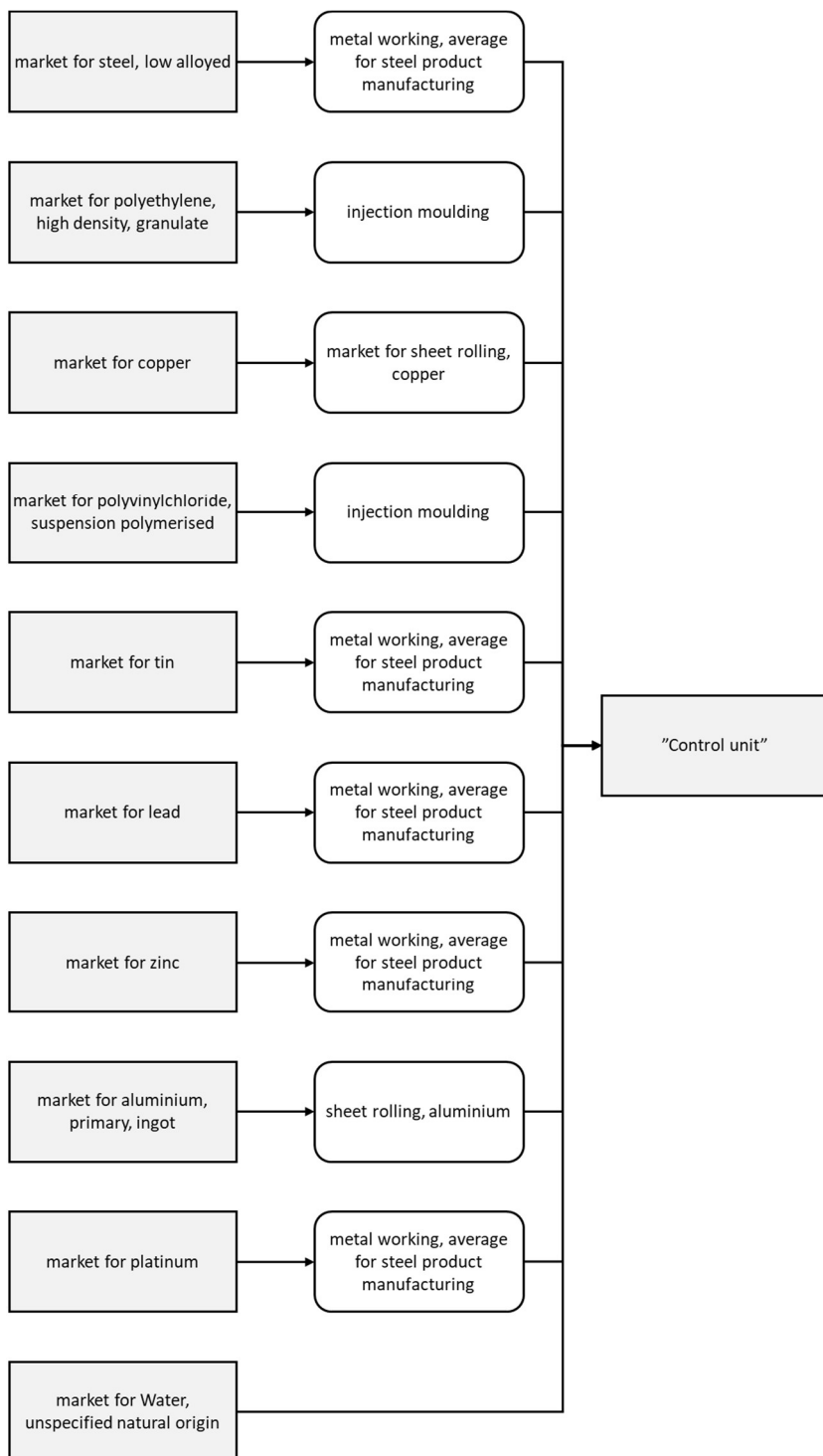


Figure S1-13: Schematic representation of a manufacturing process of a control unit with ecoinvent data sets

5.1.1.2.3 Data cable

A total of 2 kilometers of data cable are required, a large part is for the control unit. The required length depends on the planning of the system. The ecoinvent data set “cable production, data cable in infrastructure” (Figure S1-14) was used for this. This data set represents a copper cable and a fiber optic cable in equal proportions.

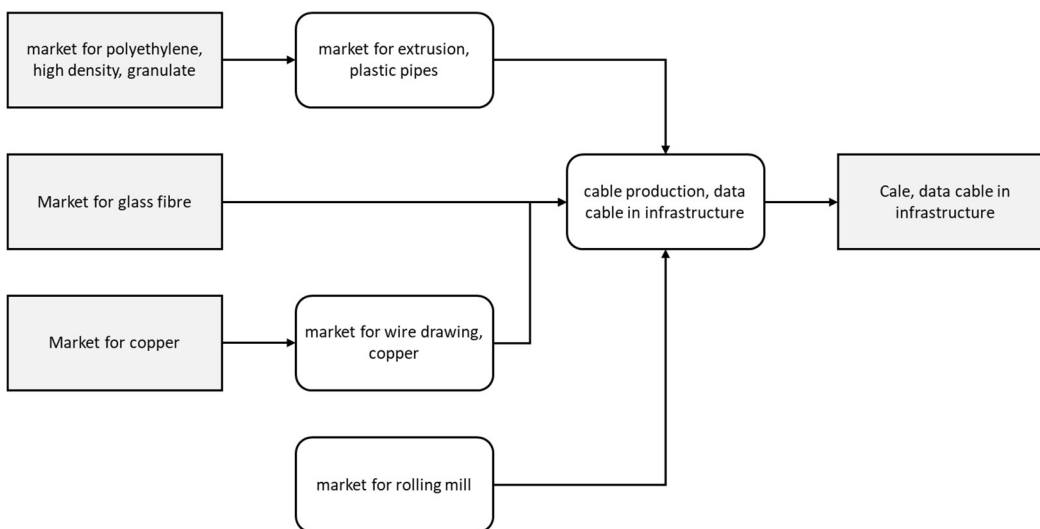


Figure S1-14: Schematic representation of a manufacturing process of a data cable with ecoinvent data sets.

5.1.1.2.4 Power cable

For the cabling 50 m of power cable is needed to connect the ten stacks. The remaining cabling, especially that of the control systems, is not considered in this section. For cost reasons, the cables are made of aluminum instead of copper, resulting in a comparatively large diameter of 43 mm

for the cables without the insulation. A cable from the company HELUKABEL-Information-System serves as a reference, but the cable with the required diameter cannot be found among the products on the Internet. Likewise, there is no possibility to examine the corresponding standard DIN VDE 0250-813 (German Institute for Standardization) for a design of the cable. For these reasons, the ratio between insulation and aluminum was estimated using the strongest aluminum cable (part number: 706085) from the company HELUKABEL-Information-System and assuming that the ratio is linear (HELUKABEL-Information-System). By means of static extrapolation, the diameter with the insulation of 58.9 mm results. Then, the weight was calculated with the respective densities to obtain the weight of the materials in proportion. By the process “market for cable, unspecified [GLO]” the upstream processes “market for extrusion, plastic pipes [GLO]” and “market for wire drawing, copper [GLO]” were given. The latter dataset defines the production of copper cables without insulation. The data set was adopted to model the production of aluminum cables. Aluminum was used as the starting material in the model instead of copper. These processes are illustrated in Figure S1-15.

In general, aluminum cables are only made of primary aluminum because of its electrical conductivity, as this is the only way to achieve a purity of at least 99.7 wt% (Grimaud et al., 2016). Theoretically it is possible to manufacture with secondary material, since the circumference is not an important influencing parameter for stationary batteries. However, it is not clear whether this will be implemented. The transport data was defined by the “market for cable, unspecified [GLO]” process of the ecoinvent database.

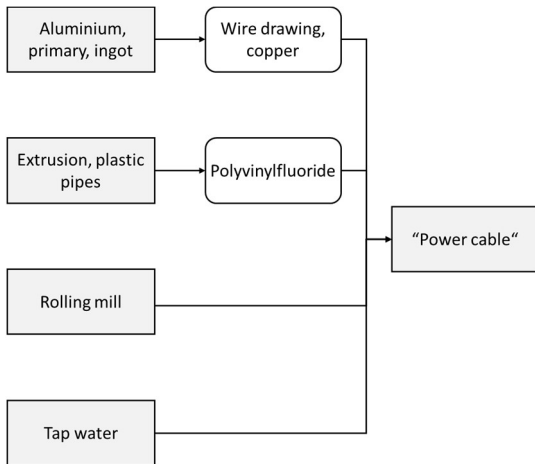


Figure S1-15: Schematic representation of a manufacturing process of a power cable with ecoinvent data sets.

5.1.1.2.5 Inverter

For the overall system, a gross power of 1 MW is required, which is modeled with an existing data set of a 500kW inverter from ecoinvent. The name of the data set is “market for inverter, 500kW [RER]”. For this purpose, two inverters of this type are mapped in the model; these inverters have a cumulative net power of 954 kW. In practice, one 12-inch container inverter and two 6-inch container inverters, respectively, would be used with an efficiency of 98%. The difference of 26 kW between model and practice is considered negligible.

5.1.1.2.6 Pumps

In the industry there are various concepts for the implementation of pump design. In the industrial practice several variants are existing. The designs differ from two pumps per stack up to two pumps per battery. A compromise of these two measures are the a cluster of pumps. A uniform

standard has yet to be established due to the different advantages and disadvantages. One advantage of planning two pumps for each stack is that if one pump fails, only one stack can no longer be controlled. If only two pumps are planned for the whole battery, a failure of one pump would prevent the complete operation of the battery. The decisive disadvantage of several small pumps is the price. To generate the same pumping performance with small pumps as with two large pump systems, a multiple of investment is necessary. The cluster of pumps as an alternative are not significant cheaper than using many small pumps because the valvets for this system are expensive.

In the model, individual pumps are modelled. This assumption has a considerable influence on the costs as well as on the mass balances. Especially because of the life time of the pumps of 10 years, so this components are accounted twice. The ecoinvent data set name is “market for water pump, 22kW [GLO]”.

5.1.1.2.7 Heat exchanger

Figure S1-16 shows the manufacture of the heat exchanger. This consists only of the material steel.

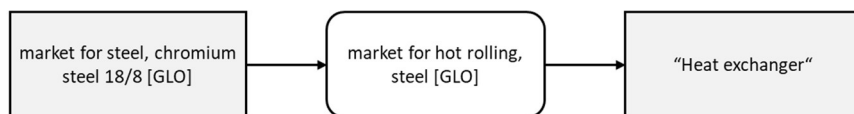


Figure S1-16: Schematic representation of a manufacturing process of a heat exchanger with ecoinvent data sets.

5.1.1.2.8 Pipe

In a VFB, different types of pipes exist to ensure a functional operation of the battery. Basically, two different tubing systems are considered in the system due to the complexity. Connecting elements, pipe fittings and support structures are not considered in this model, as they have a minor influence on the indicators compared to the actual main components.

The first type of pipe is defined as a total 400 m long chemical conveying suction pipe, this is installed from the tanks to the stacks. The total 400 m pipe length corresponds to the sum of all pipes of this type, because they are in individual smaller pipe sections. The CHEM 50-8 UPE SD pipe from the HANSA-FLEX company serves as a reference product for the geometry and properties. The inner layer is made of electrolyte-resistant ultra high molecular weight polyethylene (UHMWPE) with a density of $0.94 \text{ g (cm}^3\text{)}^{-1}$ (Wall et al., 2005). The reference process is defined as “market for polyethylene, high density, granulate [GLO]” because the “high density” polyethylene has approximately the same density of $0.960 \text{ g (cm}^3\text{)}^{-1}$ (Mizutani & Ieda, 1979). For the required ethylene-propylene-diene mixture, the material polypropylene (PP) is assumed, PP has a density of $0.95 \text{ g (cm}^3\text{)}^{-1}$. Due to the missing ratio in the product description, a 50:50 ratio of the diameter was assumed. This results in a mass ratio of 53.5 wt% PP and 46.5 wt% of UHMWPE. The manufacturing process “tube insulation production, elastomers [DE]” was deliberately not used, since the PE and PP are not elastomers but thermoplastics. The “extrusion, plastic pipes [RER]” process serves as a reference from the database. This was modified so that, just as in the following process, no losses occur during production. The second type of pipe is made of heat-resistant PP with a density of $0.95 \text{ g (cm}^3\text{)}^{-1}$. The total length of the pipes is 30 m and they have a wall thickness of 40 mm. This was calculated with the same assumptions as the first type of pipe. Both pipes can be balanced based on one process, because the process in the output does not refer to the length, but to the weight of the pipe. The weight of the two pipes was determined for the model. The data “extrusion, plastic pipes [RER]” is used for both pipes.

5.1.1.3 Stack

5.1.1.3.1 Compression plate

Each stack requires two compression plates, which are screwed together with 30 M16 threads. Due to the thickness of 80 mm and the area of 1'800'000 mm², these have a high proportion of the weight of a stack. The screws as well as the disc springs are not considered due to their marginal influence. Possible recesses in the front of the compression plate were not considered due to their complexity. Accordingly, the compression plate was presented with the process shown in Figure S1-17. Whereas the drillings were considered in the balance.

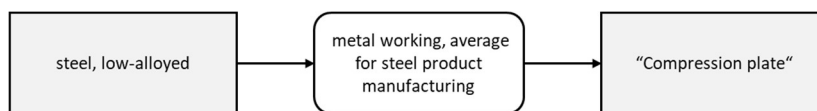


Figure S1-17: Schematic representation of a manufacturing process of a compression plate with ecoinvent data sets.

5.1.1.3.2 Electrode

The electrode is an important component of a VFB because it plays a major role in the energy efficiency of the battery. Figure S1-18 schematically shows the process of manufacturing the electrode. Regarding of the given requirements of the cell design only a carbon-based electrode can be considered (Minke, 2016). Basically, this type of electrode consists of polyacrylonitrile fibers (PAN). In the first step, acrylonitrile is first prepared by Sohio process. This process was not represented in the model because acrylonitrile is in the database and thus the process can be made clearer. The energy and mass balances from the literature are almost identical to the data from the ecoinvent database (Johnson M.C., 2014; Minke, 2016; Minke et al., 2017a; Pellegrino,

2000). This is followed by the polymerization of 1.9 kg acrylonitrile and 0.1 kg methacrylic acid methyl ester (MMA) to produce 2 kg acrylic fibers. The production of the 2 kg of acrylic fibers requires a total of 50.1 MJ and 13.92 kWh, respectively, which is composed of various energy sources in the process (Minke, 2016; Minke et al., 2017a; Pellegrino, 2000). Dry felting is not considered because of the low energy requirement. The subsequent carbonization process requires 181.8 MJ in the form of electricity and gas, which is equivalent to 50.5 kWh. This process produces 1 kg of carbon felt from 2 kg of acrylic fibers (Minke et al., 2017a). When calculating the total weight, the porosity of 95% is taken into account, since only the volume of the electrode is known. Thermal treatment to activate the felt is not considered and needed.

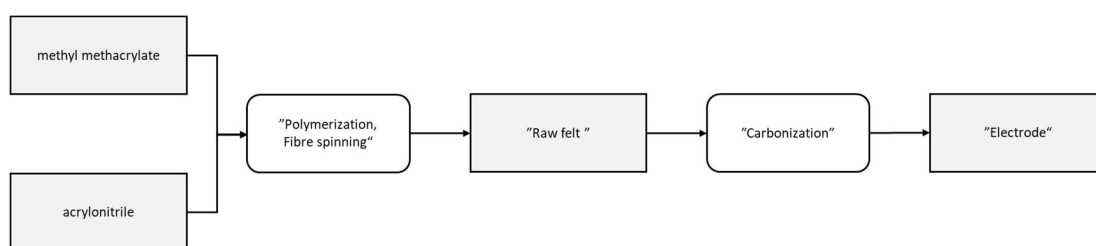


Figure S1-18: Schematic representation of a manufacturing process of an electrode with ecoinvent data sets.

5.1.1.3.3 Bipolar plate

The bipolar plate (BPP) ensures on the one hand a homogeneous distribution of the electrolyte at the electrode and on the other hand the component acts as a separator with respect to the electrolytes of neighboring cells. However, the component ensures an electrical connection between the cells in a stack. The BPP has to meet many partly contradictory requirements in a VFB (Minke, 2016).

The BPP is manufactured by extrusion and the production is based on the corresponding process from the ecoinvent database. The modelled BPP are 600 mm high and 1200 mm wide. The volume was calculated based on the thickness of the sheet of 5 mm. The composition is based on the data sheet of the PPG86. This type of BPP consists of 86 wt% Graphite and 14 wt% PP (Eisenhuth; Minke, 2016). In Figure S1-19 it is illustrated that the PP is delivered as a granulate but to extrude a compound also the graphite has to be crushed. Afterwards both can be injection molded to a thermoplastic graphite compound. The injection molding for the compound needs more energy and a higher pressure due to its thermal conductivity and high viscosity. This is also favored by the long flow path of the compound, whereas the strength compensates this effect (Kreuz, 2010). The process steps cannot be applied to a thermoset compound. The BPP in this dimension has to be milled because of the different plastic layers and the curvature of the plate. The milling of the BPP highlights the importance of differentiating between material usage and, ultimately, system weight. This is related to the assumption that the production of BPP on an industrial scale generates 40-50 wt% milling residues. Due to the size of the BPP, there is a strong curvature, which has to be milled away at great expense. Another problem is the size of the large industrial cells and the complex manufacturing, this leads to a high risk of cost-intensive production faults. However, in our previous work, a clear cost advantage could be worked out by scale-up (Minke et al., 2017b). For this reason, it is imperative to consider the development during production in subsequent work. The manufacturing loss will be significantly minimized by other manufacturing processes. In particular, production by micro casting and 3D printing offer a very large potential for larger cell areas (Arenas et al., 2019).

This results in a loss of material, which is no longer recycled in this model, but declared as waste. By combining the cell frame and the BPP into one component, not only working time but also material can be saved. For example, by manufacturing with injection molding, the channels can be integrated directly into the BPP, resulting in a total material saving of 3 wt% for each BPP with a flowfield volume of 1'800 mm³. It is unclear to what extent the production step for a BPP can

already be realized on the scale used, so this possibility is not considered. The PPG86 from Eisenhuth was used as a reference; it can only process a maximum shot volume of 1,250 cm³ (Eisenhuth). In this model the BPP without the flowfield has a shot volume of 3'600 cm³. This assumption is confirmed by the study of Minke et al. (Minke et al., 2016), in which the maximum production area for injection molding is assumed to be 2,500 cm² (Minke et al., 2016). The BPP used in the model has an area of 7,200 cm².

The simplified manufacturing process in Figure S1-19 is for understanding purposes only. With the help of the Supporting Information S2, the balancing can be reproduced. Although the manufacturing losses are considered, the manufacturing losses are balanced in the system design. Accordingly, they are included, but it is not visible in the balance sheet for manufacturing.

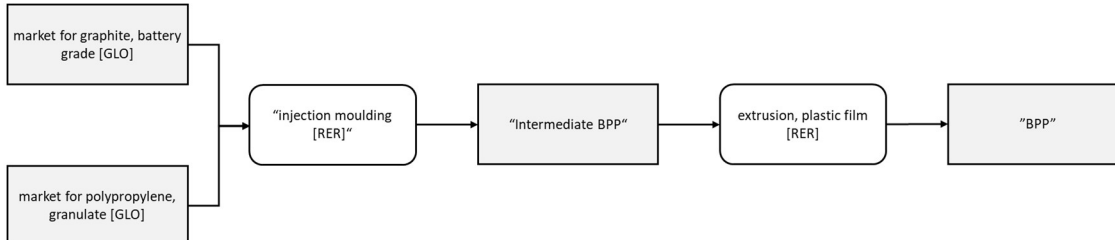


Figure S1-19: Schematic representation of a manufacturing process of a bipolar plate with ecoinvent data sets.

5.1.1.3.4 Frame

Two types of frames are modeled in the model. Both frame types are 1000 mm high and 1300 mm wide according to the cell. On the one hand, there is the "stack frame", which is attached at the beginning and end of each stack. Like the "cell frame", it also has 12 headers for the electrolyte inlet and outlet channel. However, the cell frame also has a recess with the area of the BPP.

Assuming that the surface is subsequently milled away, this results in a material loss of 57 wt%. Both frame types consist of polypropylene random copolymer (PP-R) and are modelled by the manufacturing process “injection moulding [RER]” (Figure S1-20).

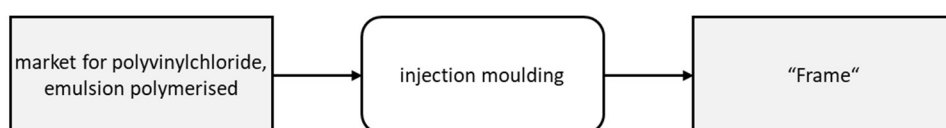


Figure S1-20: Schematic representation of a manufacturing process of two frame types with ecoinvent data sets

5.1.1.3.5 Membrane

Different ion exchange membranes are existing for the VFB. The cationic perfluorinated Nafion membrane is chosen for the model (Minke, 2016). For other membranes the production can show significant differences. The Nafion, patented since 1966, is the most commonly used membrane in an FB (Flow Battery), especially the chemical resistance and the high ion conductivity characterize this type. The patent for many versions of the product is no longer protected by patent law, since the term of many patents has already expired (Gebert, 2004). As a result, the approximate composition can be found in the literature (Minke, 2016)

In the model, a Nafion membrane with a thickness of 50 μm is assumed, corresponding to the cell a height of 1000 mm and a width of 1300 mm is assumed. The polymerization reaction of tetrafluoroethylene (TFE) and the co-monomer PSEPVE (perfluorosulfonyl fluoride ethyl-propyl-vinyl ether) forms the basis of the Nafion. Other materials used for the production are listed in Supporting Information S2. (Gebert, 2004; Minke, 2016). The manufacturing process used to be melt extrusion. Due to a simpler handling with e.g. fillers and optimized material properties, the membrane is currently produced by a casting process (Gebert, 2004).

The balance is based on data from the literature (Minke, 2016). Due to missing data sets, the modified reference process “polyvinyl chloride production, suspension polymerization” is used, as this is the most concrete representation of the process with high uncertainty. The complexity of the co-monomer representation is high, therefore a simplified molar mass balance without solvent is assumed (Minke, 2016). However, this assumption, shown in simplified form in Figure S1-21, does not mean that a substance polymerization is carried out. A substance polymerization takes place without solvent, and consequently a suspension polymerization is used as an approximation for all processes as a reference process (Lechner et al., 2014).

In total, the FDA synthesis, HFPO synthesis, diadduct and PSEPVE polymerization result in an output of 5.65 kg. The output of 5.65 kg results from the amount required to produce 1 kg of Nafion. The individual process steps with the respective quantities for 1 kg of Nafion are illustrated in Figure S1-21, where it is clear that a total input of 8.6 kg is required for the subsystems. All processes are represented by the reference process “polyvinyl chloride production, suspension polymerization” and the energy balances and mass balances are calculated accordingly. Accordingly, the resulting inputs and outputs were adjusted with the given materials and balances. In the last step, a polymerization with a yield of 90.09% follows, thus an input of 1.1 kg results in an output of 1 kg of Nafion (Gebert, 2004). With a lower yield, the required raw material quantities would increase linearly. In the polymerization process the functional unit is 1 kg of Nafion and in the synthesis steps it is always the resulting product, but a total of 5.65 kg output is produced, which is why the energy balances refer to this value. The by-products resulting from the synthesis of Nafion are listed in detail in the outputs in the Supporting Information S2. These are based on assumptions of the chemical synthesis chain in Nafion, which makes it clear that many by-products must be disposed of. The data were validated based on the values of Weber et al. (2018).

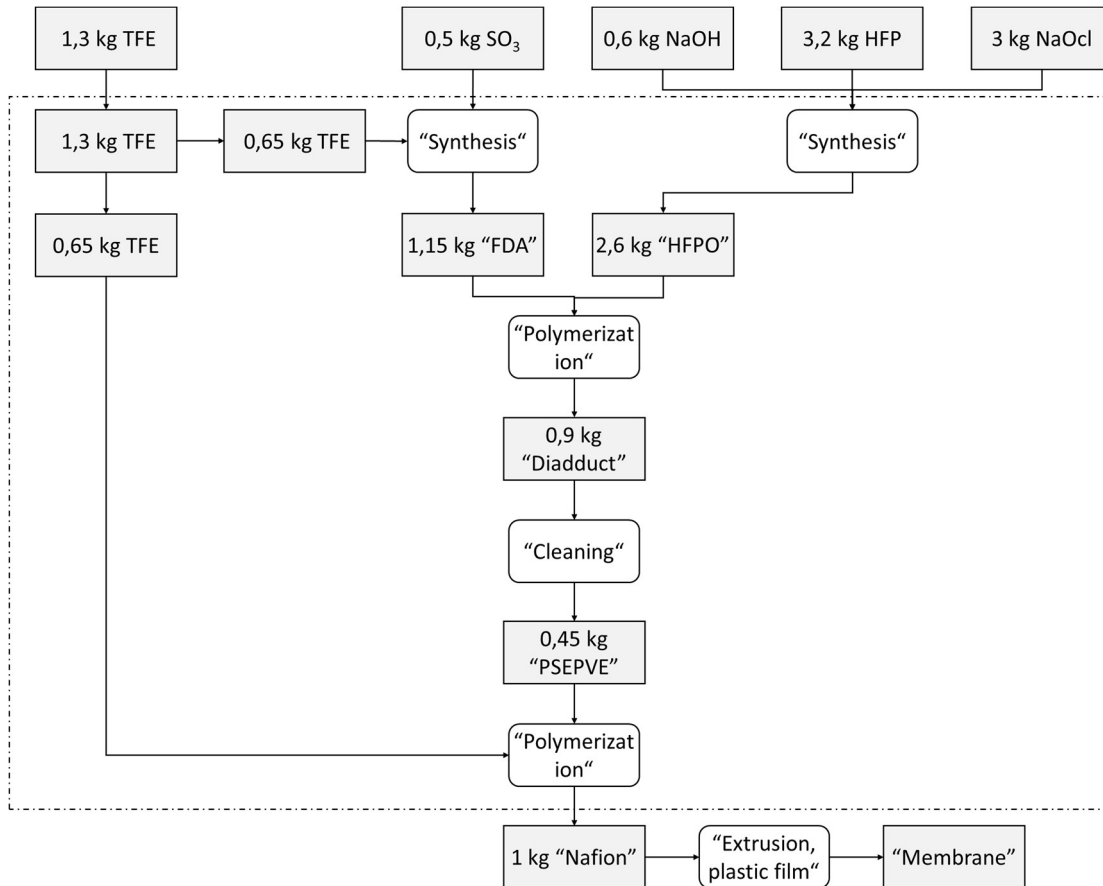


Figure S1-21: Schematic representation of a manufacturing process of a Nafion mebrane with ecoinvent data sets.

5.1.1.3.6 Gasket

A leak in the stack or rather in den gasket can lead to the complete exchange of the stack. Therefore several potential gaskets are on the market that are suitable for a FB. The fluoro rubber gasket (FKM) is particularly suitable for a VFB because of its chemical resistance. The gasket is manufactured in the form of an O-ring and 122 gaskets are required for a stack, whereas a gasket with a length of 14.7 m is required for one cell. A safety factor of 20% is already included in the

length. The mass balance of the gasket bases on the patent of the company E.I. Du Pont De Nemours & Company (1978). In this patent different compositions of the FKM are defined. For the composition of the gasket a percentage of 49.1 wt% of vinylidene fluoride, 33.2 wt% hexafluoropropene and 17.7 wt% tetrafluoroethylene is chosen (J. R. Pailthorp & S. H. Elbert, 1978). These data sets are also illustrated in Figure S1-22. Because of the emulsion polymerization of the three monomere mixture the process “polyvinylchloride production, emulsion polymerization” is used as a reference. The mass and energy balances for the extruding process were calculated using the process “market for extrusion, plastic pipes” as a reference. The double-sided chemical resistant adhesive tape has not been considered due to its negligible impact. In this design a fluorinated gasket is not needed.

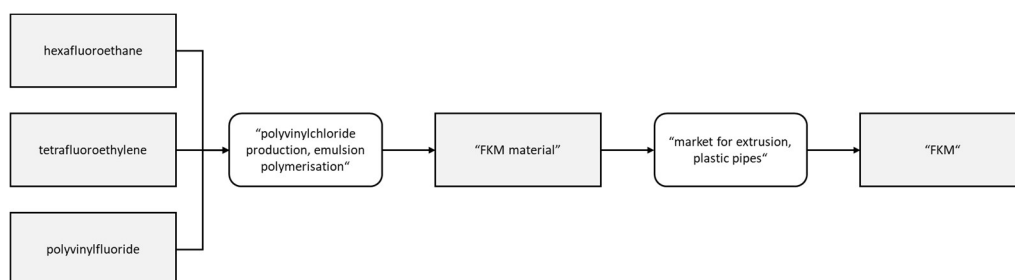


Figure S1-22: Schematic representation of a manufacturing process of a gasket with ecoinvent data sets

5.1.1.3.7 Current collector

The manufacturing of the current collector is done by the process “market for sheet rolling, copper [GLO]”. Eight holes are drilled in each copper sheet so that they can be fixed in the stack, but this results in a lower system weight. For the balance, the material used is used as a reference. The lower weight is only relevant for the design of the foundation. Machining or milling of the current collector has not been considered. The density of copper was assumed to be 8.95 g/cm³.

5.1.2 Technical data for the system design

This chapter still describes the technical details for the VFB. Table S1-7 describes the number of components for a stack and Table S1-8 describes the technical data of a stack. The performance data and parameters for the VFB can change relatively quickly, so it is also important to supply the technical data of the battery. Likewise, incorrect data could be found in the literature. In addition, the following data can be used to ensure that the prerequisites for a comparison with other battery systems are given. However, these tables only supplement the tables already presented in the paper. With the help of this information, the model can still be understood more easily and transparently, and the reader can correctly assess the results in relation to a possible comparison.

Table S1-7: Number of components for one stack.

Number of components per stack	
Component	Pcs
Cells	60
Compression plate	2
Cell frame	61
BPP	61
Current collector	2
Membrane	60
Electrode	122
Stack frame	2
Gasket o-ring	122

Table S1-8: Technical data of one stack.

Total stack data		
Function	Number	Unit
Target current density	2	kA/m ²

Specific volume flow	466	L/(hm ²)
Total volume flow	20148,21	L/h
Nominal power density	2,6	kW/m ²
Nominal output stack	112,32	kW
Height	1200	mm
Width	1500	mm
Thickness (cells only)	427	mm

5.1.3 Local environmental impacts and hazards

As outlined in the Inception Report, a more complete view on environmental impact is required besides lifecycle impacts.

Table 19. Local environmental impacts of the selected energy storage technologies

	VRFB
Water use	- VRFBs use diluted sulfuric acid with vanadium salts in aqueous solution. - Significant water demand during electrolyte production and maintenance (refill/losses). - Risk of contamination if spills occur.
Land use	0,0125 m ² / kWh
Pollution	- Vanadium electrolyte spills can acidify soil or harm aquatic systems. - Electrolyte leaks may release sulfur compounds. - No emissions during use, but manufacturing and mining have localized pollution risks (e.g., vanadium dust, tailings).
Other	- Noise from pumps during operation (minor). - Visual impact (bulky tanks). - Low fire risk (non-flammable electrolyte), unlike Li-ion.
Recommended "Go-to" zones	Existing battery or renewable energy installations, Industrial areas,



Life Cycle Impact Assessment (LCIA)

The LCIA is the third phase of a life cycle assessment (LCA), in which the potential environmental impacts of a product or system are evaluated based on the inventory data collected in the previous phase. In LCIA, the inputs and outputs from the secondary datasets, such as emissions, resource use, and waste, from the life cycle inventory are classified into impact categories (e.g., climate change, acidification, eutrophication, resource depletion). These flows are then characterized to quantify their contribution to each category, using scientifically established models. In this study the modeling software is Umberto LCA+ with ecoinvent (cut-off model) as background LCA database (Ecoinvent Centre, 2019). The CML-2001 method is used as life cycle impact assessment (LCIA) method.

The following impact indicators are selected:

1. terrestrial ecotoxicity potential (TAETP),
2. stratospheric ozone depletion potential (ODP),
3. abiotic resource depletion potential (ADP),
4. photochemical oxidation (PO),
5. marine aquatic ecotoxicity potential (MAETP).
6. human toxicity potential (HTP),
7. freshwater aquatic ecotoxicity potential (FAETP),
8. eutrophication potential (EP),
9. global warming potential (GWP), and
10. acidification potential (AP).

The complex and high-impact upstream processes of vanadium electrolyte manufacturing are modeled in an original approach in the present study and considers the ISO standards 14040 (2006), 14044 (2006), and 20915 (2018). The minor part is the manufacturing of the aqueous

electrolytes by preparing solutions with the active material vanadium pentoxide (V₂O₅). But the major part is the V₂O₅ extraction on the basis of coupled mining and steelmaking processes.

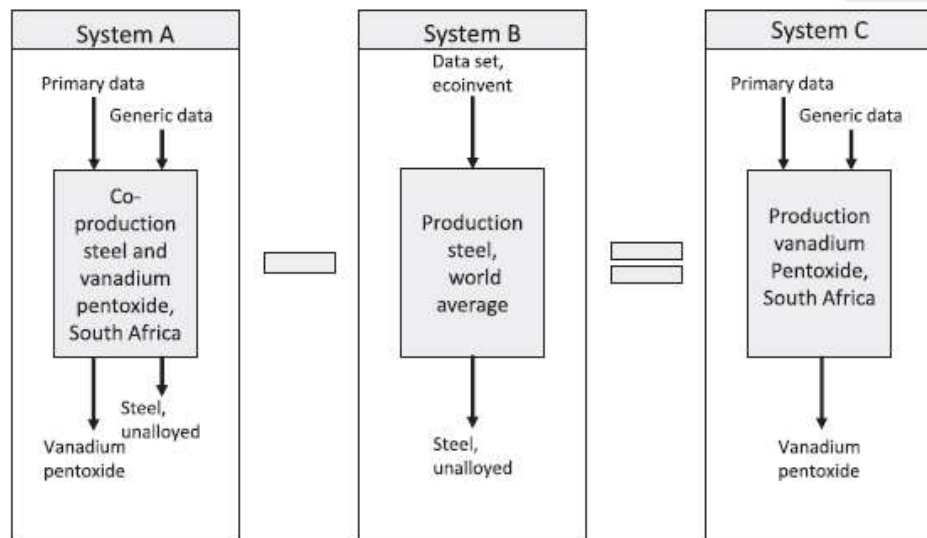


FIGURE 3 Scheme of system expansion approach for calculation of vanadium pentoxide production in South Africa

Detailed LCIA results along with the optional resource use and output indicators can be found in the Annex (Mass and energy balances for VRFB: 1 MW / 8 MWh).

1. Interpretation of results and discussion

In this chapter, the results of the impact assessment are analyzed to identify key environmental hotspots and the most significant impact categories.

First, the percentage shares of the individual components are analyzed. Second, a spotlight is put on GWP in terms of CO₂ equivalents. In addition, the study examines how potential emissions evolve over an extended time horizon by considering multiple subsequent life cycles of the emission-intensive and long-lasting vanadium electrolyte. Finally, a sensitivity analysis is performed using comparison of the potential environmental impacts of the VFB with primary electrolyte and a reuse scenario.

1.1 LCIA results

LCIA results are illustrated in Figure 5, which shows the relative contribution of battery components to the various environmental impact indicators. Additionally, absolute emissions per FU are stated for all indicators.

Table XX: Ranking of impact for battery components (own calculation, marked are data above 10%)

	AP average European	GWP 100	EP generic	FAETP 100	HTP 100	MAETP 100	PO high NOx POCF	ADP	ODP steady state	TAETP 100	Average impact	Rank of impact
Electrolyte	91,82%	74,41%	84,25%	25,86%	1,71%	27,23%	40,49%	82,40%	0,97%	45,70%	47,48%	1
Generation electricity	5,10%	16,81%	9,56%	36,00%	64,04%	35,49%	39,90%	12,13%	7,02%	42,99%	26,90%	2
Membrane	0,05%	0,56%	0,07%	0,06%	0,11%	0,06%	0,40%	0,10%	68,35%	0,06%	6,98%	3
Pumps	0,58%	0,62%	1,08%	9,73%	10,13%	9,47%	2,97%	0,42%	0,20%	1,98%	3,72%	4
End-of Life	0,08%	0,84%	0,10%	16,41%	0,18%	15,57%	0,32%	0,24%	0,51%	0,19%	3,44%	5
Compression plate	0,44%	2,03%	1,15%	2,58%	5,97%	2,69%	4,90%	1,34%	0,89%	4,24%	2,62%	6
Inverter	0,70%	0,77%	1,32%	4,34%	6,79%	4,38%	3,37%	0,56%	0,35%	1,69%	2,43%	7
Gasket	0,02%	0,18%	0,02%	0,02%	0,04%	0,02%	0,10%	0,04%	19,41%	0,02%	1,99%	8
Current collector	0,53%	0,10%	1,00%	3,77%	5,60%	3,80%	2,13%	0,07%	0,03%	0,80%	1,78%	9
Bipolar plate	0,17%	0,72%	0,51%	0,27%	2,46%	0,29%	1,83%	0,86%	0,44%	0,61%	0,82%	10
Container	0,08%	0,35%	0,21%	0,37%	1,31%	0,38%	1,07%	0,24%	0,12%	0,96%	0,51%	11
Frame	0,11%	0,52%	0,22%	0,15%	0,27%	0,16%	0,70%	0,55%	1,18%	0,18%	0,40%	12
Tank	0,13%	0,87%	0,21%	0,11%	0,47%	0,11%	0,89%	0,53%	0,18%	0,19%	0,37%	13
Foundation	0,10%	0,90%	0,10%	0,02%	0,08%	0,02%	0,37%	0,23%	0,24%	0,19%	0,23%	14
Cable	0,03%	0,08%	0,05%	0,13%	0,27%	0,13%	0,19%	0,05%	0,02%	0,04%	0,10%	15
Control unit	0,03%	0,03%	0,04%	0,10%	0,16%	0,10%	0,16%	0,03%	0,01%	0,07%	0,07%	16
Electrode	0,02%	0,15%	0,08%	0,03%	0,02%	0,03%	0,08%	0,12%	0,05%	0,03%	0,06%	17
Pipe	0,02%	0,05%	0,02%	0,05%	0,09%	0,05%	0,10%	0,06%	0,01%	0,02%	0,05%	18
Heat exchanger	0,00%	0,02%	0,01%	0,02%	0,27%	0,02%	0,03%	0,01%	0,00%	0,02%	0,04%	19
Emissions per FU (kWh-1)	0,00084 kg SO2 eq	0,04494 kg CO2 eq	0,00019 kg PO4 eq	0,10572 kg 1.4-DCB eq	0,043277 kg 1.4 DCB eq	0,335764 kg 1.4 DCB eq	7,84E-06 kg C2H4 eq	0,00046 kg Sb eq	8,22E-09 kg R 11 eq	3,12E-05 1.4-DCB eq		

*terrestrial ecotoxicity potential (TAETP), stratospheric ozone depletion potential (ODP), abiotic resource depletion potential (ADP), photochemical oxidation (PO), marine aquatic ecotoxicity potential (MAETP), human toxicity potential (HTP), freshwater aquatic ecotoxicity potential (FAETP), eutrophication potential (EP), global warming potential (GWP), acidification potential (AP)

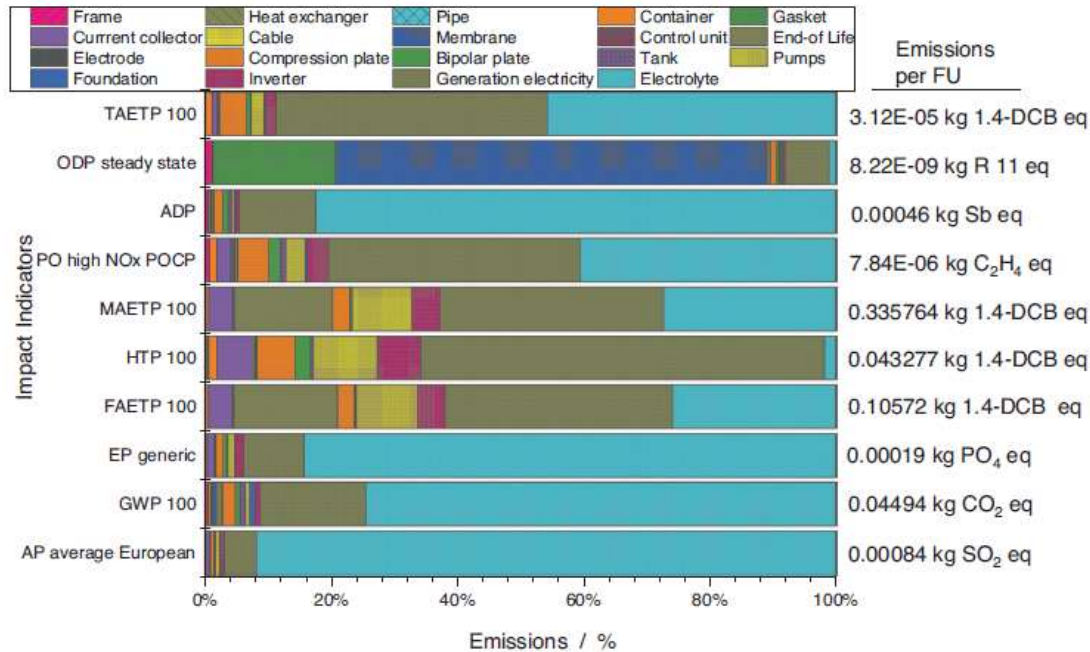


FIGURE 5 A breakdown in percentage of the emissions of the different impact indicators. The emissions are based on a cradle-to-grave approach. Impact categories: AP (acidification potential), EP (eutrophication potential), PO (photochemical oxidation), ADP (abiotic resource depletion potential), GWP (global warming potential), ODP (stratospheric ozone depletion potential), TAETP (terrestrial ecotoxicity potential), FAETP (freshwater aquatic ecotoxicity potential), HTP (human toxicity potential), MAETP (marine aquatic ecotoxicity potential). Underlying data for Figure 5 are available in tab "Data plotted in Figure 5" in Supporting Information S2

The electrolyte as well as the electric energy supply dominates almost all indicators. Since the electrolyte has a high non-quantifiable value after 20 000 cycles, this effect must be investigated in a sensitivity analysis. In the considered period of 20 years, the generation of electricity with a share of 16.8% of CO₂ eq is only dominated by the electrolyte (74.4%) in the GWP indicator. The provision of electricity causes high percentages of emissions, especially for the indicators TAETP (43%) and HTP (64%). In the model, the term "generation of electricity" refers only to the losses caused by system efficiency of the battery and energy provision of the battery is accounted for. Thus, battery efficiency has a significant impact on the emissions. Likewise, reduced efficiency would result in higher electrolyte demand. However, the assumed total system efficiency of 70%

is a very conservative estimation; in the literature, figures of 75–90% for the system efficiency are provided (Hu et al., 2017).

The electrolyte clearly dominates the acidification potential (AP) at 91.8%. Whereas the electrolyte has the lowest impact on the ODP with 0.9%, which is dominated by the membrane (68.3%). The reason lies in the perfluorinated Nafion membrane material with an elaborate synthesis, including a polymerization reaction of tetrafluoroethylene and perfluoro sulfonyl fluoride ethyl-propyl-vinyl ether and losses in the upstream processes (Gebert, 2004; Minke, 2016; Minke & Turek, 2015).

Besides the impact of the Nafion membrane on ODP, the stack components have a significantly lower share of the emissions. It has to be noted that this result corresponds to the specific design and maintenance assumptions used in this study. In general, influencing factors are the E/P ratio (energy/capacity to power ratio), the current density, and the lifetime or cycle life of the stacks. For example, halving the current density would lead to an almost doubling of the required stacks. The E/P ratio must always be considered as the power and the capacity can be scaled independently. A strong relationship between the E/P ratio and the resulting emissions of the electrolyte and the stacks can be demonstrated.

6.2 Carbon footprint

The GWP per FU equals 0,045 kg CO₂ (kWh)^{–1} (see Figure 5). In the previous section, the importance of accounting for the use phase on the basis of battery efficiency has already been emphasized. The 16.8% of CO₂ eq emissions are caused by the energy losses during the use phase of the VFB.

This figure is strongly dependent on the renewable energy chosen. In the model a 1–3 MW onshore wind power located in Germany is assumed, which is a preferable energy generation technology in terms of GWP. For comparison, the GWP per kWh of supplied renewable energy for a 570 kWp open ground photovoltaic system located in Germany is five times higher (Ecoinvent Centre, 2019). The major contributor to the total GWP is the vanadium electrolyte with a share of 74.4% of CO₂ eq (Figure 5). In this light, a correct elaboration of the production process and corresponding emissions of vanadium pentoxide (V₂O₅) is crucial. The production of primary V₂O₅ is coupled to the steelmaking process in South Africa. In particular, the poor extraction ratio of V₂O₅ from ore has a major impact on emissions. Despite the unfavorable electricity mix in South Africa, the production of steel is not significantly more CO₂ intensive than the usual European production. The electricity mix from South Africa emits 71% (1.06 kg CO₂ eq (kWh)^{–1}) more CO₂ eq than the German electricity mix. This effect is enhanced by the use of an electric arc furnace, which requires mainly electricity and no coke. The CO₂ eq emissions from the steelmaking and V₂O₅ production process (see process flow chart in Figure 4) are shown in a Sankey diagram in Figure 6.

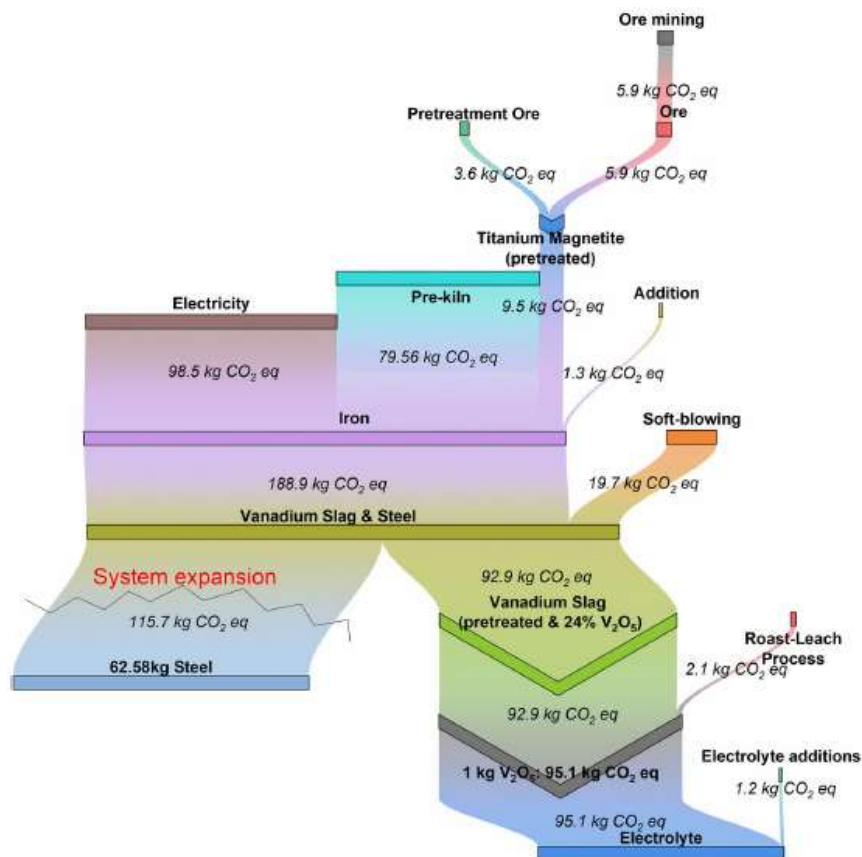


FIGURE 6 The CO₂ eq caused in the production of steel and vanadium pentoxide (V₂O₅) from raw material extraction to the finished 1 kg of V₂O₅ with a purity of 97.5 wt%. On the basis of the manufacturing steps, the allocation of emissions and the designation of the system boundaries become clear. Underlying data for Figure 6 are available in tab "Data plotted in Figure 6" in Supporting Information S2

It shows that most of the emissions result from energy demand for the furnace as well as the preparation of the ore with coal in the pre-kiln. Up to the "soft-blowing" step, all necessary processes for the production of vanadium and steel are identical. Starting with the resulting vanadium slag all emissions can be fully attributed to the V₂O₅. For the production of 1 kg of V₂O₅ 62.58 kg of steel are produced. Most of the electrolyte emissions, 47.8%, result from the provision of electricity for the furnace. The pretreatment of the ore by burning the coal in the pre-kiln also causes a significant share of the CO₂ for the electrolyte production with 38.6%. However, this pre-kiln treatment is necessary due to the ore composition and is not addressed in the previous LCAs.

The roast-leach process with a resulting purity of 97.5 wt% of the V₂O₅ has a very low impact on the GWP at 1%. Consequently, the purity of the V₂O₅ is only relevant from an economic but not from an environmental point of view, whereas the roast-leach processes are always strongly dependent on the ore. In the future, steelmaking will generate significantly reduced emissions, especially through renewable energies and the use of hydrogen as a reduction agent in electrical arc furnaces. Compared to 1990, technological advances are expected to reduce CO₂ emissions by 47–95% (Otto et al., 2017). Accordingly, the electrolyte will only cause a fraction of the emissions. In the next chapter, a very important point will be considered for a potential reduction of the emissions, the reuse of electrolytes.

6.3 Circularity and recyclability

In the discussion we refer to the criteria outlined in Section 1. For comparison of LCA results, two requirements have to be met: an appropriate FU for the **cradle-to-gate** approach and a high level of transparency in the LCI usually provided in extensive Supporting Information S2. For a valid comparison of the results with Weber et al. (2018) we first need to fit the model. The model is changed to a **cradle-to-gate** approach, accordingly the use phase and the EOL are not considered.

In our analysis we find 37 kg CO₂ eq (MWh)^{−1} for a cradle-to-gate approach. A similar value is provided by Weber et al. (2018) with 38.2 kg CO₂ eq (MWh)^{−1}. However, for a valid comparison, the three most significant differences of the Weber et al. LCA also need to be addressed. First, in Weber et al. (2018) only about half of the required electrolyte is accounted for (272 t ≠ 507 t), but this is compensated by the assumptions for the composition of 1 L electrolyte (0.148 kg V₂O₅ ≠ 0.286 kg V₂O₅). In addition, the assumption of 8.176 cycles is very detrimental to the battery, since the electrolyte must be assumed to have a minimum of 20 000 cycles, after which it still has a high unquantifiable value. However, our more detailed consideration also results in significantly more emissions for the electrolyte in our LCA.

The next interesting aspect would be a comparison of GWP from V₂O₅ production, unfortunately no explicit data is found in the literature. We therefore use the approach of validation by GWP results for the upstream steelmaking process in which V₂O₅ is a co-product. Chen et al. calculate a GWP of 2.84 kg CO₂ eq (kg steel)⁻¹ considering a vanadium titano-magnetite from South Africa. In our LCA, the result is 3.3 kg CO₂ eq (kg steel)⁻¹ based on our conservative approach (Figure 6). For the validation, the total steel production emissions are accounted for without the allocation due to the system expansion approach. Further quantitative validation of emissions is included in the SI of this article. At this point, further qualitative statements are discussed.

When considering the ore with the V₂O₅ from South Africa, two significant disadvantages were highlighted for the first time in the literature despite the high percentage. First, a high loss of V₂O₅ is generated during extraction, which cannot be further processed economically. Second, due to its composition, the ore has to be pretreated at great expense, which also causes high emissions. However, these factors are partially compensated by the use of an electric arc furnace. The data only refer to the V₂O₅ from one site in South Africa, in order to make general statements on V₂O₅ different processes and sites also need to be examined in detail. In the long term, a data set for primary V₂O₅ is needed so that the results in the literature no longer vary greatly and thus prevent the sustainability analysis of the battery. In perspective, a switch to hydrogen as a reducing agent in a more sustainable steel process would also need to be analyzed along with the consequences (Axelson et al., 2021; Gielen et al., 2020).

In our previous work, a cost advantage of large cell areas was calculated on the basis of mathematical models, which is why large cell areas were analyzed in this work (Minke et al., 2017). Due to the complex manufacturing process, there is still a high manufacturing loss, for example, 40–50% for BPP (Bipolar Plate). In the future, there may be other manufacturing strategies such as injection molding or 3D printing, making also entirely new cell characteristics possible (Arenas et al., 2019).

Conservative assumptions were initially made throughout the balance sheet in order to gain further important insights based on these results. This concerns both the quality of the steel in the system expansion, recycling and, in particular, the consideration of the electrolyte after 20 years. In the model, the electrolyte is considered neutral after 20 years; this assumption is not correct and questionable. However, the value of the electrolyte cannot be quantified at that point. Equally speculative would be the accounting of failures within the operating time. In the model, an optimal course of the battery was assumed. In the literature, no in-depth understanding failures of the battery in the long term exist. In practice, stack components may fail partially or completely, or an oxidation of the electrolyte is also possible (Gundlapalli & Jayanti, 2021). Also, the importance of balancing the foundation must be put into perspective for a longer time period, but nonetheless this factor must be considered. The weight of different flow batteries and especially other storage systems can vary greatly.

Similarly, more attention needs to be paid to circular economy and material circularity in LCA (Saidani et al., 2017). The use of a flow battery offers many advantages, especially the use of modular stacks. The stacks are divided into different components which are often available in pure form with respect to the material. Accordingly, the current collector or the compression plates, for example, can possibly be recycled very efficiently. Likewise, in a further analysis, both the open-loop and the closed-loop recycling process should be analyzed with a corresponding data quality. Another point is independence from materials from critical countries of origin; this aspect must also be considered for a comprehensive sustainability analysis.

2. Sensitivity and uncertainty analysis

1.

Since an assessment of the electrolyte at the end of the period is difficult for many reasons, this aspect is examined by means of a sensitivity analysis. The statement that the electrolyte can be used for another 20 years without further treatment is just as wrong as considering the electrolyte

as waste at the end of the operation phase. The residual value of the electrolyte cannot be quantified at this point based on the literature, but its consideration has a significant impact on battery emissions. There are various irreversible contaminants that cannot be remedied by rebalancing. For example, long-term oxygen diffusion through tubes, hoses, and electrolyte vessels may lead to electrolyte oxidation to some extent. If the BPP is broken, the electrolyte may be contaminated with copper from the current collector. Furthermore, the critical concentrations of various substances are not clearly defined (Skyllas-Kazacos et al., 2016). However, further use of the electrolyte after 20 years is very likely, and measures exist to recycle and rebalance the electrolyte. The worst-case scenario would be the precipitation of the vanadium, but it would still cause significantly less emissions than the primary electrolyte. **Since there are no estimates and scenarios for the reprocessing of the electrolyte up to this point, in the reuse scenarios in this study zero emissions for the electrolyte are accounted for.**

Figure 7a shows the direct comparison of the potential environmental impacts of the VFB with primary electrolyte and a reuse scenario. In the reuse scenario, the reprocessed electrolyte has zero emissions. Thus, only emissions by the new VFB are accounted for. The figure shows the percentage savings due to the continued use of the electrolyte. Any emissions for the reprocessing are not considered due to insufficient data.

These emissions are assumed to be relatively small compared to the production of the electrolyte. In addition, the foundation is not considered again. **The influence of the foundation is marginal compared to the electrolyte.** In the 10 considered impact indicators, this leads to a reduction of emission between 0.97% (ODP) and 91.8% (AP). On average, a VFB using reprocessed vanadium electrolyte instead of primary electrolyte has only 53% of potential environmental impacts.

It is widely anticipated that the vanadium electrolyte may be reused in several life cycles. Thus, a fair allocation of the primary electrolyte's emissions over the life cycles is desirable. In this work, emissions of primary vanadium electrolyte are equally divided over the primary and subsequent

reuse life cycles. In Figure 7b the influence of up to four reuse scenarios on AP, GWP, and HTP are illustrated. The curves are flattening significantly after the first reuse scenario, but GWP and AP show strong decreases in the following product life cycles. In contrast, emissions can only be slightly reduced in the HTP, because its main emissions result from the stack and the electricity generation.

The indicator values decrease to a varying extent over the 100 years considered. This is intended as a model proposal for the differentiated consideration of electrolyte and battery with their very different lifetimes.

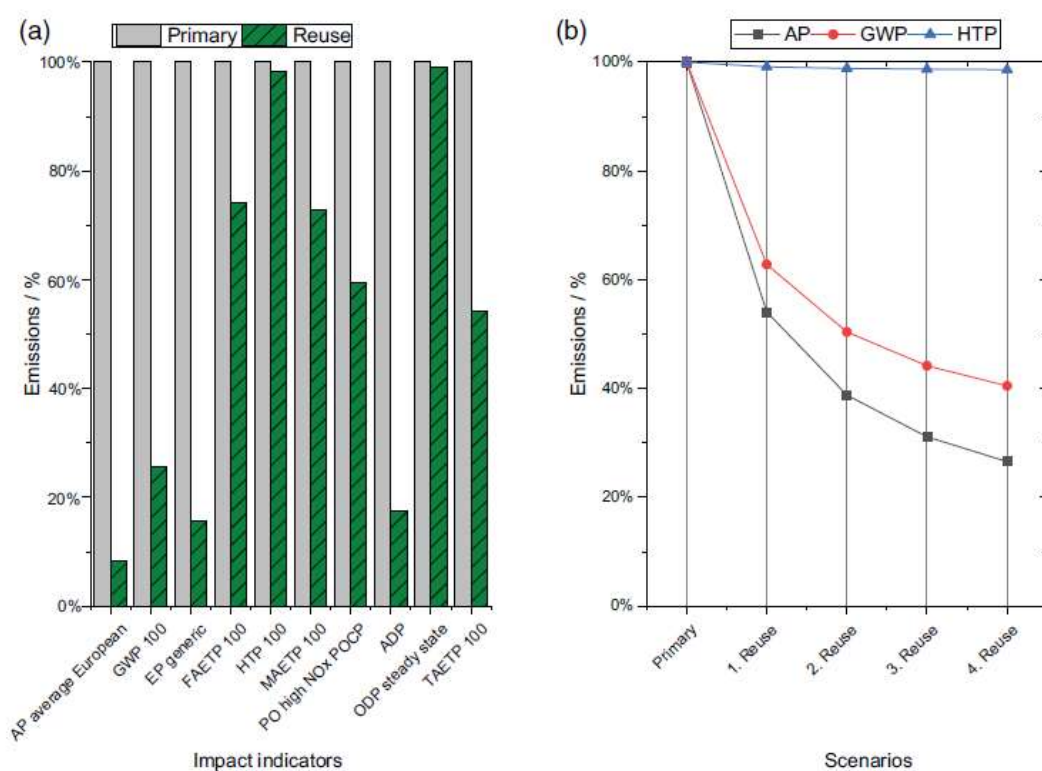


FIGURE 7 (a) Comparison of potential environmental impacts of a 1 MW/8 MWh vanadium flow battery (VFB) with primary vanadium electrolyte and reuse of electrolyte (zero emissions for second life cycle of electrolyte). (b) Development of potential environmental impacts of VFB over up to four reuse cycles of electrolyte in new VFB (emissions of primary electrolyte equally divided over life cycles). Underlying data for Figure 7 are available in tab "Data plotted in Figure 7" in Supporting Information S2

5.4 Technical Implementation

VRFBs are **commercially available** from a number of manufacturers globally, though the industry is relatively specialized. The technology is thus *available for purchase*, although often via custom or project-specific orders rather than off-the-shelf commodities. Below is a comprehensive list of global companies (established providers and emerging startups) engaged in Vanadium Redox Flow Battery (VRFB) technology.

Table 5.2. List of global companies engaged in Vanadium Redox Flow Battery (VRFB) technology.

Company Name	Country	Product Size Range	Website
Australia VRFB ESS Company Pty Ltd	Australia	Grid-scale (planned, multi-kW to MW prototypes)	¹⁴
CellCube (Enerox GmbH)	Austria	50 kW – multi-MW (containerized VRFB systems)	¹⁵
H2 Inc.	South Korea	42 kW modules (200 kWh each) scalable to multi-MW	¹⁶
HydraRedox	Spain	Modular (100+kW up to “multi-MW”, 4–24hour duration) (	¹⁷
Invinity Energy Systems	UK (global)	200 kWh modules (VS3) scalable to multi-MWh systems	¹⁸
Le System Co., Ltd.	Japan	focus on electrolyte supply for VRFB systems	¹⁹
LG Chem	South Korea	research stage for VRFB	²⁰
Pinflow Energy Storage	Czech Republic	kW-scale stacks (for modular combination into larger systems)	²¹
Schmid Energy Systems	Germany	5kW – 500kW modules (containerized to multi-MW)	²²

It's important to note that many VRFB installations to date have been **demonstration projects or pilot deployments** (often supported by research grants or innovation funds) rather than purely commercial, profit-driven purchases. This is changing as the technology proves itself. In China and

the United States, government incentives and utility interest are leading to more commercial rollouts of flow batteries ⁷⁴. In Europe, a recent milestone was the EU's Innovation Fund selection of a hybrid storage project in France that will pair VRFBs with lithium-ion batteries at a solar farm – a strong signal of market entry for VRFBs in a commercial context ⁷⁸. By 2024, **over 200 VRFB systems** have been deployed worldwide (cumulatively), and the pipeline of announced projects is rapidly expanding, especially in Asia-Pacific.

The **EU region** currently has limited local manufacturing (Enerox in Austria is a notable regional manufacturer), so most VRFB hardware would be imported. However, this also presents an opportunity – with the right support, regional industry could collaborate with established players to set up assembly or maintenance hubs. Early adopters in the region might leverage European innovation programs (as Hungary did) to co-fund the initial projects, building confidence among financiers and policymakers that **VRFB technology is commercially ready to deliver** on its promises.

5.4.1 Safety and Risks

One of the most touted advantages of VRFB technology is its **intrinsic safety**. VRFBs are **water-based and operate at ambient conditions**, which means they do not pose the fire and explosion hazards associated with many other batteries. The electrolyte is an aqueous solution of vanadium sulfate in sulfuric acid – it is non-flammable. In contrast, lithium-ion batteries contain highly flammable organic electrolytes and can experience thermal runaway. A VRFB will not catch fire; even under abuse conditions like overcharging, the worst it might do is generate some hydrogen gas (from electrolysis of water) if pushed far beyond normal operation, which can be mitigated with proper venting. There is no risk of a chain-reaction explosion or burning, making VRFBs very safe to install even in sensitive locations (for example, inside buildings or in urban areas) . This safety profile has been validated in tests and real incidents – essentially, VRFB systems have an

excellent record of not causing fires, whereas large Li-ion battery fires, though rare relative to installations, have made headlines and raised concern for community safety.

The primary **hazard with VRFBs** is the chemical nature of the electrolyte. Sulfuric acid is corrosive, and vanadium compounds can be toxic in high concentration. **Risk of leakage** or spillage must therefore be managed. VRFB systems usually incorporate secondary containment: if a tank or pipe leaks, the spill is captured in a bunded area or a double-walled container. Personnel handling the electrolyte wear protective gear similar to handling industrial acids. In normal operation, the system is closed and pressurized only by pump action (typically a few bar at most), so a catastrophic rupture is highly unlikely. Monitoring systems can detect leaks (for instance, liquid sensors in the battery container floor). Should a leak occur, the response would be similar to a chemical spill response – neutralize the acid (often with soda ash or lime) and clean up. The area would need flushing and maybe soil remediation if any escaped containment. While such an event is undesirable, it is generally far less dangerous to public safety than a fire or explosion. There are also no high-pressure vessels or toxic gases produced in VRFBs under normal conditions.

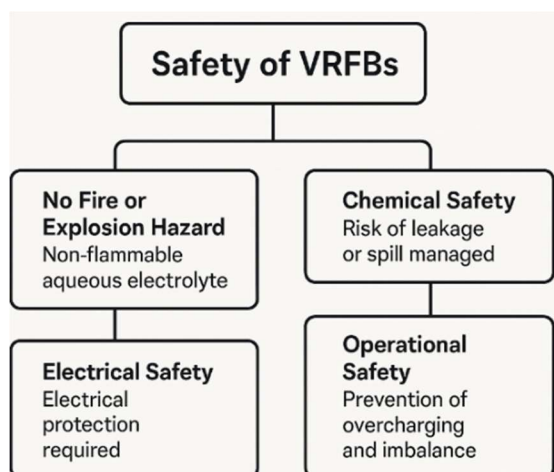


Figure 5.5 : Safety and Risk Management Features of Vanadium Redox Flow Batteries (VRFBs)

Cybersecurity or misuse could be another angle – as with any grid-connected tech, control systems must be secure to prevent malicious operation (like someone intentionally overcharging to try to force hydrogen evolution or mixing). Standard cybersecurity for industrial control systems applies.

Overall, VRFBs are considered a **very safe technology**, one that can often lower the risk profile of energy storage deployment. This can translate into **easier insurance and potentially smoother community acceptance**. For example, you could site a VRFB near a hospital or in a dense area with less worry about evacuation zones or fire suppression systems, compared to a Li-ion container which might need significant firefighting resources on standby. In the Project's region, where some areas have strict safety regulations (and public sensitivity might be high after seeing news of battery fires elsewhere), promoting VRFB's safety merits is important. Emphasizing “**no fire/explosion hazard**” and demonstrating robust spill containment will be key to obtaining permits and community buy-in. The region's emergency services would need only minor adjustments (focusing on chemical handling rather than firefighting).

5.4.2 Maintenance and Operational Requirements

Maintenance Needs and Schedule

VRFB systems are often advertised as **low-maintenance energy storage**, which is generally true relative to other complex energy systems. The maintenance requirements revolve around keeping the mechanical and fluid systems in good working order and ensuring the electrochemical components remain healthy. There are no moving parts inside the cells, but the **pumps** that circulate electrolyte are mechanical devices that require periodic maintenance. Typically, a VRFB installation will have multiple pumps (for redundancy and for each electrolyte loop). Maintenance tasks include checking pump operation, replacing bearings or seals after a certain number of operating hours, and ensuring there are no clogs or deposits in the flow system. The **electrolyte filters** (if any are used to keep the solution clean of debris) might need occasional replacement.

The cell stacks themselves usually require little attention; however, over years, one might schedule an inspection or refurbishment. For example, after 8-10 years, an operator might inspect a stack for any membrane degradation or electrode fouling, and potentially refurbish by replacing membranes or cleaning electrodes if needed. Some manufacturers provide refurbishment services that can essentially make the stack “as good as new” for the second decade of operation, at a fraction of the cost of a new system.

Day-to-day, a VRFB can be largely automated. **Monitoring software** continually checks parameters like electrolyte temperature, pump pressure, cell voltages, and state of charge. If anything strays out of normal range, operators are alerted. Most of the time, operators only need to perform routine inspections perhaps monthly or quarterly – for instance, verifying fluid levels (though in a closed system levels shouldn’t change), inspecting for any minor leaks or weeps at pipe joints, and testing backup systems like pump switchover. Because VRFBs are typically stationary and in one place, getting maintenance crews to them is straightforward (unlike something like wind turbines which are tall or remote). Operators should be trained in handling the electrolyte safely if any interaction with it is needed (e.g., drawing a sample for analysis). Analytical checks on the electrolyte can be part of maintenance: perhaps annually, a sample is taken to check vanadium concentration and valence balance, as well as impurity levels. If, for example, air has introduced any contamination or there are side reactions building up impurities, the electrolyte might need a conditioning step (like filtering or chemical adjustment). These are usually infrequent.

The **operational management** of a VRFB might include software updates (since control algorithms can be improved or adjusted to site needs), which is a simple maintenance action. Cooling systems (if a VRFB has a cooling loop or fans to dissipate heat from the stacks) should be checked and cleaned – ensuring fans are operational and heat exchangers are not clogged with

dust. This is analogous to maintaining an HVAC system. Compared to a lithium-ion battery installation, VRFB maintenance is slightly different: Li-ion has less mechanical parts but more emphasis on monitoring battery health and possibly replacing failed modules; VRFB has more mechanical components but the core battery doesn't degrade much, so you don't have to keep swapping out cells. In many cases, VRFB suppliers suggest that the **routine maintenance cost is low enough** that it substantially offsets the initial cost over time. For instance, no expensive cell replacements every few years (as happens with some other chemistries) is a big advantage.

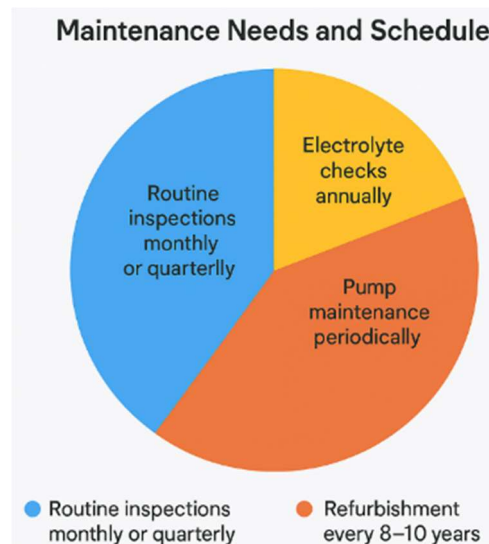


Figure 5.6 : Maintenance Needs and Lifecycle Schedule of VRFB Systems

5.4.3 Ease of Integration and Operational Compatibility

Integrating a VRFB into existing energy infrastructure is generally not very complex, but there are a few considerations to ensure smooth operation. **Physically**, as mentioned, one needs adequate space and a supportive foundation (tanks full of electrolyte are heavy – design floor loading appropriately). VRFB containers or modules can often be placed at ground level outdoors; they need to be relatively close to the point of electrical interconnection to minimize losses (though

distance is not a huge issue at low frequencies). They also need a nearby supply of auxiliary power (to run pumps when the system is down or starting up, unless there's a small backup battery or grid connection for that). Integration into a building or "current site" might require reinforcement of floors (if indoors) and ensuring the room can handle acid (coatings that resist corrosion, good ventilation). Many deployments choose outdoor siting in containers to simplify this.

From the **electrical integration** perspective, VRFBs connect via a power conversion system (PCS) that is similar to an inverter for any battery or solar array. This PCS can be connected to the facility's low or medium voltage network. For medium-sized installations, a step-up transformer might be used to go to 10 kV or so for a factory feeder, or if smaller, it might tie in at 400 V three-phase. Standard grid interconnection protection (relays, isolation) applies. VRFBs can seamlessly integrate with other onsite generation – for example, pairing with solar PV. They can absorb fluctuations from PV and release power as needed, controlled by an energy management system.

Training for staff is a part of integration – ensuring that site operators know how the battery interacts with the rest of the system. If the VRFB is providing backup power, the facility's existing UPS or backup scheme might be reconfigured to prioritize the VRFB discharge when mains fails. If integrated into a grid substation, coordination with grid control systems (SCADA) would be necessary – VRFB can receive setpoints from the grid operator to charge or discharge as part of a demand-response scheme, for example.

Modularity and flexibility: VRFBs can be integrated in a modular fashion. A company could start with one unit and later integrate a second unit in parallel as needs grow. This incremental approach is a nice feature – similar to adding extra server racks in a data center as needed. The new unit would just connect alongside the old one, controlled either independently or by a common controller, scaling up the capacity.

In summary, integrating VRFBs is **comparatively easy** for anyone used to working with industrial equipment. In the Project's region, where many facilities are modernizing their energy systems, VRFBs can be slotted in like any other piece of electrical equipment. It requires multidisciplinary coordination (electrical engineers for grid tie-in, chemical safety for electrolyte, civil for siting), but nothing out of the ordinary for a medium-scale project. Ensuring the local workforce is aware and trained (via workshops or vendor training sessions) will make integration even smoother. It's recommended that early adopters share their integration experience through regional forums or energy conferences (perhaps under EU project dissemination) so that best practices for integrating VRFBs in local context (climate, grid codes, etc.) are spread. This will help demystify the process and encourage more sites to follow suit, confident that VRFBs can be **plugged into existing energy systems with relative ease**.

Lifespan and Cycle Life

VRFBs are renowned for their **long operational life**. A well-designed VRFB system can last **20 years or more** in service with proper maintenance ⁶². This longevity is primarily due to the chemistry: all reactions are in solution, and the electrodes and electrolyte don't undergo the kind of structural breakdown seen in solid batteries. Manufacturers and field data indicate that VRFB stacks can achieve **15,000 to 20,000 full charge-discharge cycles** (at 100% depth of discharge) without significant degradation ⁶². To put this in perspective, cycling once per day, 15,000 cycles corresponds to about 41 years! Most systems have not been around that long to prove it in real-time, but accelerated tests and historical data (some large VRFBs have been running for ~10 years) support these high cycle numbers. In practice, other components (pumps, membranes) might set the practical life limit before the chemistry does. However, even if a membrane needed replacement at, say, year 12, that is a refurbishing action and the system continues; the electrolyte remains as potent in year 20 as it was in year 1.

Performance degradation in VRFBs is very low. Unlike lithium-ion batteries, which gradually lose capacity with each cycle (perhaps 2-4% per year depending on usage), a VRFB's capacity is tied to the amount of vanadium in the tanks, which does not diminish unless physically lost or imbalanced. There can be minor capacity fade over time due to side reactions or electrolyte imbalance, but these are often correctable. For instance, if some vanadium in one tank migrates to the other in a different oxidation state, you might lose some capacity until you re-balance (which can be done by techniques like chemical adjustment or running a re-balancing charge). If hydrogen gas was generated by slight overcharge, that might remove a tiny bit of hydrogen from the electrolyte (affecting acid concentration), which can be recombined later. All this is to say, **VRFBs can maintain near-original capacity over decades**, with one source noting *negligible capacity loss* and excellent stability over tens of thousands of cycles .

The **electrolyte's life** is essentially indefinite. Vanadium doesn't "wear out" – it's an element. As long as it's not contaminated or thrown away, it can be used perpetually. There are VRFB installations where after a decade, the electrolyte was transferred to a new upgraded stack, effectively giving a new life at minimal cost. This is a sharp contrast with most batteries where the active materials degrade and eventually you have to replace the entire battery module. The stack hardware (membranes, electrodes) might eventually need replacement or overhaul, likely on the order of 10-20 years. Membranes might slowly degrade or foul, and electrodes could get clogged with precipitates after many years. But these parts can be replaced to refurbish the system at a cost substantially lower than buying a new battery. Some companies claim that if you factor in a mid-life refurbishment (say at year 10 or 12), the VRFB could easily run for 20-25 years total. **Warranties** in the industry vary, but it's not uncommon to see warranties of 5-10 years on the system, often with performance guarantees that capacity will remain above a certain level (like 90%+ of original) over that period. Given the confidence in longevity, one can expect warranty extensions or maintenance contracts that effectively guarantee performance for 20 years (with

scheduled refurbishments included). In fact, one project example is CellCube's systems, which are marketed with a 20-year design life and thousands of cycles with minimal loss ⁷⁹.

The **life cycles at partial depth** are even higher – e.g., 20,000 full cycles could correspond to 40,000 cycles at 50% depth. This is relevant for applications like frequency regulation where the battery might cycle in shallow swings many times a day; VRFBs can handle that superbly with virtually no wear. Such resilience means VRFBs can do both energy shifting and heavy cycling tasks without trade-off, unlike some chemistries where you either operate in a shallow range to extend life or accept a shorter life.

A subtle aspect of long life is **component warranties** – the power electronics (inverters) might have their own 10-15 year life (with capacitors, etc., that might need replacing). So a truly 20-year VRFB installation might need an inverter swap or refurb at some point, but that's more of a general issue for any electrical equipment. It's a manageable part of life-cycle planning.

Table 5.3 : **Component Lifespans and Maintenance Intervals in Vanadium Redox Flow Batteries (VRFBs)**

Component	Lifespan	Maintenance Action
Membrane	10-12 years	Replace during refurbishment
Electrodes	10-20 years	Clean/Replace as needed
Pumps	10-15 years	Scheduled replacement
Electrolyte	Indefinite	Transfer between systems

Performance Degradation and Guarantees

As noted, performance degradation for VRFBs is minimal. A user could expect that after 5 years of daily cycling, the VRFB still has ~100% of its initial capacity and maybe a tiny drop in efficiency if anything. After 10 years, perhaps a small capacity loss might emerge if there's been some electrolyte imbalance, but likely still >90-95% of original. Many vendors will guarantee something

like “<2% degradation per year” or a total of perhaps 20% over 20 years, but actual field data so far suggests even better outcomes in many cases. For example, some early VRFB installations from the 2010s have reported essentially flat capacity over years – any slight losses were recovered with maintenance. The **round-trip efficiency** might also hold steady; you’re not accumulating internal resistance the way a Li-ion cell does, except if a membrane loses a bit of selectivity or a pump becomes less efficient. Those are serviceable issues.

Because VRFBs are relatively new in widespread commercial use, **bankability** considerations have meant suppliers often include performance guarantees. They might guarantee that after 10 years or X cycles, the system will still deliver Y% of rated energy at Y% efficiency, or they will repair/replace components to make it so. Given the simplicity of meeting those guarantees (since the chemistry is stable), this adds confidence for projects.

Typical warranty could be 5 years full warranty + performance guarantee up to 10 or more, or some have offered throughput-based warranties (like a certain number of MWh of energy throughput without degradation). In comparison, Li-ion warranties often end after, say, 8 years or a certain cycle count, and allow 20% or more degradation.

Table: 5.4 Performance Retention and Degradation Timeline for Vanadium Redox Flow Batteries (VRFBs)"

Time in Service	Expected Capacity Retention	Notes on Degradation and Maintenance	Typical Warranty/Guarantee
0-5 years	~100%	Negligible degradation, minor efficiency loss	5-year full warranty
6-10 years	>90-95%	Minor losses, often correctable	10-year performance guarantee

Time in Service	Expected Capacity Retention	Notes on Degradation and Maintenance	Typical Warranty/Guarantee
11-20 years	>80-90%	Most losses due to serviceable parts	Throughput or extended warranty
20+ years	70-80%+ (with maintenance)	Refurbishment possible, electrolyte reusable	Performance underwriting possible

Spatial and Site Considerations

Footprint and Space Requirements

Deploying a VRFB system requires a consideration of **space and layout**, as the technology has a sizeable physical footprint. A typical VRFB installation consists of storage tanks (often large cylindrical or rectangular tanks for the electrolytes), the stack units (which may be containerized or housed in a building), and auxiliary equipment like pumps and power electronics. The space needed scales with the energy capacity (tank size) and power (number of stacks). As discussed under energy density, VRFBs need more volume per kWh stored than lithium-ion. For example, a

5 MWh VRFB might require a small building or a pad the size of a basketball court to accommodate tanks and racks, whereas 5 MWh of Li-ion could fit in two standard 40-ft containers.



Figure 5.5 A 1 MW / 4 MWh containerized VRFB system installed in Washington (USA)⁶³

VRFB is housed in standard shipping containers (with vanadium electrolyte tanks and cell stacks inside), illustrating a modular layout that can be sited in a parking-like area⁶³.

The image above shows a real-world VRFB project with **ten 20-ft containers** (for 4 MWh) placed on a pad, giving an idea of the footprint⁶³. While this might seem large, it's still manageable in many settings – roughly a few hundred square meters for multi-MWh scale. Many VRFB providers design their systems to be **modular and containerized** specifically to streamline site planning. A client can be told, for instance, that each 1 MWh requires one container (plus perhaps a smaller container for the power conversion system), and they can arrange these on site accordingly.

Geographical considerations: VRFBs don't impose unique geographic constraints like some other storage. There's no need for a hillside or water source (as with pumped hydro), or deep shafts (as with compressed air storage). Any fairly level piece of land that can support the weight can host a VRFB. This flexibility means even areas without natural storage sites can implement

battery storage with VRFBs. However, extremely cold sites would need a heated building to keep electrolyte above freezing, and extremely hot sites need to ensure cooling (shading or building).

Structural and location needs: The weight of the electrolyte is significant – roughly 1.3 kg per liter. A 1 MWh electrolyte (depending on concentration) might be on the order of 50–100 m³ per tank (for each half-cell), which could weigh ~130–260 tons of liquid total. So the foundation should handle that. Usually a concrete slab or reinforced pad is required. If installing indoors, floors must be able to handle these loads or the tanks must be on ground floor. For seismic areas, tanks and racks should be secured to withstand earthquakes (slosh dynamics of electrolyte need to be accounted for in tank design).

Modularity and expansion: Spatial flexibility is a plus – you can start with a certain footprint and leave room for expansion tanks. If later more capacity is needed, additional tanks can be added if space was reserved, and maybe a few more stack units, effectively expanding on the same site. In planning a VRFB site, it might be wise to allocate extra space for potential future capacity increases, especially given how the energy transition could accelerate storage needs. In an industrial park in the Project's region, for example, you might fence off a corner for the energy storage system with room to double capacity later.

Additional site needs: VRFBs don't need fuel delivery, etc., but they do need an electrical connection (cables to the grid or facility), a water source for mixing electrolyte initially (once filled, they do not consume water, though a small water top-up might be needed if evaporation occurs in vented systems), and drainage for any cleanup water in case of spill (which should go to a contained sump, not regular sewer). Many installations have a small control room or control panel area – either integrated in a container or separate – which just needs a bit of sheltered space.

Table 5.4: Key Site and Environmental Requirements for VRFB Installation

Factor	Requirement/Consideration	Risk if Not Addressed	Mitigation/Design Solution
Temperature	Operate best at 10–40 °C	Below 10 °C: electrolyte can freeze or crystallize; Above 40 °C: precipitation, side reactions ⁸⁰	Insulation, heating for cold; cooling, shading for heat; advanced additives for higher stability ⁸⁰
Weatherproofing	Outdoor units must be sealed (NEMA 4/IP65)	Water/dust ingress, corrosion ⁸¹	Weatherproof containers, air filters, sump pumps ⁸¹
Grid Resilience	Black start/island mode capability	Loss of power to pumps/inverters ⁸¹	System design to support microgrid operation ⁸¹
Flood/Water Risk	Elevate or seal equipment in flood-prone areas	Water damage, electrolyte leak ⁸²	Raised pads, sealed basins, sump pumps ⁸²
Expansion/Flexibility	Modular containers can be relocated	Stranded investment if site changes ⁸²	Reserve space, use containerized systems ⁸²
Maintenance Access	Space for crane/hoist, mixing area if needed	Difficult maintenance, refilling ⁸³	Plan for clearance, road access, mixing area ⁸³
Environmental Resilience	Non-flammable, robust to wildfire/flood ⁸	Fire/flood damage ⁸³	Use fire-resistant materials, above flood line ⁸³
Grid Impact	Can support voltage, reduce peak loads	Grid instability ⁸³	Strategic placement at weak grid nodes ⁸³

5.5 Practical Case Studies

5.1.4 Successful Grid-Level Deployments

Sumitomo Electric VRFB System – Hokkaido, Japan One of the world's largest operational VRFB installations, the 60 MWh system was deployed in Hokkaido to stabilize the integration of wind power into the regional grid. The system provides peak shaving, frequency regulation, and voltage control. With a planned lifespan exceeding 20 years and 13,000+ cycles, the project demonstrates the reliability and scalability of VRFBs in renewable-rich grids. Operated by Sumitomo Electric, it also serves as a commercial testbed for recycling and electrolyte recovery strategies.

Puertollano Hybrid Solar-VRFB Plant – Spain This 3 MW / 9 MWh hybrid installation integrates a vanadium flow battery with a photovoltaic solar plant in Castilla-La Mancha. Developed by a Spanish-German consortium, it provides smoothing and time-shifting of solar generation for improved dispatchability. The plant features a modular containerized design, enabling simplified maintenance and scalability. Its success confirmed the technology's ability to maintain constant output during cloud variability, offering a robust solution for grid resilience in high-solar irradiance regions.

CellCube VRFB System – Fronius Research Campus, Austria A commercial pilot deployment of the CellCube VRFB system at the Fronius Innovation Center supports local PV energy storage and microgrid optimization. Rated at 100 kW / 400 kWh, the system provides load balancing and backup services. It serves as a demonstration platform for R&D on smart grid control and modular flow battery expansion. The system's performance is continuously monitored under various load conditions to assess long-term efficiency and degradation-free operation.

5.1.5 Case Studies in Remote Applications

Bushlight Indigenous Microgrids – Northern Territory, Australia Pilot microgrid deployments utilizing 30–80 kWh VRFB systems have been implemented in off-grid Indigenous communities. These systems store excess solar power and provide reliable nighttime electricity, replacing diesel generators. Designed for harsh environments and low maintenance, the batteries have endured ambient temperatures above 45°C without significant performance loss. Community feedback emphasizes enhanced reliability, safety, and autonomy.

Pacific Islands Resilience Projects – Tonga and Fiji VRFBs are being tested as part of island energy transition efforts to replace imported fossil fuels. Small-scale (50–200 kWh) deployments have been coupled with solar generation to provide energy autonomy for schools, clinics, and

water desalination systems. Results show improved load shifting and reduced curtailment of solar PV output, with high resilience against cyclone-induced disruptions.

These projects illustrate the adaptability of VRFBs across climates, scales, and use cases—offering stable performance, low degradation, and strong environmental credentials.

5.6 Typical Use Cases of VRFB Energy storage

VRFB technology is primarily used for **large-scale stationary energy storage**, where its traits of long duration and longevity outweigh its lower energy density. Current applications span **renewable energy integration, grid balancing, and microgrid support**. For instance, VRFBs are deployed to **store excess solar or wind energy** when production exceeds demand and release it during evening or low-generation periods (“solar shifting” and firming of renewables) ⁵⁸. A recent example is a 1.1 MW/5.5 MWh VRFB installed at a solar farm in Mallorca, Spain, by Enel Green Power, which is among the largest flow batteries tied to PV in Europe ⁶⁷. The utility (Endesa) touted it as a “high-performance solution with no negative impact on the environment” for delivering solar power after sunset . VRFBs are also used for **grid ancillary services** such as frequency regulation, voltage support, and peak shaving. A utility pilot in Georgia, USA is testing a VRFB’s ability to perform “a wide range of applications such as energy cost control, peak shaving, avoiding curtailment and renewable integration,” cycling multiple times daily to support the local grid. In industrial microgrids or remote sites, VRFBs can provide reliable backup power and reduce reliance on diesel generators. For example, high-altitude facilities (like a military base in Wyoming) have adopted VRFB units to power critical infrastructure with 6–8 hours of storage, taking advantage of the battery’s stability and zero degradation in harsh conditions ⁷⁹.



Figure 5.6: The largest vanadium redox flow battery (VRFB) at a solar farm in Europe has been switched on by Enel Green Power in Mallorca, Spain⁶⁷

Globally, VRFB deployments are growing in scale. The world's largest VRFB project to date is a 100 MW/400 MWh system in Dalian, China (with plans to expand to 200 MW/800 MWh), aimed at providing long-duration grid support for renewable integration. In Europe, demonstration projects have proven VRFB viability: for instance, the "Energy Superhub" in Oxford, UK combines a 5 MWh VRFB with lithium-ion batteries to deliver both rapid response and long-duration storage in a hybrid system⁶⁷. Within the Project's region, a notable milestone is the deployment of a 1.5 MWh Invinity VRFB in Hungary (Öskü) in early 2024 as part of an EU-funded project⁸⁴. This system, installed alongside a solar plant, provides daily grid-balancing and peak shifting services, and demonstrates the technology's readiness to help Hungary reach its renewable energy targets⁸⁴.

5.7 Conclusions and recommendations

For local communities, a VRFB project can be more than just an infrastructure installation; it can be an opportunity for education and engagement with clean energy. Municipalities could incorporate on-site informational displays or collaborate with schools to use the battery as a STEM learning example (since the operating principle of a flow battery is quite visual and educational).

Community ownership models could even be explored: for instance, a cooperative could invest in a VRFB to store community solar power, giving residents a stake (and possibly a dividend via energy savings) in the project. This level of engagement tends to heighten public support and pride.

In terms of social license to operate, VRFBs are likely to face few barriers. By proactively communicating and ensuring transparent operation (monitoring data could even be shared in real-time on a public website, showing how the battery helps balance the local grid), operators can maintain trust. Should any incident occur (like a minor leak, which is unlikely and containable), prompt and honest communication with the community will be key. But given the track record of VRFB safety, significant incidents are improbable. In fact, communities may appreciate that a technology with virtually zero risk of fire or toxic smoke is chosen for energy storage, especially after seeing reports of lithium battery fires elsewhere ⁵¹. This comparative safety can be a talking point in favor of VRFBs when securing local approvals.

Recommendations specific to the Project's region include:

- Encourage government and utility stakeholders to consider VRFBs in medium-sized storage procurements, highlighting that local industries (like Austria's CellCube) are already part of this sector, thus supporting regional high-tech jobs.
- Integrate VRFB pilot projects with regional renewable energy initiatives (for example, adding a flow battery to a new solar park funded by EU structural funds) to demonstrate the synergy and gather performance data in local climate conditions.
- Develop training programs at technical colleges focusing on flow battery maintenance and safety, ensuring the skill base is there for widespread deployment.
- Foster public-private partnerships where city authorities, local companies, and perhaps European programs collectively invest in demonstration flow battery systems in city districts or industrial parks. Such collaborative models can spread both the cost and the know-how, leading to broader acceptance.

In conclusion, the social impact of VRFB storage technology in the Project's region is large **positive**. With careful implementation, communities will experience the benefits of cleaner, more reliable energy with minimal drawbacks. VRFB projects can become local showcases for innovation, catalyze green job creation, and strengthen regional energy independence. By proactively addressing any community concerns and tying projects to local development goals, stakeholders can ensure strong public support and successful, socially sustainable outcomes for VRFB deployment in the years ahead

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6 Ultracapacitors

6.1 Overview of Ultracapacitors/Supercapacitors

Ultracapacitors, also known as supercapacitors, are advanced energy storage devices that offer unique benefits compared to traditional batteries. The term "ultracapacitor" was initially used as a brand name by Maxwell Technologies, but it has become a synonym for supercapacitors in general. 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 reliability⁸⁵.

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.

6.1.1 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. Figure 1 below is the schematic illustration of an ultracapacitor.

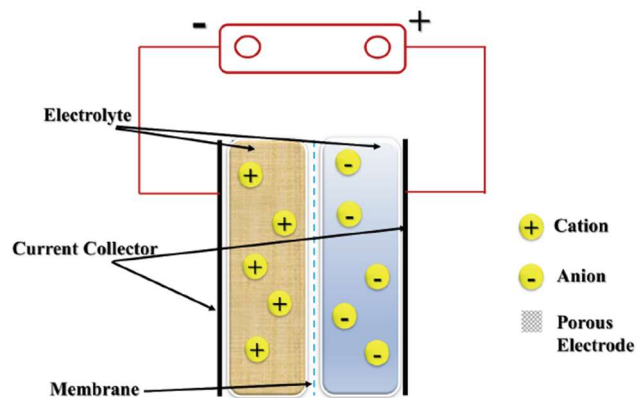


Figure 6.1 Schematic illustration of a Supercapacitor⁸⁶

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 electrodes⁸⁷.

The energy stored in an ultracapacitor can be calculated using the following formula⁸⁸:

$$E = \frac{1}{2} * CV^2$$

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.⁸⁵

Unlike ordinary capacitors, ultracapacitors do not use the conventional solid dielectric, but rather, they use electrostatic double-layer capacitance and electrochemical pseudocapacitance^{89,90} both of which contribute to the total capacitance of the capacitor.

6.1.2 Classification of Ultracapacitors

There are three types of ultracapacitors based on the charge storing mechanism, namely electrochemical double-layer capacitors, pseudocapacitors, and hybrid electrochemical capacitors as shown in the figure below.

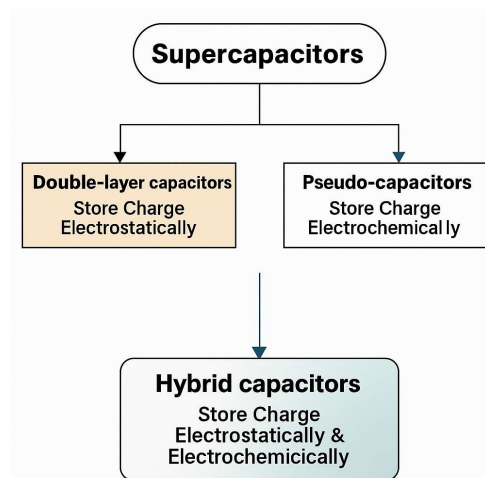


Figure 6.2 Classification of supercapacitors

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 electrolyte⁹¹. 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 ⁹² 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 ⁹³.

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 more⁹⁴.

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 electrodes⁹³. 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 cycles⁹². 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 metal oxide and conducting polymers⁹⁵. The figure below is the representation of the transition from EDLC to Battery.

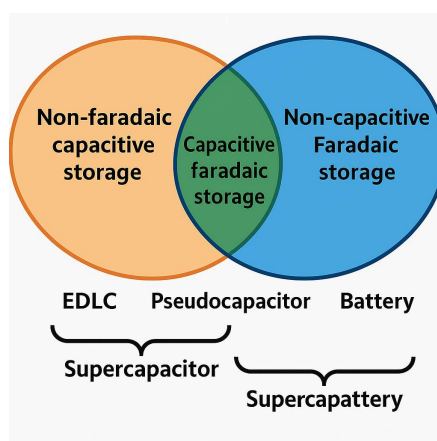


Figure 6.3 Schematic correlation between an EDL capacitor, pseudocapacitor, battery, and supercapattery according to charge storage processes- was generated using artificial intelligence (AI) tools and subsequently verified for accuracy and validity by the authors.

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 PCs⁹². 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 space⁹⁶. They are also used in power plant frequency regulation⁹⁷.

An interesting addition in the domain of HECs is the concept of Supercapattery (Figure .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 batteries⁹⁸. 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)⁹⁹, 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 supply¹⁰⁰.

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 storage¹⁰¹. The table below shows the comparison of attributes for three types of supercapacitors.

Table 6.1 Comparison of attributes for three types of supercapacitors⁹³

Type	Charge Mechanism	Advantages
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
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

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, lower discharge rate

6.1.3 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 prototypes¹⁰².

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 application¹⁰³.

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 management¹⁰⁴.

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 acceleration¹⁰⁵.

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 Park⁹².

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.

6.1.4 Technological barriers, regulatory framework and scalability

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.

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 batteries^{92,94}.

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.

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 costs⁹³.

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 technologies¹⁰⁶.

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^{107,108}.

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 managed¹⁰⁹.

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.

6.1.5 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 equipment¹¹⁰. 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*⁹² 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.*

6.1.6 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 momentum¹¹¹. 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 2030¹¹². 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 ultracapacitors⁹².

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) technology¹¹³, 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.

6.2 Financial Analysis

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:

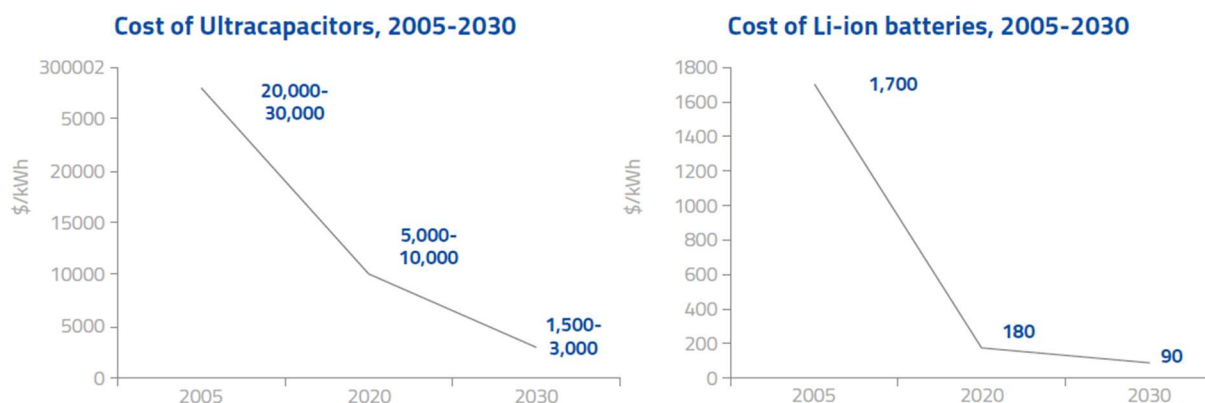


Figure 6.4 Cost forecast of ultracapacitors and Li-ion batteries⁹²

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 ⁹².
- The report ¹¹⁴ 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.

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 services⁹².
- **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 lifespan⁹².
- **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 requirements⁹².

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 al¹¹⁵, 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)⁹² 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)¹¹². 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.

Table 6.2. EDLC cost and performance estimates for 1 MW, 45 seconds of storage (2025 estimates)⁹³

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	19200	Baseline storage block costs (\$/kWh)
Balance of plant costs	7600	Baseline balance of plant costs (\$/kWh)
Controls and communication costs	33.04	Controls and communication costs (\$/kWh)
Power equipment costs	142.5	Power equipment costs (\$/kW)
System integration costs	7824	System integration costs (\$/kWh)
Project development costs	11058	Project development costs (\$/kWh)
Engineering, procurement, and construction (EPC) costs	8731	EPC costs (\$/kWh)
Grid integration costs	27.73	Grid integration costs (\$/kWh)
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)

Cost Trends

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 applications⁹².

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 costly⁸⁵.

6.3 Environmental Impact

Ultracapacitors, also known as supercapacitors, are energy storage devices characterized by high power density, rapid charge/discharge cycles, and long lifespan. They are increasingly used in transportation, renewable energy systems, grid stability, and consumer electronics. As their adoption grows, understanding their environmental impacts—ranging from raw material extraction to end-of-life disposal—is crucial. This study provides a detailed assessment based on current scientific literature and industry data.

Types and Construction of Ultracapacitors

Ultracapacitors are generally classified into three main types:

1. *Electrochemical Double-Layer Capacitors (EDLCs):*

- **Principle:** EDLCs store energy by accumulating ions at the interface between an electrode and an electrolyte, forming an electrical double layer. No chemical reactions occur during charge and discharge, which allows for very rapid charge/discharge rates and long cycle life.
- **Construction:** Typically consists of two porous electrodes (often made of activated carbon) separated by an electrolyte and an ion-permeable membrane (separator).
- **Electrode Materials:** Activated carbon, carbon nanotubes, graphene.
- **Electrolytes:** Aqueous, organic, ionic liquids.
- **Characteristics:** High power density, long cycle life, relatively lower energy density compared to other types.
- **Limitations:** Lower energy density compared to batteries.

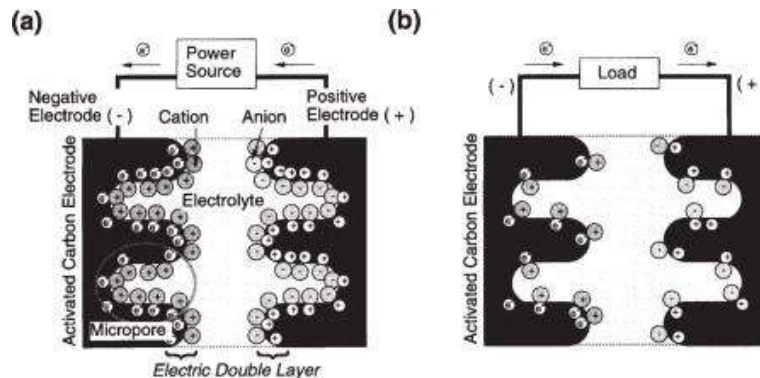


Figure 1. Schematic illustration of electric double layer capacitor: (a) charge state, (b) discharge state. (Soshi Shiraishi et al. 2003)

2. Pseudocapacitors:

- **Principle:** Pseudocapacitors utilize Faradaic (redox) reactions at the electrode surface to enhance charge storage. These reactions contribute to higher capacitance and energy density compared to EDLCs.
- **Construction:** Similar to EDLCs but uses electrode materials that undergo redox reactions.
- **Electrode Materials:** Transition metal oxides (e.g., RuO_2 , MnO_2 , NiO), conducting polymers (e.g., polypyrrole, polyaniline).
- **Electrolytes:** Aqueous, organic.
- **Characteristics:** Higher energy density than EDLCs, but lower power density and cycle life.
- **Limitations:** Lower power density and shorter cycle life due to Faradaic reactions.

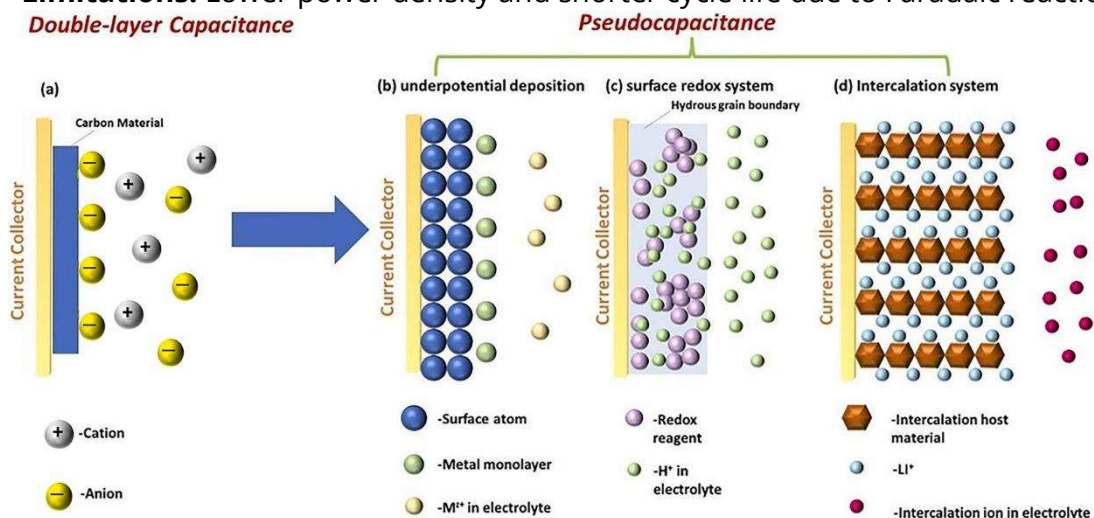


Figure 2. (a) Schematic diagram of electric double layer capacitors (EDLCs). Schematic diagram of pseudocapacitors: (b) underpotential deposition (c) surface redox reaction (d) intercalation system. (Zihao Zhu et al. 2025)

3. Hybrid Capacitors:

- **Principle:** Hybrid capacitors combine the characteristics of EDLCs and pseudocapacitors (or batteries) to achieve both high energy and power density.
- **Construction:** Integrates different electrode materials or configurations to optimize performance.
- **Electrode Materials:** Combination of activated carbon with metal oxides or conducting polymers; lithium-ion capacitor (LIC) which combines an EDLC-type positive electrode with a battery-type negative electrode.
- **Electrolytes:** Depends on the materials used.
- **Characteristics:** Balances high energy and power density, offering improved overall performance.
- **Limitations:** More complex construction and higher cost.

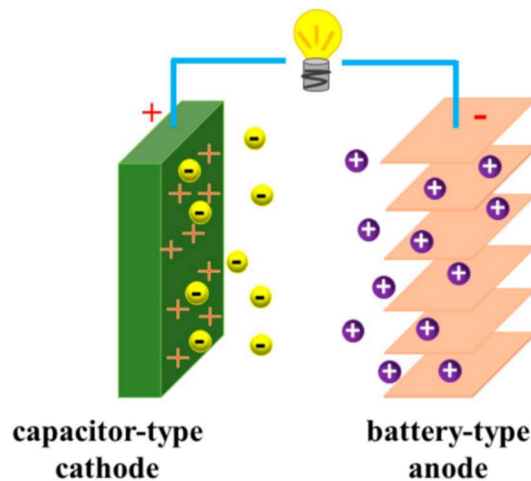


Figure 3. Schematic illustration of the configuration of hybrid capacitors. (Chao Han et al. 2021; Xuan Gao et al. 2023)

Construction of Ultracapacitors

The basic components of an ultracapacitor include:

1. Electrodes:

- Porous materials with high surface area for charge accumulation.
- Materials: Activated carbon (most common for EDLCs), carbon nanotubes, graphene, metal oxides, conducting polymers.
- Configuration: Electrodes are typically coated onto a current collector (e.g., aluminum foil).

In the fabrication of a supercapacitor, electrode materials play a vital role in deciding the charge storage mechanism. For instance, carbon-based materials (such as carbon nanotubes (CNTs), graphene, and AC) are used for a non-faradaic process, whereas metal oxides, conducting polymers, and non-metal oxides are used for the faradaic process (G. J. Navathe et al. 2022). Besides electrode, the electrolyte is also a crucial element in the

fabrication of supercapacitor because it influences the potential window of the supercapacitor. In general, there are five types of electrolytes that are commonly used: a) aqueous electrolyte, b) organic electrolyte, c) ionic electrolyte, d) redox-active electrolyte, and e) solid-state/quasi solid-state electrolyte depending on the desired electrochemical characteristics. As an example, an organic electrolyte is used to widen the potential window of the supercapacitor to open up space for higher energy storage. The chart in Figure 4 shows the classification of the supercapacitor and its electrode material for each type (M. Pershaanaa et al. 2022).

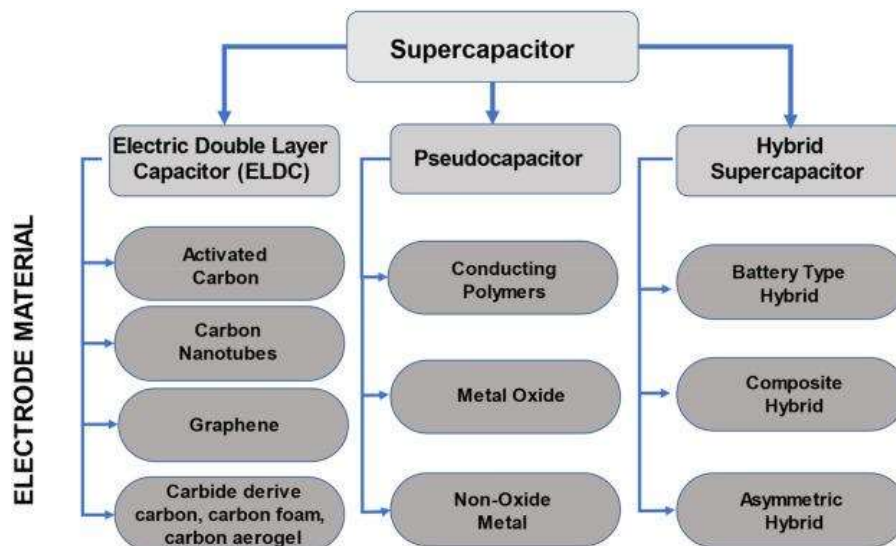


Figure 4. Classification of supercapacitor and its electrode material. (Simon et al. 2008)

2. Electrolyte:

- Provides ionic conductivity between the electrodes.
- Types:
 - Aqueous Electrolytes: High ionic conductivity but limited voltage window (e.g., KOH, H₂SO₄).
 - Organic Electrolytes: Wider voltage window but lower ionic conductivity (e.g., acetonitrile-based salts).
 - Ionic Liquids: Wide electrochemical window and good thermal stability.

3. Separator:

- An ion-permeable membrane that physically separates the electrodes to prevent short circuits while allowing ion transport.
- Materials: Porous polymers (e.g., polypropylene, polyethylene).

4. Current Collectors:

- Provide electrical contact to the electrodes and facilitate charge transport to the external circuit.
- Materials: Aluminum, nickel, titanium.

5. Packaging:

- Encloses and protects the ultracapacitor components.
- Types: Cylindrical, prismatic, pouch cells.

Key Parameters and Performance Metrics

- **Capacitance (F):** Measure of the charge stored per unit voltage.
- **Energy Density (Wh/kg or Wh/L):** Amount of energy stored per unit mass or volume.
- **Power Density (W/kg or W/L):** Rate at which energy can be delivered per unit mass or volume.
- **Equivalent Series Resistance (ESR):** Represents the internal resistance of the capacitor.
- **Cycle Life:** Number of charge-discharge cycles the capacitor can withstand before significant performance degradation.
- **Voltage Window:** Range of operating voltages.
- **Temperature Range:** Operating temperature limits.

Key Characteristics

1. Energy Density:

- Ultracapacitors have lower energy density (5-30 Wh/kg) compared to batteries (100-265 Wh/kg for Li-ion).
- Energy density is influenced by the electrode material and electrolyte.

2. Power Density:

- Ultracapacitors offer high power density (up to 10,000 W/kg), enabling rapid charge/discharge cycles.
- This makes them suitable for applications requiring bursts of power, such as regenerative braking in electric vehicles.

3. Cycle Life:

- Ultracapacitors have a long cycle life (100,000 to 1,000,000 cycles) due to their non-Faradaic charge storage mechanism.
- This is significantly higher than batteries, which typically last 500-2000 cycles.

4. Efficiency:

- Ultracapacitors have high charge/discharge efficiency (90-95%) due to low internal resistance.

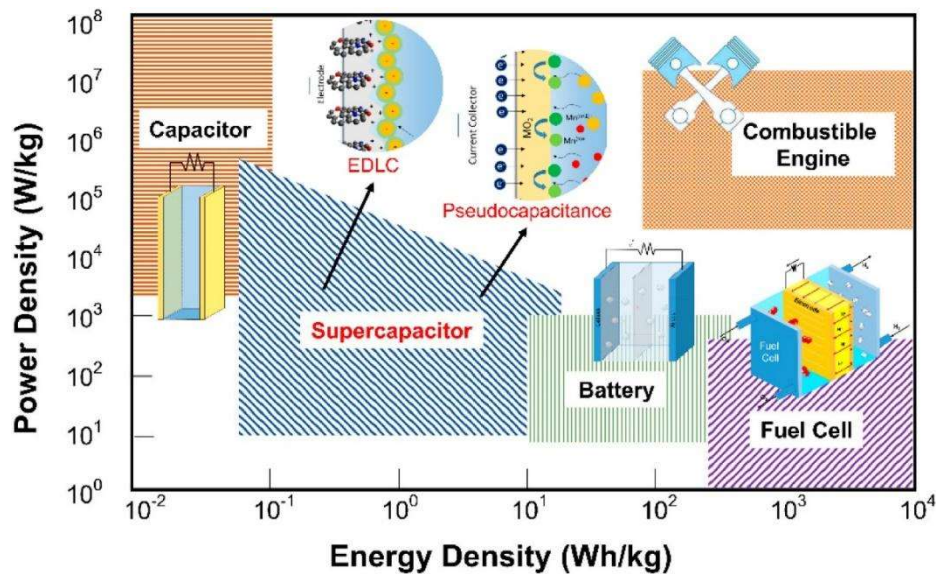


Figure 5. Ragone plot of energy storage device: Power density versus Energy density.

(M. Pershaanaa et al. 2022)

Applications

(Convay et al. 1999; Zhang et al. 2009; Maxwell Technologies; Skeleton Technologies; Panasonic)

1. Electric Vehicles (EVs):

- Ultracapacitors are used for regenerative braking and quick acceleration in EVs.
- Example: Maxwell Technologies' ultracapacitors in hybrid buses.

2. Renewable Energy:

- Ultracapacitors provide short-term energy storage for solar and wind power systems.
- Example: Skeleton Technologies' ultracapacitors in wind turbine pitch control.

3. Consumer Electronics:

- Ultracapacitors are used in smartphones, cameras, and laptops for quick charging and power backup.
- Example: Panasonic's hybrid capacitors in portable devices.

4. Industrial Equipment:

- Ultracapacitors are used in cranes, forklifts, and elevators for peak power support.
- Example: Ioxus ultracapacitors in material handling equipment.

6.3.1 Material Sourcing and Lifecycle Assessment

Key Raw Materials and Their Extraction

Ultracapacitors (supercapacitors) rely on several key raw materials for their construction, including electrode materials, electrolytes, separators, and current collectors. The extraction and processing of these materials have significant environmental and economic implications. Below is a detailed overview of the raw materials used in ultracapacitors, their extraction processes, and the associated challenges (Ehsanul Kabir et al. 2018; Bin Lu et al. 2018).

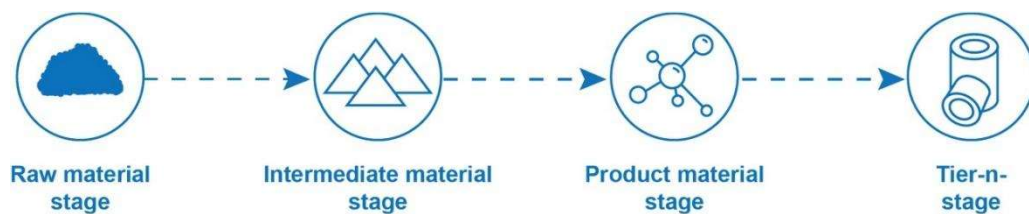


Figure 6. Overview on value chain stages for lithium-ion batteries from the raw material perspective. (Lucas Weimer et al. 2019)

1. **Electrode Materials:** (Li Li Zhang et al. 2009)

- **Activated Carbon:**
 - Source: Derived from organic materials such as coconut shells, wood, or coal.
 - Extraction Process: The raw material is carbonized at high temperatures (600-900°C) in an inert atmosphere, followed by activation using steam or chemicals (e.g., KOH) to create a porous structure.
 - Environmental Impact: The process is energy-intensive but generally considered sustainable if sourced from renewable materials like coconut shells.
- **Graphene:**
 - Source: Extracted from graphite, which is mined from natural deposits.
 - Extraction Process: Graphene can be produced via mechanical exfoliation, chemical vapor deposition (CVD), or chemical reduction of graphene oxide.
 - Environmental Impact: Graphite mining can lead to habitat destruction and water pollution. Graphene production via CVD is energy-intensive and requires high-purity gases.
- **Carbon Nanotubes (CNTs):**
 - Source: Synthesized from carbon-rich precursors such as methane or ethylene.

- Extraction Process: CNTs are produced via arc discharge, laser ablation, or CVD.
- Environmental Impact: The synthesis of CNTs involves high energy consumption and the use of toxic gases.
- Metal Oxides (e.g., RuO_2 , MnO_2):
 - Source: Mined from natural ores (e.g., ruthenium, manganese).
 - Extraction Process: Metal oxides are typically obtained through mining, followed by chemical processing to produce the desired oxide.
 - Environmental Impact: Mining of rare metals like ruthenium can lead to environmental degradation and resource depletion.

Raw Material Extraction

Material	Environmental Concerns	Impact Summary
Activated carbon (carbon)	Land use, deforestation, energy consumption during production	Significant if sourced unsustainably; renewable sources preferable
Graphene and Carbon Nanotubes	Intensive energy use, nanotoxicity risks	High energy consumption during synthesis; nanomaterials may pose health hazards
Electrolyte chemicals	Toxicity, emissions during synthesis	Organic solvents toxic and volatile; ionic liquids can be persistent pollutants
Metal oxides (e.g., MnO_2 , RuO_2)	Mining impacts, energy and chemical use	Potential ecological harm from mining, high energy during manufacturing

2. **Electrolytes:**(Simon et al. 2008)

- Aqueous Electrolytes (e.g., KOH , H_2SO_4):
 - Source: Produced from chemical synthesis using raw materials like potassium hydroxide and sulfuric acid.
 - Extraction Process: These electrolytes are synthesized through chemical reactions in industrial plants.
 - Environmental Impact: The production of strong acids and bases can result in hazardous waste and air pollution.
- Organic Electrolytes (e.g., acetonitrile, propylene carbonate):
 - Source: Derived from petrochemicals.
 - Extraction Process: Organic solvents are synthesized from crude oil through fractional distillation and chemical processing.
 - Environmental Impact: The petrochemical industry is associated with greenhouse gas emissions and oil spills.
- Ionic Liquids:
 - Source: Synthesized from organic salts.
 - Extraction Process: Ionic liquids are produced through chemical reactions between organic cations and anions.

- Environmental Impact: While ionic liquids are considered "green" solvents, their synthesis can involve toxic chemicals.

3. Separators:

- Polypropylene (PP) and Polyethylene (PE):
 - Source: Derived from petrochemicals.
 - Extraction Process: Polymers are synthesized from ethylene or propylene monomers, which are obtained from crude oil refining.
 - Environmental Impact: The production of polymers is energy-intensive and contributes to plastic waste.
- Cellulose-Based Separators:
 - Source: Derived from plant fibers (e.g., wood pulp).
 - Extraction Process: Cellulose is extracted from plant material through chemical pulping and bleaching.
 - Environmental Impact: Cellulose production can lead to deforestation and water pollution from chemical pulping.

4. Current Collectors:

- Aluminum and Copper Foils:
 - Source: Mined from bauxite (aluminum) and copper ores.
 - Extraction Process: Aluminum is extracted via the Bayer process and electrolysis, while copper is extracted through smelting and refining.
 - Environmental Impact: Mining and processing of metals can lead to habitat destruction, water pollution, and high energy consumption.

	 Raw material stage	 Intermediate material stage	 Product material stage	 Tier-n-stage	 Product stage
Nickel	Sulphide	Nickel metal and nickel salts (incl. sulphate and hydroxide)	e.g. NMC	e.g. coated current collector with NMC	Lithium-ion battery cell
	Laterite				
Lithium	Salt brines	Lithium carbonate, -hydroxide (battery grade)	e.g. NMC	e.g. coated current collector with NMC	Lithium-ion battery cell
	Mineral (e.g. spodumene, petalite)				
Graphite	Natural flake graphite	Spherical graphite	Coated spherical graphite	Coated current collector with coated spherical graphite	Lithium-ion battery cell

Figure 7. Newly defined value chain classification for battery raw materials exemplified for nickel and lithium (Lucas Weimer et al.2019)

Among the 5 stages of the LIB life cycle, the consumption stage is considered to be the only process that stores materials, so stocks in production or recycling factories could be neglected; the flow from raw materials to the final product was regarded as a continuous process. A static approach was applied to assess the material flows in the abovementioned stages (Fig. 3a). However, for the consumption process, products often stay in service for several years, and a few products would be considered stock after ending their life, so it is difficult to describe the amount of product entering the next stage. Hence, a dynamic top-down approach was used to describe waste entering into the waste management route (Fig. 3b) (Pandolfo et al. 2006).

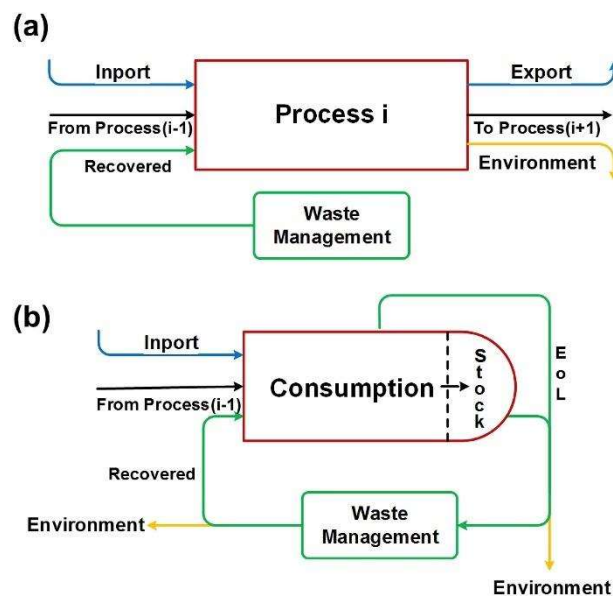


Figure 8. Material flow model of a unit as a static process (a) or a consumption process (b) with in-use stock. (Jiali Song et al. 2019)

Environmental and Economic Challenges

1. Resource Depletion:

- The extraction of rare materials like ruthenium and graphite can lead to resource depletion and geopolitical tensions over mineral reserves.

2. Energy Consumption:

- The production of graphene, CNTs, and metal oxides is energy-intensive, contributing to greenhouse gas emissions.

3. Pollution:

- Mining and chemical processing of raw materials can result in air and water pollution, as well as hazardous waste generation.

4. Sustainability:

- The reliance on petrochemicals for electrolytes and separators raises concerns about the long-term sustainability of ultracapacitor production. (Winter et al. 2004)

Manufacturing and Assembly

Impact Area	Details	Environmental Concerns
Energy consumption	High during electrode synthesis, electrolyte production	Carbon footprint, resource depletion
Waste generation	Chemical waste from electrolyte production, electrode fabrication	Toxic waste, contamination risk
Process emissions	Volatile organic compounds (VOCs) from solvents	Air quality concerns

Lifecycle Assessment

Conducting a Life Cycle Assessment (LCA) for large-scale supercapacitor systems requires a comprehensive, systems-level approach to accurately capture their environmental footprint. Beyond the standard cradle-to-grave analysis, these assessments must emphasize both material and energy intensity throughout each lifecycle stage. Within the production phase, evaluating the sourcing and processing of materials is critical due to the varied impacts of extraction and synthesis methods. A regional or site-specific electricity grid mix during both the manufacturing and operational phases can significantly affect greenhouse gas emissions, and should be incorporated with detail. It's also key to consider degradation factors and the effects of realistic operating conditions to create an effective result. At the end of its functional life, careful attention should be paid to the transportation logistics, processing, and waste processing technologies. Using both of those practices will lead to great results and improvements of the technology. Ultimately, a detailed and systematic LCA not only offers crucial environmental performance insights, but also improves design with sustainable practices across the entire value chain of supercapacitors, promoting large-scale deployment for a more sustainable energy future.

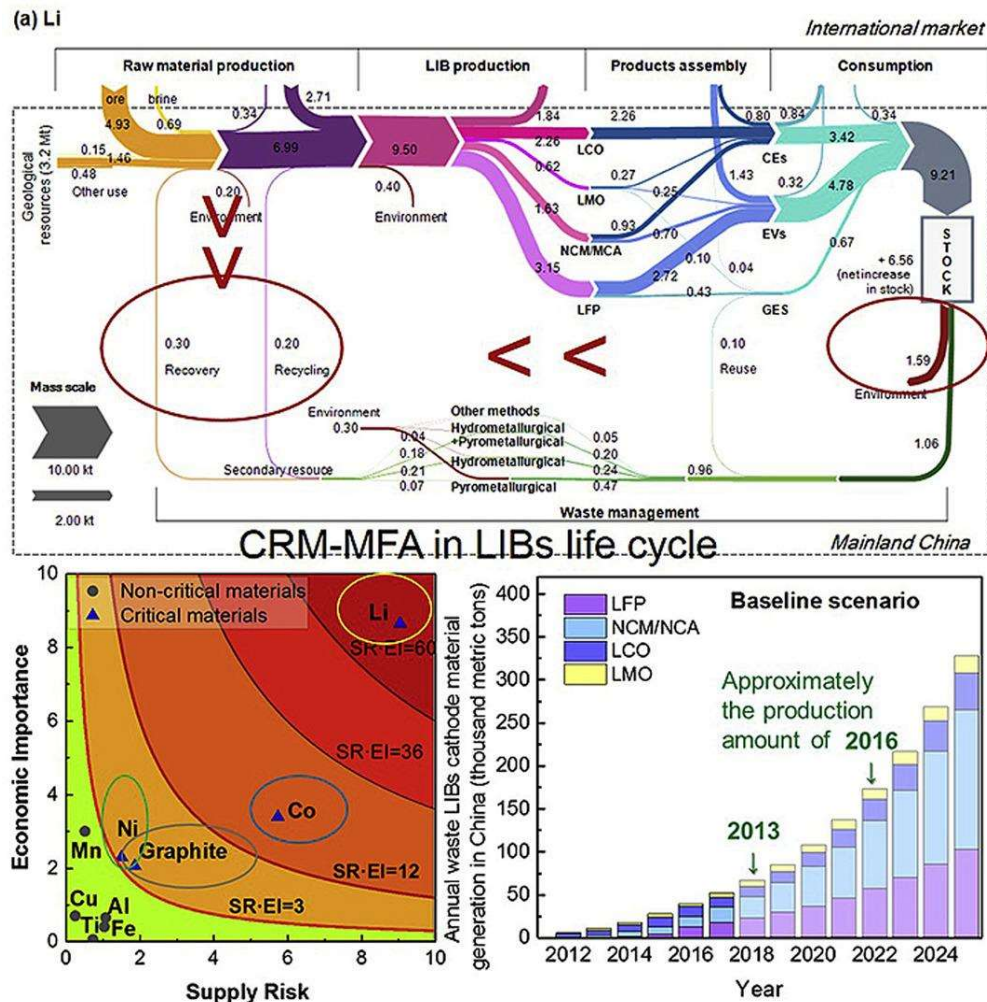


Figure 9: Material flow analysis (MFA) for critical raw material (CRM) in lithium - ion batteries (LIB) life cycle. (Jiali Song et al.,2019)

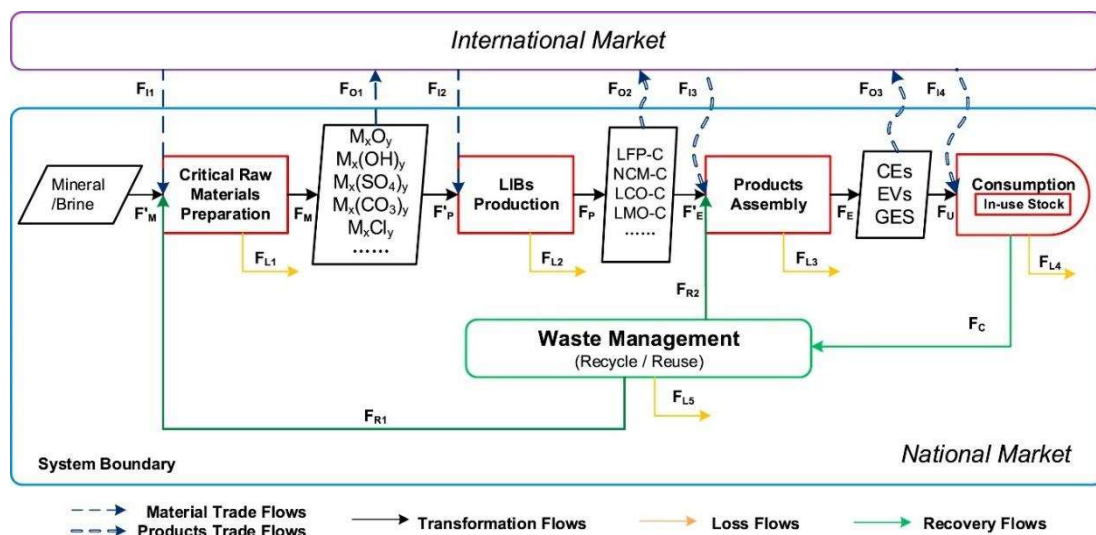


Fig. 10. Lithium-ion battery life cycle and system boundaries. (Jiali Song et al., 2019)

Function and functional units

Supercapacitors (ultracapacitors) are produced using various technologies, each with distinct materials, manufacturing processes, and environmental impacts. This section compares the most common technologies used in supercapacitor production, focusing on their material composition, manufacturing processes, performance characteristics, and environmental impacts (Frackowiak et al. 2001; Yanwu et al. 2011; Pandolfo et al. 2006 Simon et al. 2008; Burke et al. 2000; Li Li Zhang et al. 2009; Rydh et al. 2005; Rahman et al. 2020).

1. Electric Double-Layer Capacitors (EDLCs)

Material Composition

- Electrodes: Activated carbon, carbon nanotubes (CNTs), graphene.
- Electrolyte: Aqueous (e.g., KOH, H₂SO₄), organic (e.g., acetonitrile, propylene carbonate), or ionic liquids.
- Separator: Polypropylene (PP), polyethylene (PE), or cellulose-based materials.
- Current Collectors: Aluminum or copper foil.

Manufacturing Process

- Electrode Preparation: Activated carbon or graphene is mixed with a binder (e.g., PVDF) and coated onto a current collector.
- Assembly: The electrodes are separated by a porous membrane, and the electrolyte is added.
- Encapsulation: The supercapacitor is sealed in a metal or plastic casing.

Performance Characteristics

- Energy Density: 5-10 Wh/kg (lower than batteries but higher than traditional capacitors).
- Power Density: Up to 10,000 W/kg (extremely high, suitable for rapid charge/discharge).
- Cycle Life: 100,000 to 1,000,000 cycles (very long due to non-Faradaic charge storage).
- Efficiency: 90-95% (high due to low internal resistance).

Environmental Impact

- Raw Materials: Activated carbon is relatively sustainable, but graphene and CNTs are energy-intensive to produce.

- Electrolytes: Organic solvents are derived from petrochemicals, contributing to greenhouse gas emissions.
- End-of-Life: Aluminum and copper are recyclable, but organic electrolytes may pose disposal challenges.

2. Pseudocapacitors

(Conway 1999; Augustin et al. 2013; Wang et al. 2012; Shohan et al. 2025; Simon et al. 2008; Zheng et al. 1995; Zhe Wei et al. 2025)

Material Composition

- Electrodes: Transition metal oxides (e.g., RuO_2 , MnO_2) or conductive polymers (e.g., polyaniline, polypyrrole).
- Electrolyte: Similar to EDLCs (aqueous, organic, or ionic liquids).
- Separator: Polypropylene or polyethylene.
- Current Collectors: Aluminum or copper foil.

Manufacturing Process

- Electrode Preparation: Metal oxides or conductive polymers are deposited onto a current collector.
- Assembly: Similar to EDLCs, with electrodes separated by a membrane and electrolyte added.
- Encapsulation: The supercapacitor is sealed in a casing.

Performance Characteristics

- Energy Density: 10-30 Wh/kg (higher than EDLCs due to Faradaic reactions).
- Power Density: 1,000-5,000 W/kg (lower than EDLCs due to slower redox reactions).
- Cycle Life: 10,000-100,000 cycles (shorter than EDLCs due to Faradaic degradation).
- Efficiency: 85-90% (slightly lower than EDLCs due to redox reactions).

Environmental Impact

- Raw Materials: Metal oxides like ruthenium are rare and environmentally costly to extract.
- Electrolytes: Similar to EDLCs, with organic solvents contributing to emissions.
- End-of-Life: Metal oxides can be recycled, but conductive polymers may pose disposal challenges.

3. Hybrid Capacitors

Material Composition

- Electrodes: One electrode is capacitive (e.g., activated carbon), and the other is Faradaic (e.g., Li-ion battery material).
- Electrolyte: Organic or ionic liquids.
- Separator: Polypropylene or polyethylene.
- Current Collectors: Aluminum or copper foil.

Manufacturing Process

- **Electrode Preparation:** The capacitive electrode is made from activated carbon, while the Faradaic electrode is made from a battery-like material (e.g., LiCoO_2).
- **Assembly:** The electrodes are separated by a membrane, and the electrolyte is added.
- **Encapsulation:** The supercapacitor is sealed in a casing.

Performance Characteristics

- **Energy Density:** 20-50 Wh/kg (higher than EDLCs and pseudocapacitors due to hybrid storage).
- **Power Density:** 5,000-10,000 W/kg (high, but slightly lower than EDLCs).
- **Cycle Life:** 50,000-500,000 cycles (longer than pseudocapacitors but shorter than EDLCs).
- **Efficiency:** 90-95% (similar to EDLCs).

Environmental Impact

- **Raw Materials:** The use of battery-like materials (e.g., Li-ion) increases the environmental impact due to mining and processing.
- **Electrolytes:** Organic solvents contribute to emissions, similar to EDLCs and pseudocapacitors.
- **End-of-Life:** The recycling of battery-like materials is complex and energy-intensive.

4. Graphene-Based Supercapacitors

(Yang et al. 2015; Wang et al. 2012; Mateen et al. 2022; Muthu et al. 2025; Mandal et al. 2025; Muzaffar et al. 2019; Zaharaddeen et al. 2016; Cossutta et al. 2020)

Material Composition

- **Electrodes:** Graphene or graphene oxide.
- **Electrolyte:** Aqueous, organic, or ionic liquids.
- **Separator:** Polypropylene or polyethylene.
- **Current Collectors:** Aluminum or copper foil.

Manufacturing Process

- **Electrode Preparation:** Graphene is synthesized via chemical vapor deposition (CVD) or chemical reduction of graphene oxide.
- **Assembly:** Similar to EDLCs, with electrodes separated by a membrane and electrolyte added.
- **Encapsulation:** The supercapacitor is sealed in a casing.

Performance Characteristics

- **Energy Density:** 10-50 Wh/kg (higher than traditional EDLCs due to graphene's high surface area).
- **Power Density:** Up to 10,000 W/kg (similar to EDLCs).

- Cycle Life: 100,000 to 1,000,000 cycles (very long, similar to EDLCs).
- Efficiency: 90-95% (high, similar to EDLCs).

Environmental Impact

- Raw Materials: Graphene production is energy-intensive and relies on graphite mining, which can be environmentally damaging.
- Electrolytes: Similar to other technologies, with organic solvents contributing to emissions.
- End-of-Life: Graphene is not biodegradable, but aluminum and copper can be recycled.

5. Carbon Nanotube (CNT)-Based Supercapacitors

(Wang et al. 2012; Moothi et al. 2012; Jagadeesan et al. 2020; Gorduk et al. 2021; Perez-Gonzales et al. 2020; Dong et al. 2020; Muniraj et al. 2022; Cai et al. 2023; Justin et al. 2024; Lindsay et al. 2013)

Material Composition

- Electrodes: Carbon nanotubes (CNTs).
- Electrolyte: Aqueous, organic, or ionic liquids.
- Separator: Polypropylene or polyethylene.
- Current Collectors: Aluminum or copper foil.

Manufacturing Process

- Electrode Preparation: CNTs are synthesized via arc discharge, laser ablation, or chemical vapor deposition (CVD).
- Assembly: Similar to EDLCs, with electrodes separated by a membrane and electrolyte added.
- Encapsulation: The supercapacitor is sealed in a casing.

Performance Characteristics

- Energy Density: 10-30 Wh/kg (higher than traditional EDLCs due to CNTs' high surface area).
- Power Density: Up to 10,000 W/kg (similar to EDLCs).
- Cycle Life: 100,000 to 1,000,000 cycles (very long, similar to EDLCs).
- Efficiency: 90-95% (high, similar to EDLCs).

Environmental Impact

- Raw Materials: CNT synthesis is energy-intensive and relies on carbon-rich precursors, which can be derived from fossil fuels.
- Electrolytes: Similar to other technologies, with organic solvents contributing to emissions.
- End-of-Life: CNTs are not biodegradable, but aluminum and copper can be recycled.

Comparison Table

Technology	EDLCs	CNT- Based	Graphene- Based	Pseudocapacitors	Hybrid Capacitors	Notes
Energy Density [Wh/kg]	5 - 10	10 - 30	10 - 50	10 - 30	20 - 50	Higher numbers indicate better energy storage capacity; Hybrid can vary widely depending on the specific mix.
Power Density [W/kg]	Up to 10.000	Up to 10.000	Up to 10.000	1.000-5.000	5.000-10.000	Higher numbers indicate faster charge/discharge rates
Cycle Life	100.000 - 1.000.000	100.000 - 1.000.000	100.000 - 1.000.000	10.000 - 100.000	50.000 - 500.000	Cycle life is a core advantage of supercapacitors.
Cost [€/Wh]	0.03 - 0.05	0.10 - 0.50	0.20 - 1.00	0.15 - 0.75	0.25 - 1.25	Costs are approximate and can vary widely based on manufacturing scale and materials.
Operating Voltage [V]	2.5 - 3	3 - 4	3 - 5	1 - 2	2 - 4	Impacts design, the voltage per is often material-dependant.
Efficiency [%]	90 - 95	90 - 95	90 - 95	85 - 90	90 - 95	Defines losses, the total ratio of input and output energy
Environmental Impact	Moderate (activated carbon sustainable, but organic solvents are not).	High (CNT synthesis is energy-intensive).	High (graphene production is energy-intensive).	High (metal oxides are rare and costly to extract).	High (battery-like materials increase environmental impact).	Assessed primarily through LCA.

Detailed Advantages and Disadvantages by Technology:

1. Electric Double-Layer Capacitors (EDLCs):

Advantages:

- **High Power Density:** EDLCs can deliver extremely high power (up to 10,000 W/kg), making them ideal for applications requiring rapid charge/discharge cycles, such as regenerative braking in electric vehicles.
- **Long Cycle Life:** EDLCs can endure 100,000 to 1,000,000 charge/discharge cycles, making them highly durable and suitable for long-term use.
- **High Efficiency:** With roundtrip efficiencies of 90-95%, EDLCs minimize energy losses during operation.

- Low Cost: Activated carbon, the primary electrode material, is relatively inexpensive and widely available.
- Wide Temperature Range: EDLCs can operate effectively across a broad temperature range, making them suitable for various environments.

Weaknesses:

- Low Energy Density: EDLCs have a lower energy density (5-10 Wh/kg) compared to batteries, limiting their use in applications requiring long-term energy storage.
- Environmental Impact of Electrolytes: Organic electrolytes, commonly used in EDLCs, are derived from petrochemicals and contribute to greenhouse gas emissions.
- Limited Energy Storage Duration: EDLCs are best suited for short-term energy storage (seconds to minutes) rather than long-term storage.

2. Carbon Nanotube (CNT) Supercapacitors:

Advantages:

- High Energy Density: CNT-based supercapacitors offer higher energy density (10-30 Wh/kg) compared to traditional EDLCs, thanks to the high surface area of CNTs.
- High Power Density: CNT-based supercapacitors can deliver high power density (up to 10,000 W/kg), similar to EDLCs.
- Long Cycle Life: CNT-based supercapacitors have a long cycle life (100,000 to 1,000,000 cycles), similar to EDLCs.
- High Efficiency: CNT-based supercapacitors maintain high roundtrip efficiencies (90-95%).

Weaknesses:

- High Cost: CNTs are expensive to produce, making CNT-based supercapacitors more costly than traditional EDLCs.
- Energy-Intensive Production: The synthesis of CNTs is energy-intensive and relies on carbon-rich precursors, which can be derived from fossil fuels.
- Environmental Concerns: The production of CNTs can have a significant environmental impact due to the energy-intensive processes and potential toxicity of CNTs.

3. Graphene Supercapacitors:

Advantages:

- High Energy Density: Graphene-based supercapacitors offer higher energy density (10-50 Wh/kg) compared to traditional EDLCs, thanks to graphene's high surface area and conductivity.
- High Power Density: Graphene-based supercapacitors can deliver high power density (up to 10,000 W/kg), similar to EDLCs.
- Long Cycle Life: Graphene-based supercapacitors have a long cycle life (100,000 to 1,000,000 cycles), similar to EDLCs.

- High Efficiency: Graphene-based supercapacitors maintain high roundtrip efficiencies (90-95%).

Weaknesses:

- High Cost: Graphene is expensive to produce, making graphene-based supercapacitors more costly than traditional EDLCs.
- Energy-Intensive Production: The production of graphene is energy-intensive and relies on graphite mining, which can be environmentally damaging.
- Limited Scalability: While graphene-based supercapacitors show great promise in the lab, scaling up production for commercial use remains a challenge.

4. Pseudocapacitors (Metal Oxide Supercapacitors):

Advantages:

- Higher Energy Density: Pseudocapacitors offer higher energy density (10-30 Wh/kg) than EDLCs due to Faradaic redox reactions, making them suitable for applications requiring more energy storage.
- Good Power Density: While not as high as EDLCs, pseudocapacitors still offer decent power density (1,000-5,000 W/kg), making them suitable for applications requiring moderate power output.
- Flexible Material Options: Pseudocapacitors can use a variety of materials, including transition metal oxides (e.g., RuO_2 , MnO_2) and conductive polymers (e.g., polyaniline), allowing for customization based on application needs.

Weaknesses:

- Shorter Cycle Life: Pseudocapacitors have a shorter cycle life (10,000-100,000 cycles) compared to EDLCs due to the degradation caused by Faradaic reactions.
- Higher Environmental Impact: The use of rare metal oxides (e.g., ruthenium) increases the environmental impact of pseudocapacitors, both in terms of resource depletion and energy-intensive extraction processes.
- Lower Efficiency: Pseudocapacitors have slightly lower roundtrip efficiencies (85-90%) compared to EDLCs due to the energy losses associated with redox reactions.

5. Hybrid Supercapacitors:

Advantages

- Balanced Energy and Power Density: Hybrid capacitors offer a balance between energy density (20-50 Wh/kg) and power density (5,000-10,000 W/kg), making them suitable for a wide range of applications, from energy storage to high-power delivery.
- Longer Cycle Life Than Pseudocapacitors: Hybrid capacitors have a longer cycle life (50,000-500,000 cycles) compared to pseudocapacitors, though not as long as EDLCs.
- High Efficiency: Hybrid capacitors maintain high roundtrip efficiencies (90-95%), similar to EDLCs.

Weaknesses:

- **Complex Manufacturing:** The combination of capacitive and Faradaic electrodes makes hybrid capacitors more complex and expensive to manufacture compared to EDLCs and pseudocapacitors.
- **Higher Environmental Impact:** The use of battery-like materials (e.g., Li-ion) in hybrid capacitors increases their environmental impact, particularly in terms of resource extraction and end-of-life recycling.
- **Moderate Cost:** Hybrid capacitors are generally more expensive than EDLCs due to the use of advanced materials and more complex manufacturing processes.

Summary Table: Strengths and Weaknesses

Technology	Strengths	Weaknesses
EDLCs	High power density, long cycle life, high efficiency, low cost, wide temperature range.	Low energy density, environmental impact of organic electrolytes, limited energy storage duration.
Pseudocapacitors	Higher energy density, good power density, flexible material options.	Shorter cycle life, higher environmental impact, lower efficiency.
Hybrid Capacitors	Balanced energy and power density, longer cycle life than pseudocapacitors, high efficiency.	Complex manufacturing, higher environmental impact, moderate cost.
Graphene-Based	High energy density, high power density, long cycle life, high efficiency.	High cost, energy-intensive production, limited scalability.
CNT-Based	High energy density, high power density, long cycle life, high efficiency.	High cost, energy-intensive production, environmental concerns.

- EDLCs are the most mature and cost-effective technology, offering high power density and long cycle life, but they are limited by their low energy density and the environmental impact of organic electrolytes.
- Pseudocapacitors offer higher energy density than EDLCs but have a shorter cycle life and higher environmental impact due to the use of rare metal oxides.
- Hybrid Capacitors strike a balance between energy and power density, making them versatile, but they are more complex to manufacture and have a higher environmental impact due to the use of battery-like materials.
- Graphene-Based and CNT-Based supercapacitors offer improved energy density and performance but come with significant cost and environmental challenges due to the energy-intensive production of graphene and CNTs.

The choice of technology depends on the specific application requirements, such as the need for high power density, long cycle life, or higher energy density, as well as considerations of cost and environmental impact.

Technical information

Supercapacitors have emerged as a promising class of energy storage devices, bridging the gap between traditional batteries and capacitors. Their ability to deliver rapid power, endure millions of charge-discharge cycles, and operate over a wide temperature range makes them invaluable for applications such as renewable energy integration, transportation, and grid stabilization. This overview summarizes the key technical parameters and performance metrics for various supercapacitor technologies—including electric double-layer capacitors (EDLCs), pseudocapacitors, hybrid systems, and carbon nanotube-based devices—highlighting their advantages, limitations, and typical lifecycle impacts (Burke 2000; Augustin et al. 2013).

Detailed Description of Supercapacitor Technologies

1. *Electric Double-Layer Capacitors (EDLCs):*

- Service Life: 10 - 15 years.
- Cycles: 500,000 - 1,000,000 cycles.
- Energy Capacity: 0.001 - 0.01 MWh.
- Power Rating: 0.1 - 10 MW.
- Roundtrip Efficiency: 90 - 95%.
- Depth of Discharge: 100%.
- Storage Duration: Seconds to hours.
- Description: EDLCs store energy electrostatically at the electrode-electrolyte interface, offering high power density and long cycle life.

2. *Pseudocapacitors:*

- Service Life: 5 - 10 years.
- Cycles: 100,000 - 500,000 cycles.
- Energy Capacity: 0.01 - 0.1 MWh.
- Power Rating: 0.1 - 10 MW.
- Roundtrip Efficiency: 85 - 90%.
- Depth of Discharge: 100%.
- Storage Duration: Seconds to hours.

- Description: Pseudocapacitors store energy through faradaic redox reactions, providing higher energy density than EDLCs but with a shorter cycle life.

3. Hybrid Capacitors:

- Service Life: 8 - 12 years.
- Cycles: 200,000 - 500,000 cycles.
- Energy Capacity: 0.01 - 0.1 MWh.
- Power Rating: 0.1 - 10 MW.
- Roundtrip Efficiency: 90 - 95%.
- Depth of Discharge: 100%.
- Storage Duration: Seconds to hours.
- Description: Hybrid capacitors combine the features of EDLCs and pseudocapacitors, offering a balance between energy density, power density, and cycle life.

4. Graphene-Based Supercapacitors:

- Service Life: 10 - 15 years.
- Cycles: 500,000 - 1,000,000 cycles.
- Energy Capacity: 0.01 - 0.1 MWh.
- Power Rating: 0.1 - 10 MW.
- Roundtrip Efficiency: 90 - 95%.
- Depth of Discharge: 100%.
- Storage Duration: Seconds to hours.
- Description: Graphene-based supercapacitors leverage the high surface area and conductivity of graphene to enhance energy storage capabilities, offering high power density and long cycle life.

5. Carbon Nanotube (CNT)-Based Supercapacitors:

- Service Life: 10 - 15 years.
- Cycles: 500,000 - 1,000,000 cycles.
- Energy Capacity: 0.001 - 0.01 MWh.
- Power Rating: 0.1 - 10 MW.
- Roundtrip Efficiency: 90 - 95%.
- Depth of Discharge: 100%.
- Storage Duration: Seconds to hours.
- Description: CNT-based supercapacitors utilize the high surface area and conductivity of carbon nanotubes to enhance energy storage capabilities, offering high power density and long cycle life.

Overview of Supercapacitor Technologies

Parameter	EDLCs	Pseudocapacitors	Hybrid Capacitors	Graphene-Based Supercapacitors	CNT-Based Supercapacitors

Reference Service Life (years)	10 - 15	5 - 10	8 - 12	10 - 15	10 - 15
Number of Cycles	500,000 - 1,000,000	100,000 - 500,000	200,000 - 500,000	500,000 - 1,000,000	500,000 - 1,000,000
Average Energy Capacity (MWh)	0.001 - 0.01	0.01 - 0.1	0.01 - 0.1	0.01 - 0.1	0.001 - 0.01
Power Rating (MW)	0.1 - 10	0.1 - 10	0.1 - 10	0.1 - 10	0.1 - 10
Roundtrip Efficiency (%)	90 - 95	85 - 90	90 - 95	90 - 95	90 - 95
Depth of Discharge (%)	100	100	100	100	100
Suitable Storage Duration	Seconds to hours	Seconds to hours	Seconds to hours	Seconds to hours	Seconds to hours

Comparison and Application Suitability

- **EDLCs** are ideal for high-power, rapid charge-discharge applications but lack the energy density needed for long-term storage. They are commonly used in power backup systems, regenerative braking, and grid stabilization.
- **Pseudocapacitors** offer higher energy density but have a shorter cycle life and lower efficiency, making them suitable for applications requiring more energy storage, such as hybrid vehicles and renewable energy systems.
- **Hybrid Capacitors** provide a balanced approach, combining the strengths of EDLCs and pseudocapacitors, but at a higher cost and complexity. They are suitable for applications that require both high power and moderate energy density, such as electric vehicles and portable electronics.
- **Graphene-Based Supercapacitors** excel in energy density and flexibility but face challenges in scalability and cost. They are ideal for flexible and wearable electronics, as well as high-energy applications like electric vehicles.
- **CNT-Based Supercapacitors** offer high power density and mechanical strength, with better scalability than graphene, but have slightly lower energy density. They are suitable for high-power applications like power backup systems and flexible electronics.

Each type of supercapacitor has its own set of advantages and weaknesses, making them suitable for different applications. The choice of supercapacitor depends on the specific requirements of the application, such as power density, energy density, cycle life, and cost. As research and development continue, advancements in materials and manufacturing

techniques are likely to further enhance the performance and reduce the cost of these technologies, expanding their applicability in various fields (Wang et al. 2012; Rhyd et al. 2005).

System boundaries

Supercapacitors are advanced energy storage devices that have gained significant attention due to their high power density, rapid charge-discharge capabilities, and long cycle life. As the demand for efficient energy storage solutions grows, understanding the environmental impact of these technologies becomes crucial. This report focuses on the system boundaries of five main types of supercapacitors: Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based Supercapacitors, and Carbon Nanotube (CNT)-Based Supercapacitors. The analysis follows a cradle-to-gate approach according to EN15804, which covers the environmental impact from raw material extraction to the point where the product leaves the manufacturing facility (gate). By defining the system boundaries, we aim to provide a clear understanding of the environmental implications of each supercapacitor type.

Detailed System Boundaries (Cradle-to-Gate)

1. Electric Double-Layer Capacitors (EDLCs)

- Raw Material Extraction: Extraction of raw materials such as carbon (for activated carbon), electrolytes (organic or aqueous), and binders.
- Material Processing: Production of activated carbon, synthesis of electrolytes, and processing of other materials like separators and current collectors.
- Component Manufacturing: Manufacturing of electrodes, separators, and current collectors.
- Assembly: Assembly of the supercapacitor components into the final product.
- Transportation: Transport of raw materials and components to the manufacturing facility.
- System Boundary: Cradle-to-gate, covering raw material extraction to the finished product.

2. Pseudocapacitors

- Raw Material Extraction: Extraction of transition metals (e.g., ruthenium, manganese), carbon, and electrolytes.

- Material Processing: Synthesis of metal oxides, processing of carbon materials, and electrolyte production.
- Component Manufacturing: Manufacturing of electrodes (with metal oxides), separators, and current collectors.
- Assembly: Assembly of the supercapacitor components into the final product.
- Transportation: Transport of raw materials and components to the manufacturing facility.
- System Boundary: Cradle-to-gate, covering raw material extraction to the finished product.

3. Hybrid Capacitors

- Raw Material Extraction: Extraction of carbon, transition metals, and electrolytes.
- Material Processing: Production of activated carbon, synthesis of metal oxides, and electrolyte production.
- Component Manufacturing: Manufacturing of electrodes (combining carbon and metal oxides), separators, and current collectors.
- Assembly: Assembly of the supercapacitor components into the final product.
- Transportation: Transport of raw materials and components to the manufacturing facility.
- System Boundary: Cradle-to-gate, covering raw material extraction to the finished product.

4. Graphene-Based Supercapacitors

- Raw Material Extraction: Extraction of graphite (for graphene production), electrolytes, and other materials.
- Material Processing: Synthesis of graphene, production of electrolytes, and processing of other materials.
- Component Manufacturing: Manufacturing of graphene-based electrodes, separators, and current collectors.
- Assembly: Assembly of the supercapacitor components into the final product.
- Transportation: Transport of raw materials and components to the manufacturing facility.
- System Boundary: Cradle-to-gate, covering raw material extraction to the finished product.

5. Carbon Nanotube (CNT)-Based Supercapacitors

- Raw Material Extraction: Extraction of carbon (for CNT production), electrolytes, and other materials.
- Material Processing: Synthesis of CNTs, production of electrolytes, and processing of other materials.
- Component Manufacturing: Manufacturing of CNT-based electrodes, separators, and current collectors.

- Assembly: Assembly of the supercapacitor components into the final product.
- Transportation: Transport of raw materials and components to the manufacturing facility.
- System Boundary: Cradle-to-gate, covering raw material extraction to the finished product.

Overview of System Boundaries (Cradle-to-Gate)

Supercapacitor Type	Raw Material Extraction	Material Processing	Component Manufacturing	Assembly	Transportation	System Boundary (Cradle-to-Gate)
EDLCs	Carbon, electrolytes, etc.	Activated carbon production, electrolyte synthesis	Electrode production, separator manufacturing	Supercapacitor assembly	Transport of raw materials and components	Raw material extraction to finished product
Pseudocapacitors	Transition metals, carbon, electrolytes	Metal oxide synthesis, carbon processing	Electrode production, separator manufacturing	Supercapacitor assembly	Transport of raw materials and components	Raw material extraction to finished product
Hybrid Capacitors	Carbon, metal oxides, electrolytes	Activated carbon production, metal oxide synthesis	Electrode production, separator manufacturing	Supercapacitor assembly	Transport of raw materials and components	Raw material extraction to finished product
Graphene-Based Supercapacitors	Graphite, electrolytes, etc.	Graphene synthesis, electrolyte production	Electrode production, separator manufacturing	Supercapacitor assembly	Transport of raw materials and components	Raw material extraction to finished product
CNT-Based Supercapacitors	Carbon, electrolytes, etc.	CNT synthesis, electrolyte production	Electrode production, separator manufacturing	Supercapacitor assembly	Transport of raw materials and components	Raw material extraction to finished product

The cradle-to-gate system boundaries for the five types of supercapacitors—EDLCs, pseudocapacitors, hybrid capacitors, graphene-based supercapacitors, and CNT-based supercapacitors—highlight the key stages of their lifecycle, from raw material extraction to the point where the product leaves the manufacturing facility. Each type of supercapacitor has distinct material requirements and processing steps, which influence their environmental impact:

- **EDLCs** rely heavily on activated carbon and electrolytes, with relatively straightforward processing but high energy consumption during material production.
- **Pseudocapacitors** involve the extraction and synthesis of transition metals, which can be resource-intensive and environmentally impactful.
- **Hybrid Capacitors** combine the materials and processes of EDLCs and pseudocapacitors, offering a balance but with increased complexity.

- **Graphene-Based Supercapacitors** require high-quality graphene, which is energy-intensive to produce, but offer high performance.
- **CNT-Based Supercapacitors** involve the synthesis of CNTs, which is less energy-intensive than graphene but still costly.

Understanding these system boundaries is essential for assessing the environmental impact of supercapacitors and guiding future research toward more sustainable materials and manufacturing processes.

Impact assessment

Supercapacitors are increasingly being recognized as a key technology for energy storage due to their high power density, rapid charge-discharge capabilities, and long cycle life. However, as the demand for energy storage solutions grows, it is essential to evaluate the environmental impact of these technologies to ensure sustainable development. This report provides a comprehensive impact assessment analysis of five main types of supercapacitors: Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based Supercapacitors, and Carbon Nanotube (CNT)-Based Supercapacitors. The analysis follows the Environmental Footprint (EF) 3.1 impact assessment method, which includes a comprehensive set of relevant impact categories for energy storage systems, such as climate change, land use, water use, and human toxicity. Additionally, the EF 3.1 method provides default normalization and weighting factors tailored for European contexts, allowing the results to be aggregated into a single Product Environmental Footprint (PEF) score. This approach is increasingly being adopted due to recent EU legislation, such as the Battery Regulation, which mandates the inclusion of environmental footprint indicators in the battery passport.

This report provides an overview of environmental impacts across several key categories based on the EF 3.1 methodology, with specific focus on different supercapacitor technologies to help identify areas for improvement.

1. Electric Double-Layer Capacitors (EDLCs):

- Climate Change (10-30 kg CO₂ eq.): Generally lower than other types due to simpler materials and well-established manufacturing. Emphasis on sourcing sustainable carbon and renewable energy during manufacturing.
- Land Use (0.5-2 m²-yr): Moderate impacts tied to activated carbon extraction. Improved sustainable carbon and renewable energy sources extraction can reduce this impact.
- Water Use (0.1-0.8 m³): Water use depends on manufacturing location and water source used for both activated carbon and electrolytes processing.
- Human Toxicity (5-20 CTU): Lower side impact for the toxic material is used. A strong recommendation of a safer materials is well recommended to improve the toxicity impact.
- Resource Depletion (0.01-0.05 kg Sb eq.): Sourcing carbon materials and manufacturing location matters significantly.
- Water Pollution (0.01-0.05 kg 1,4-DCB eq.): Again, sourcing is key. A green material will greatly improve.
- PEF Score (0.4-1.2 normalized): Good overall potential, making them one of the best choices.

2. Pseudocapacitors:

- Climate Change (20-50 kg CO₂ eq.): Higher due to metal oxide/polymer synthesis, often energy-intensive. Reduction can occur with using materials that don't require heat and renewable electricity for high-impact equipment.
- Land Use (1-4 m²-yr): Driven by metal extraction processes (mining sites) and waste products of synthetic material. Can improve with alternative synthetic material and improving extraction methods.
- Water Use (0.2-1.0 m³): Depends on specific manufacturing process, with improved water management systems the impact can be improved.
- Human Toxicity (10-30 CTU): Synthetic processes tend to be the cause. So finding more green materials, or less synthetic material is key.
- Resource Depletion (0.02-0.07 kg Sb eq.): Driven by the raw extraction and the usage of materials during extraction and synthesis. Improved method extraction, and finding alternative materials key.
- Water Pollution (0.02-0.07 kg 1,4-DCB eq.): Improvement of chemical materials key, along with handling of toxic byproducts.
- PEF Score (0.6-1.5 normalized): Highest range, so must be improved with finding alternative extraction, reducing waste or synthetic materials.

3. Hybrid Capacitors:

- Climate Change (15-35 kg CO₂ eq.): A blend of materials, has a mix of problems with a bit of goodness.
- Land Use (0.8-3 m²·yr): A mix and match so improved extraction, and use of alternative synthetic materials can improve the score here.
- Water Use (0.15-0.9 m³): A good improvement, by making a well managed system of reducing water and improving extraction methods.
- Human Toxicity (8-22 CTU): Focus can be placed on the chemicals to find green alternatives.
- Resource Depletion (0.015-0.04 kg Sb eq.): Well, same as land use, focus on synthetic extraction will lead to success.
- Water Pollution (0.015-0.04 kg 1,4-DCB eq.): With improved extraction and green material.
- PEF Score (0.5-1.4 normalized): Best method that all can be good, depends on finding sustainable manufacturing.

4. Graphene Supercapacitors:

- Climate Change (20-55 kg CO₂ eq.): Well, a large number compared to others, there is a great need for renewable sources of energy to reduce green house gasses.
- Land Use (0.3-1.5 m²·yr): Well, it depends on extracting. Alternative synthetic materials can improve it a bit.
- Water Use (0.05-0.3 m³): This is good, if water management is prioritized.
- Human Toxicity (7-25 CTU): Green synthetic processes are key to greatly improving the numbers here.
- Resource Depletion (0.005-0.03 kg Sb eq.): So far, a good range depending on the choice of materials during synthesis.
- Water Pollution (0.005-0.03 kg 1,4-DCB eq.): Synthetic material is what determines the best results, choose it wisely.
- PEF Score (0.3-1.2 normalized): With focus on sustainable design and green practices it will improve very well.

5. CNT Supercapacitors:

- Climate Change (15-45 kg CO₂ eq.): Similar needs as graphene, with renewable energy focus, can drop the number
- Land Use (0.2-1.2 m²·yr): Again, alternative synthetic extraction materials is key to achieve the best performance here.
- Water Use (0.05-0.4 m³): Here the need for a sustainable practice is the core focus.
- Human Toxicity (6-18 CTU): Similar approach to graphene, is with green synthetic.
- Resource Depletion (0.004-0.025 kg Sb eq.): Sustainable sourcing is key to obtain this.
- Water Pollution (0.004-0.025 kg 1,4-DCB eq.): And again, it is all in materials that are carefully picked.

- PEF Score (0.4-1.3 normalized): If all processes and components are sustainable, then the result can be good.

Impact Assessment Overview Table

Impact Category	EDLCs	Pseudocapacitors	Hybrid Capacitors	Graphene Supercapacitors	CNT Supercapacitors	Notes
Climate Change (kg CO ₂ eq.)	10–30	20–50	15–35	20–55	15–45	Dominated by electrode material synthesis and manufacturing energy use
Land Use (m ² ·yr)	0,5–2	1–4	0,8–3	0,3–1,5	0,2–1,2	Higher land use in electrode material extraction, especially for nanomaterials
Water Use (m ³)	0,1–0,8	0,2–1,0	0,15–0,9	0,05–0,3	0,05–0,4	More impactful during electrode synthesis, especially for nanomaterials
Human Toxicity (CTU)	5–20	10–30	8–22	7–25	6–18	High impact linked to toxic chemicals (e.g., solvents, nanomaterials) used in production
Resource Depletion (kg Sb eq.)	0,01–0,05	0,02–0,07	0,015–0,04	0,005–0,03	0,004–0,025	Material sourcing for electrodes and electrolytes significant
Water Pollution (kg 1,4-DCB eq.)	0,01–0,05	0,02–0,07	0,015–0,04	0,005–0,03	0,004–0,025	Related to solvent handling and chemical processing
PEF Score (normalized)	0,4–1,2	0,6–1,5	0,5–1,4	0,3–1,2	0,4–1,3	Reflects combined impacts; depends heavily on materials and manufacturing energy

Note: The impact ranges reflect variability in material sourcing, manufacturing efficiency, energy mix, and product design.

Impact Category Ranges for Supercapacitors (at cradle-to-gate, considering all tech types)

Impact Category	Minimal (best case)	Maximal (worst case)	Typical (average)
Climate Change [kg CO ₂ eq.]	5–10	50–70	20–35
Land Use [m ² ·yr]	0,2–0,4	4–6	1–2
Water Use [m ³]	0,01–0,05	1,0–2,0	0,2–0,6
Human Toxicity [CTU]	2–5	40–60	10–20
Resource Depletion [kg Sb eq.]	0,001–0,002	0,05–0,07	0,02–0,03
Water Pollution [kg 1,4-DCB eq.]	0,0005–0,001	0,07–0,1	0,02–0,04
PEF Score [normalized]	< 0,5	> 1	0 – 0,5

Explanation:

- Minimal (best case): Impact values assuming optimal, low-impact material sourcing, renewable energy use, minimal chemical hazards, and efficient manufacturing.
- Maximal (worst case): Values from scenarios involving high-impact raw material extraction, energy-intensive and non-renewable manufacturing, toxic chemicals, and inefficient processes, representing high-impact situations.
- Usual (average): Typical impact values based on current industrial practices, available data, and standard materials/technologies.

Note: These ranges are approximate and meant to give a realistic view of what is technically feasible across different settings, not precise measurements for a specific product.

Explanation of Environmental Impact Categories (EF 3.1) in terms of supercapacitors

These impact categories are part of the Environmental Footprint (EF) 3.1 method and reflect different aspects of environmental harm or resource use.

Climate Change [kg CO₂ eq.]:

- What it measures: The total greenhouse gas emissions (GHGs) released during the entire life cycle of the supercapacitor, converted into an equivalent amount of carbon dioxide (CO₂). This includes emissions from electricity generation, material extraction, manufacturing processes, and transportation.
- Relevance to Supercapacitors: High values indicate high energy consumption and reliance on carbon-intensive processes, particularly during electrode material synthesis (e.g., activated carbon activation, nanomaterial production).

Land Use [m²·yr]:

- **What it measures:** The area of land used and the duration for which it's used, to produce raw materials and manufacture the product. This includes areas used for mining, forestry, agriculture, and manufacturing sites.
- **Relevance to Supercapacitors:** Land use is especially relevant for the extraction of resources like carbon, metals, and electrolytes, and for areas where processing or manufacturing facilities are located. High values are often seen in mining operations and large industrial complexes.

Water Use [m³]:

- **What it measures:** The volume of water consumed (i.e., withdrawn and not returned to the same source) or degraded during the product's lifecycle.
- **Relevance to Supercapacitors:** Significant water use occurs during electrode material synthesis, electrolyte production, and cooling processes in manufacturing plants. Nanomaterial production tends to consume more water.

Human Toxicity [CTU]:

- **What it measures:** The potential harm to human health resulting from exposure to toxic chemicals released during the product's life cycle. The unit "CTUh" refers to Comparative Toxic Unit for human health.
- **Relevance to Supercapacitors:** High impact linked to the use of toxic solvents, precursors, and nanomaterials in electrode and electrolyte manufacturing. It accounts for both cancer and non-cancer effects.

Resource Depletion [kg Sb eq.]:

- **What it measures:** The consumption of non-renewable resources, with impacts expressed in terms of antimony (Sb) equivalents. This indicator quantifies the depletion of Earth's finite resource reserves.
- **Relevance to Supercapacitors:** Material sourcing for electrodes (e.g., ruthenium, manganese oxides) and electrolytes (e.g., lithium salts) is a key driver. It estimates how much of the planet's finite material wealth is consumed.

Water Pollution [kg 1,4-DCB eq.]:

- **What it measures:** The potential to cause harmful effects on aquatic ecosystems and human health through the release of pollutants into water bodies. "kg 1,4-DCB eq." refers to kilograms of 1,4-dichlorobenzene equivalents, a reference substance for water ecotoxicity.
- **Relevance to Supercapacitors:** Significant pollution occurs during the synthesis of organic solvents and electrolytes, and during industrial processes that release heavy metals or organic compounds.

PEF Score [normalized]:

- **What it measures:** A single, aggregated score that represents the overall environmental impact of the product across all impact categories. It's calculated by normalizing and weighting the results from each impact category. Normalization involves comparing the impact to an average impact per person in a given region or year, while weighting reflects the relative importance of each impact category.
- **Relevance to Supercapacitors:** A comprehensive measure indicating the total cradle-to-gate environmental burden. The lower the score, the better the environmental performance.

Use stage and end-of-life

The analysis accounts for impacts from stored energy loss, regional waste management practices in the Danube Region, and impact allocation per the Polluter Pays Principle (PPP).

Below is a use stage and end-of-life (EOL) analysis for large-scale supercapacitor systems, specifically considering:

- Electric Double-Layer Capacitors (EDLCs)
- Pseudocapacitors
- Hybrid capacitors
- Graphene-based supercapacitors
- Carbon Nanotube (CNT)-based supercapacitors

Use Stage Analysis for Large-Scale Supercapacitor Systems in the Danube Region

1. System Size and Application Context

- Typical large-scale supercapacitor systems: 100 kWh to several MWh (e.g., for grid stabilization, renewable energy smoothing, peak shaving).
- Example system: a 1-MWh (1,000 kWh) system installed at a regional substation for grid stability.

2. Regional Energy Context

- European energy mix (approximate):
 - Fossil fuels: 40%
 - Nuclear: 20%
 - Renewables: 40% (hydropower, wind, solar)
- Grid emission factor:
 - Average emission factor: 0.3 kg CO₂ per kWh (regionally averaged, varies slightly across countries within the Danube basin).

3. Usage & Operational Data

- Cycle frequency:

- For grid support applications, typical cycling rates could be 10,000 to 50,000 cycles over 10–15 years.
 - Example: 20,000 cycles over 10 years.
- Average Power and Energy per Cycle:
 - Capacity: 100 kWh (per system module)
 - Voltage: ~2.7 V (series modules to reach the system voltage)
 - Energy per cycle: approximately 100 kWh (full charge/discharge).
 - Cycle duration: a few minutes (seconds to minutes), depending on application.
- Total energy processed during life:
Total throughput = 100 kWh * 20,000 cycles = 2.000.000 kWh = 2 GWh

4. Energy Losses & Environmental Impact

- Internal resistance / ESR losses:
 - Estimated at 3–5% per cycle (due to heat dissipation).
- Energy dissipated as heat:
 - For an energy cycle of 100 kWh, at 4% loss: $100 \text{ kWh} * 0.04 = 4 \text{ kWh}$
- Total energy lost over lifetime: $4 \text{ kWh} * 20.000 \text{ cycles} = 80.000 \text{ kWh}$
- Environmental impact of dissipated energy:
 - Using EU average emission factor (~0.3 kg CO₂/kWh):
 $80.000 \text{ kWh} * 0.3 = 24.000 \text{ kg CO}_2 = 24 \text{ tonnes CO}_2$

This reflects the impact of energy inefficiency during system operation—that is, the emissions indirectly caused by heat losses during cycling.

5. Additional Use Stage Impacts

- Material wear and degradation:
 - Over many cycles, electrode materials (graphene, CNTs, activated carbon) may undergo minor degradation, typically leading to a 10–15% capacity fade over 10–15 years.
 - The impact is mostly operational and does not significantly alter environmental impacts but may influence maintenance or replacement schedules.
- Operational benefits:
 - The supercapacitor reduces reliance on fossil-fuel peaking plants, thus indirectly decreasing regional greenhouse gas emissions.
- Estimated emission reduction:
 - For every 1 MWh of stored energy offset (e.g., from peaking plants), emissions avoided could be approximately 0.3 tonnes CO₂ per MWh.
 - Over a 10-year period with 20,000 cycles, this could dramatically reduce regional emissions.

Summary of Regional Use Stage Data

Parameter	Typical Value / Range	Regional Context & Notes
System capacity	100 kWh – 1 MWh	Used for grid stabilization, renewable smoothing, peak shaving in regional energy infrastructure
Number of cycles over lifetime	10,000 – 50,000 cycles	Over 10–15 years, depending on application and cycling frequency
Total energy processed	1–10 GWh	Depending on system size and application scope
Energy loss per cycle	3–5% (3–5 kWh per 100 kWh charge/discharge cycle)	Leads to substantial indirect emissions if unmitigated
Total heat energy dissipation	~30–50 MWh per system	Accumulated heat losses over lifetime contribute to environmental impact
Associated CO ₂ emissions (via Europe average)	~9–15 tonnes CO ₂	For a 100 kWh system, considering 4–5% losses over 20,000 cycles
Impact of shifting to cleaner energy	Potential reduction proportional to regional decarbonization efforts	Higher renewable penetration reduces the environmental impact of energy dissipation
Operational benefits	Reduces reliance on fossil peaking plants	Estimated substitution of ~0.3 tonnes CO ₂ e per MWh stored/offset

Regional Impact Summary

Impact Aspect	Impact Estimate per 1 MWh System	Regional Annual Impact (e.g., 10 systems)	Notes
Energy processed over lifetime	~2 GWh	~20 GWh	Total energy cycled during 10–15 years of operation
Energy lost as heat (due to ESR)	~80 MWh	~800 MWh	Energy dissipated during cycling, contributing to indirect emissions
Associated CO ₂ emissions (EU average 0.3 kg/kWh)	~24 tonnes CO ₂ e	~240 tonnes CO ₂ e	Emissions from energy losses, mitigable by cleaner grids
Potential reduction via renewable energy	Significant	Increased effect as renewables grow	Lower impact if energy used is from low-carbon sources
Operational benefits	Displacement of fossil peak plants	Substantial regional emission savings	Enhances regional decarbonization efforts

Influencing Factors & Regional Considerations

- Grid decarbonization:

- As renewables expand in the Danube region, the emission factor (~ 0.3 kg CO₂/kWh) is expected to decline, reducing the environmental impacts of the heat losses.
- Operational configurations:
 - More frequent cycling (e.g., >50,000 cycles) increases total heat dissipation impacts.
 - Use of high-efficiency supercapacitors with lower ESR can reduce losses significantly.
- Application-specific factors:
 - Grid stabilization, renewable smoothing, or peak shaving applications have different cycling intensities, influencing impacts.
- Regional policies:
 - EU directives encourage integrating renewables and promoting energy efficiency, further lowering associated emissions.

Summary of Use Stage Data for Large-Scale Systems in the Danube Region

Parameter	Typical Value / Range	Regional Implication
System size	100 kWh – 1 MWh	Wide application scope (grid, renewables, transport)
Cycle count over lifetime	10,000 – 50,000	Influences total energy throughput and impacts
Total energy processed	1–10 GWh	Depending on system size and cycling frequency
Energy loss (heat)	4% per cycle (4–40 MWh total loss per system)	Significant contribution to indirect regional emissions
Impact impact (CO ₂ e)	~ 24 tonnes CO ₂ per system	Can be mitigated through efficiency and cleaner energy sources

This detailed analysis demonstrates that the use stage of large-scale supercapacitors in the Danube Region involves significant energy processing and associated environmental impacts primarily due to operational losses. However, these impacts can be minimized by:

- Improving material and device efficiency (reducing ESR)
- Utilizing cleaner energy sources for manufacturing and operation
- Designing for longevity and minimal degradation

Furthermore, integrating regional policies for renewables, waste management, and circular economy practices will enhance overall sustainability.

End-of-Life (EOL) Analysis of Large-Scale Supercapacitor Systems in the Danube Region

A comprehensive End-of-Life (EOL) analysis of supercapacitor systems in the Danube Region necessitates acknowledging its wide range of waste management infrastructures, from modern recycling facilities to basic landfill operations. As a significant portion of EOL components currently end up in landfills, understanding and mitigating the potential leaching of harmful substances into soil and water is paramount. Furthermore, the analysis must navigate the intricate web of diverse regulatory frameworks within each Danube country, directly influencing the handling, transportation, and potential recycling processes. With limited economic incentives for advanced recycling technologies, the economic drive for improved EOL processing remains minimal. Therefore, incineration requires close monitoring and advanced filtration, while material flow analysis must accurately chart component pathways. Embracing the Polluter Pays Principle should strongly encourage manufacturers to embrace sustainable practices. International knowledge sharing is crucial to improving these technologies as they are needed for the future.

1. Material Composition & Estimated Quantities

System size example: a 1 MWh supercapacitor installation.

Material	Approximate weight per system	Comments
Electrode materials (activated carbon, graphene, CNTs)	300–500 kg	High surface-area carbons, nanomaterials (higher value in graphene/CNTs)
Electrolytes	50–150 kg	Organic electrolytes, ionic liquids, or aqueous solutions
Separator & casing (polymers, plastics, metals)	50–150 kg	Plastic housings, metal contacts, separators

2. Regional Waste Management Practices & Recycling Rates

Based on current EU directives and practices within the Danube region, realistic expectations are:

Material	Typical Recycling Rate in the Danube Region	Impacts & Details
Electrode materials	70–85%	Pyrolysis, chemical recovery methods; high recovery reduces need for virgin raw materials
Electrolytes	50–70%	Specialized treatment for organic/ionic electrolytes; remaining hazardous waste if not recovered
Polymers & plastics	50–60%	Mechanical recycling; otherwise landfilled or incinerated
Metals (contacts, enclosures)	80–95%	Metal recycling facilities already well-established

3. Impacts of Recycling & Waste Management

Impact calculations are based on impact factors and quantities:

Material	Quantity in system	Recycled Portion	Impact avoided (kg CO ₂ e)	Note
Electrode materials	400 kg	75–85%	300–340 kg	Recovery reduces need for virgin material extraction (~5 kg CO ₂ e/kg for primary carbon production)
Electrolytes	100 kg	50–70%	50–70 kg	Recovery via advanced chemical treatments avoids environmental impacts of disposal (~10 kg CO ₂ e/kg electrolyte)
Polymers & housings	100 kg	50–60%	50–60 kg	Recycling plastics and polymer components can offset impact (~1 kg CO ₂ e/kg for plastics)
Metals (enclosures, contacts)	50 kg	90–95%	45–48 kg	Metal recycling impact (~0.5–1 kg CO ₂ e/kg)

Total impact avoided: approximately ~345–418 kg CO₂e per system.

4. Residual Waste & Environmental Risks

- Residual hazardous waste:
 - Not all materials are recyclable; residual components may include remaining organics or hazardous electrolytes.
 - Leaching risks: Organic solvents or ionic liquids if landfilled improperly, potentially releasing toxins.
- Environmental impact of residual waste:
 - Improper disposal could lead to additional impacts of +20 to 50 kg CO₂e per system due to leaching, soil, and water contamination.

5. Impact of Improper Disposal & Pollution Risks

Risk	Estimated impact	Description
Toxic leaching	+20–50 kg CO ₂ e per system	Organic electrolytes or ionic liquids pose long-term contamination risks if landfilled without proper treatment
Plastic & polymer waste	+10–20 kg CO ₂ e	Landfilling non-recycled plastics adds to environmental burden

Total additional impact from improper disposal: up to ~70 kg CO₂e per system, depending on waste handling practices.

6. Impact Allocation & Responsibility (PPP)

- Manufacturers/system suppliers: responsible for designing for recyclability, providing end-of-life solutions, and minimizing hazardous materials.
- Regulators & waste handlers: responsible for ensuring compliant collection, treatment, and safe disposal.
- Impact benefits of recycling: Displaced impacts from raw material extraction (~raw material impact avoided ~1.5–2 tonnes CO₂e per system) are attributed to the polluter (manufacturer) as per PPP.

7. Summary of EOL Impacts for a 1 MWh System in the Danube Region (continued)

Impact Component	Impact per System	Impact for 10 Systems Annually	Notes
Recycling & Raw Material Substitution	~345–418 kg CO ₂ e avoided	~3.45–4.18 tonnes CO ₂ e	Significant impact reduction by recovering electrode materials, electrolytes, and metals.
Residual Waste & Improper Disposal Risks	~20–70 kg CO ₂ e per system	~0.2–0.7 tonnes CO ₂ e	Potential impacts if waste is landfilled or improperly managed. Proper recycling reduces this impact.
Total Impact (Impact Savings - Residual Risks)	~275–348 kg CO ₂ e per system	~2.75–3.48 tonnes CO ₂ e	Net impact considering impacts from residual waste if managed properly.

8. Regional Recommendations to Minimize Environmental Impacts

- Enhance Recycling Infrastructure:
Develop and promote accessible, regionally integrated facilities for electrode, electrolyte, and plastics recycling in Danube countries.
- Design for Circularity:

Encourage manufacturers to adopt recyclable and durable system designs, facilitating easier disassembly and material recovery.

- **Implement Strict Disposal Regulations:**
Enforce EU waste directives and regional policies to ensure hazardous electrolytes are recovered or safely disposed of, reducing leaching risks.
- **Encourage Extended Producer Responsibility (EPR):**
Make system manufacturers accountable for end-of-life impacts, promoting responsible material sourcing, system design, and take-back schemes.
- **Promote Alternatives & Safer Materials:**
Support R&D for greener electrolytes and electrode materials with lower environmental footprints and higher recyclability.
- **Regional Cooperation:**
Foster cross-border collaboration in waste management, recycling technologies, and policy harmonization across Danube countries.

Avoided impacts

The integration of Energy Storage Systems (ESS) based on supercapacitors with intermittent renewable energy sources (such as solar and wind) can significantly mitigate several environmental and energy-related impacts. Supercapacitors, due to their high power density, rapid charge-discharge capabilities, and long cycle life, are particularly well-suited for applications that require frequent cycling and quick response times. This report provides a detailed avoided impacts analysis for large-scale systems based on five types of supercapacitors: Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based Supercapacitors, and Carbon Nanotube (CNT)-Based Supercapacitors. The analysis focuses on the environmental and energy-related benefits of integrating supercapacitors with renewable energy systems, including reduced reliance on fossil fuel backup generation, lower carbon emissions, and enhanced grid resilience.

Role of Supercapacitors in Reducing Environmental Impacts

a. Enabling Higher Renewable Penetration

- Supercapacitors store excess electricity generated during peak renewable conditions (e.g., windy nights or sunny days).
- Releasing stored energy during periods of low renewable output smooths supply fluctuations.
- This process reduces the need for dispatching fossil-fuel generators solely for balancing, thus avoiding emissions.

b. Counteracting Intermittency and Power Fluctuations

- ESS dampens rapid load changes, lessening wear on the grid infrastructure.
- Fewer start-ups and shut-downs of conventional plants decrease associated emissions and maintenance impacts.

c. Displacement of Carbon-Intensive Backup Power

- ESS reduce reliance on peaking power plants (primarily fossil-fuel based), which are typically inefficient and high-emission.
- This directly lowers greenhouse gas (GHG) emissions and local air pollutants.

1 Detailed Avoided Impacts Analysis

Reduced Reliance on Fossil Fuel Backup Generation

- EDLCs: EDLCs can rapidly store and release energy, making them ideal for smoothing out the intermittency of renewable energy sources. By providing quick bursts of energy during periods of low renewable generation, EDLCs reduce the need for fossil fuel backup generation, such as natural gas peaker plants.
- Pseudocapacitors: Pseudocapacitors offer higher energy density than EDLCs, allowing them to store more energy for longer periods. This reduces the need for fossil fuel backup generation, though not as effectively as EDLCs due to their lower power density.
- Hybrid Capacitors: Hybrid capacitors combine the high power density of EDLCs with the higher energy density of pseudocapacitors, making them highly effective at reducing the need for fossil fuel backup generation.
- Graphene-Based Supercapacitors: Graphene-based supercapacitors offer high power and energy density, making them highly effective at reducing the need for fossil fuel backup generation.
- CNT-Based Supercapacitors: CNT-based supercapacitors also offer high power and energy density, making them highly effective at reducing the need for fossil fuel backup generation.

Lower Carbon Emissions

- EDLCs: By reducing the need for fossil fuel backup generation, EDLCs significantly lower carbon emissions. The high efficiency of EDLCs (90-95%) ensures that minimal energy is lost during charge and discharge cycles, further reducing emissions.

- Pseudocapacitors: Pseudocapacitors also lower carbon emissions, though not as effectively as EDLCs due to their lower efficiency (85-90%).
- Hybrid Capacitors: Hybrid capacitors offer a balance between high power density and energy density, making them highly effective at lowering carbon emissions.
- Graphene-Based Supercapacitors: Graphene-based supercapacitors offer high efficiency and energy density, making them highly effective at lowering carbon emissions.
- CNT-Based Supercapacitors: CNT-based supercapacitors also offer high efficiency and energy density, making them highly effective at lowering carbon emissions.

Enhanced Grid Resilience

- EDLCs: EDLCs can provide rapid response to grid fluctuations, enhancing grid resilience and stability. Their ability to quickly absorb and release energy helps to balance supply and demand, reducing the risk of blackouts.
- Pseudocapacitors: Pseudocapacitors also enhance grid resilience, though not as effectively as EDLCs due to their lower power density.
- Hybrid Capacitors: Hybrid capacitors offer a balance between high power density and energy density, making them highly effective at enhancing grid resilience.
- Graphene-Based Supercapacitors: Graphene-based supercapacitors offer high power and energy density, making them highly effective at enhancing grid resilience.
- CNT-Based Supercapacitors: CNT-based supercapacitors also offer high power and energy density, making them highly effective at enhancing grid resilience.

Reduced Wear on Grid Infrastructure

- EDLCs: By smoothing out the intermittency of renewable energy sources, EDLCs reduce the need for rapid adjustments in conventional energy generation, which can cause wear and tear on grid infrastructure.
- Pseudocapacitors: Pseudocapacitors also reduce wear on grid infrastructure, though not as effectively as EDLCs due to their lower power density.
- Hybrid Capacitors: Hybrid capacitors offer a balance between high power density and energy density, making them highly effective at reducing wear on grid infrastructure.
- Graphene-Based Supercapacitors: Graphene-based supercapacitors offer high power and energy density, making them highly effective at reducing wear on grid infrastructure.
- CNT-Based Supercapacitors: CNT-based supercapacitors also offer high power and energy density, making them highly effective at reducing wear on grid infrastructure.

Overview of Avoided Impacts

Supercapacitor Type	Reduced Fossil Fuel Backup	Lower Carbon Emissions	Grid Resilience	Reduced Grid Wear	Overall Avoided Impacts
EDLCs	High	High	High	High	High
Pseudocapacitors	Moderate	Moderate	Moderate	Moderate	Moderate
Hybrid Capacitors	High	High	High	High	High
Graphene-Based Supercapacitors	High	High	High	High	High
CNT-Based Supercapacitors	High	High	High	High	High

2. Quantifying the Avoided Impacts

a. Emissions Reduction via Grid Decarbonization

- Reference scenario:
Without ESS, regions rely more heavily on fossil backup units.
- With ESS:
Excess renewable energy is stored and dispatched, reducing fossil fuel operations.

b. Energy System Modeling Approach

- Assumption:
Each 1 MWh supercapacitor system (or large-scale ESS project) offsets a certain amount of fossil fuel generation equivalents annually.
- Impact factors:
Average CO₂ emissions from fossil plants: ~0.4–0.5 kg CO₂/kWh (regional variance).
Efficiency of ESS: 90–95% (losses accounted for, but impacts are mainly from avoided generation).

c. Estimations of Avoided Impacts

Suppose a system provides 100% replacement of fossil backup power during its operation (for simplicity):

Parameter	Values / Scenarios	Impact Explanation
Annual energy stored/dispatched	1,000,000 kWh (1 GWh)	Typical large renewable integration project
Fossil fuel generation avoided	~1,000,000 kWh	Based on high renewable penetration, displacing peaking plants
GHG emissions avoided	~400–500 tonnes CO ₂ e/year	Using ~0.4–0.5 kg CO ₂ /kWh emission factor for fossil plants

Thus, each GW-scale supercapacitor system can prevent hundreds of tonnes of CO₂ emissions annually.

3. Broader Environmental and Social Benefits

a. Reduced Air Pollutants

- Less NO_x, SO_x, and particulate matter (PM) from fossil plants.
- Improvements in air quality and public health.

b. Decreased Fossil Fuel Extraction and Transportation Impacts

- Reduced mining, drilling, and associated environmental disturbances.
- Lower risk of spills and habitat disruption.

c. Grid Infrastructure Benefits

- Less stress and wear on transformers, lines, and ancillary equipment.
- Extended lifespan of grid infrastructure reduces embedded impacts.

d. Enhanced Grid Resilience & Reliability

- Faster response times of supercapacitors improve system stability.
- Less frequency of emergency dispatches, outages, or blackouts reduces societal impacts.

4. Quantitative Summary of Total Avoided Impacts

Impact Category	Approximate Impact per 1 GWh/year ESS (or equivalent large project)	Notes
CO ₂ Emissions Avoided	~400–500 tonnes CO ₂ e/year	Based on fossil plant displacement; region-specific factors apply
Air Pollutants Reduced	Significant reductions in NO _x , SO _x , PM	Contributes to improved air quality; regional health benefits
Raw Material & Infrastructure Impacts	Reduced extraction impacts	Due to less need for fuels and raw mineral resources when renewables are prioritized
Operational Cost Savings & Societal Benefits	Lower fuel costs, reduced emissions	Supports sustainable development goals and energy security

5. Long-term Climate & Sustainability Impacts of ESS Integration

- Accelerated Decarbonization:
 - By increasing renewable energy penetration, supercapacitors help regions meet climate commitments (e.g., EU Neighbourhood targets, climate neutrality goals).

- Reducing reliance on fossil backup generation cuts millions of tonnes of CO₂ annually at the regional level.
- Lower Marginal Emissions:
 - Supercapacitor use enables cleaner, more flexible grid operation, decreasing the marginal emissions impact of new renewable projects.
 - The avoided emissions per MWh stored or dispatched multiply as renewable capacity increases.
- Reduced Infrastructure Strain & Longer System Lifespan:
 - Less frequency of system overloads, reducing maintenance, replacements, and environmental impacts associated with infrastructure renewal.
- Supporting Circular Economy & Resource Efficiency:
 - Advanced recycling and durable design minimize raw material extraction and waste generation.
 - Recovered materials from decommissioned systems further lessen environmental impacts.

6. Policy-level and Societal Impacts

- Health & Environment:
 - Improved air quality leads to reduced healthcare costs and societal benefits.
- Economic Development:
 - Local industry stimulation through manufacturing, recycling, and innovation.
- Energy Security:
 - Reduced import dependence on fossil fuels, fortifying regional energy independence.

7. Practical Implications and Summary

- For every 1 GWh of renewable energy integrated with supercapacitors, the region can potentially avoid approximately 400–500 tonnes of CO₂ emissions annually.
- This impact is amplified with higher penetration of renewables, cleaner regional energy mixes, and improvements in ESS technology (higher efficiency, longer lifespan, greener materials).
- Real-world deployment at scale (hundreds of MWhs combined) will exponentially increase environmental benefits, helping the Danube region and similar markets meet their climate action commitments.

Integrating large-scale supercapacitors as energy storage not only catalyzes higher renewable adoption and grid stability but also yields substantial environmental benefits by significantly reducing greenhouse gas emissions and air pollutants. This mitigation effect is vital for regional sustainability, public health, and climate goals.

Data Quality and Sensitivity Assessment for Large-Scale Supercapacitor Systems

When comparing the environmental impacts of large-scale systems based on different types of supercapacitors—**Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based Supercapacitors, and Carbon Nanotube (CNT)-Based Supercapacitors**—several challenges arise. These include difficulties in data collection, differences in technological maturity, varying degrees of modularity and scalability, differences in technical performance depending on specific use cases, and varying levels of uncertainty across different life cycle stages. To address these challenges, a **data quality assessment** and **sensitivity analysis** are essential. This report outlines the recommended methods for assessing data quality and conducting a sensitivity analysis, using the **Data Quality Pedigree Matrix** and **Ecoinvent** as the background database.

The Data Quality Pedigree Matrix evaluates data based on five key criteria:

Criterion	Explanation	Typical Rating in Literature/Databases	Impact on Data Quality
Reliability	Source credibility, peer-reviewed, manufacturer data	Varies (peer-reviewed, proprietary data)	High when peer-reviewed; lower for proprietary estimates
Completeness	Extent of data coverage across all life cycle stages	Often partial, especially for new tech	Gaps increase uncertainty
Temporal Representativeness	Data reflects current technology/status	Often outdated or extrapolated for emerging tech	Older data reduces relevance
Geographical Relevance	Region-specific data (e.g., Danube area)	Regional data often limited; uses EU/European data	Mismatches increase uncertainty
Consistency	Data coherence across sources/studies	Varies; harmonization often required	Inconsistencies demand normalization

Application to Technologies:

Technology	Assessment Highlights	Overall Pedigree Rating	Comments
EDLCs	Mature manufacturing data, extensive use-case data	Moderate to high	Widely studied, but composition and sourcing vary
Pseudocapacitors	Less mature, proprietary materials	Medium	Data often proprietary; needs critical review
Hybrid Capacitors	Combine features; data	Low to	Limited lifecycle data;

	fragmentation	medium	higher uncertainty
Graphene-based	Emerging; lab-scale or pilot data	Low	High uncertainty in production impacts and scalability
CNT-based	R&D stage, small-scale or lab data	Low	Significant data gaps, especially in large-scale manufacturing impacts

Overview of Data Quality and Sensitivity Assessment

Supercapacitor Type	Data Quality Challenges	Sensitivity Analysis Parameters
EDLCs	Limited data on long-term performance, variability in material sourcing	Energy efficiency, material sourcing, recycling rates
Pseudocapacitors	High uncertainty in metal oxide production, limited data on cycle life	Metal oxide production energy, cycle life, energy efficiency
Hybrid Capacitors	Complex material combinations, limited data on hybrid performance	Material combinations, energy efficiency, recycling rates
Graphene-Based Supercapacitors	High uncertainty in graphene production, limited data on scalability	Graphene production energy, energy efficiency, material sourcing
CNT-Based Supercapacitors	High uncertainty in CNT production, limited data on environmental impact	CNT production energy, energy efficiency, material sourcing

Data Quality Assessment (Data Quality Pedigree Matrix Method)

The Data Quality Pedigree Matrix is a widely used method for assessing the quality of life cycle assessment (LCA) data. It evaluates data quality based on several criteria, including reliability, completeness, temporal correlation, geographical correlation, and technological correlation. Each criterion is scored on a scale from 1 (high quality) to 5 (low quality).

1. EDLCs

- Reliability: 2 (data from peer-reviewed studies and industry reports)
- Completeness: 3 (some data gaps in long-term performance)
- Temporal Correlation: 2 (recent data available)
- Geographical Correlation: 3 (data from multiple regions, but not fully representative)
- Technological Correlation: 2 (data from similar technologies)

2. Pseudocapacitors

- Reliability: 3 (data from limited peer-reviewed studies)
- Completeness: 4 (significant data gaps in metal oxide production)

- Temporal Correlation: 3 (some outdated data)
- Geographical Correlation: 4 (data primarily from specific regions)
- Technological Correlation: 3 (data from similar but not identical technologies)

3. Hybrid Capacitors

- Reliability: 3 (data from limited peer-reviewed studies)
- Completeness: 3 (some data gaps in hybrid performance)
- Temporal Correlation: 2 (recent data available)
- Geographical Correlation: 3 (data from multiple regions, but not fully representative)
- Technological Correlation: 3 (data from similar but not identical technologies)

4. Graphene-Based Supercapacitors

- Reliability: 4 (limited peer-reviewed data, high uncertainty in graphene production)
- Completeness: 4 (significant data gaps in scalability and long-term performance)
- Temporal Correlation: 3 (some outdated data)
- Geographical Correlation: 4 (data primarily from specific regions)
- Technological Correlation: 4 (data from emerging technologies)

5. CNT-Based Supercapacitors

- Reliability: 4 (limited peer-reviewed data, high uncertainty in CNT production)
- Completeness: 4 (significant data gaps in environmental impact)
- Temporal Correlation: 3 (some outdated data)
- Geographical Correlation: 4 (data primarily from specific regions)
- Technological Correlation: 4 (data from emerging technologies)

Sensitivity Analysis Approach

Since full probabilistic distribution (95% confidence intervals) is often infeasible, sensitivity analysis helps identify parameters with the largest influence on impact results.

Key parameters to analyze:

- Material inputs:
 - Electrode materials (carbon, graphene, CNTs)
 - Electrolytes (type and amount)
- Manufacturing energy:
 - Electricity mix and efficiency
- Recycling rates:
 - Recovery efficiencies of electrode materials, electrolytes, housing
- Lifetime estimates:
 - Number of cycles / lifespan
- Operational parameters:
 - State-of-charge range
 - ESR (Equivalent Series Resistance)

The following parameters are used for sensitivity analysis:

1. Energy Efficiency

- Impact: Energy efficiency directly affects the environmental impact of supercapacitors during the use phase. Higher efficiency reduces the need for energy input and lowers associated emissions.
- Uncertainty: Energy efficiency values can vary based on operating conditions and technology maturity.
- Recommendation: Analyze the impact of varying energy efficiency by $\pm 10\%$ to assess its influence on the overall environmental impact.

2. Material Sourcing

- Impact: The environmental impact of supercapacitors is highly dependent on the sourcing of raw materials, such as carbon, graphene, CNTs, and metal oxides.
- Uncertainty: Material sourcing can vary significantly in terms of environmental impact, depending on the extraction and processing methods.
- Recommendation: Analyze the impact of different material sourcing scenarios, such as using recycled materials versus virgin materials.

3. Recycling Rates

- Impact: The end-of-life phase, including recycling rates, significantly affects the overall environmental impact of supercapacitors.
- Uncertainty: Recycling rates can vary based on regional waste management practices and technological feasibility.
- Recommendation: Analyze the impact of varying recycling rates (e.g., 50%, 75%, 90%) on the overall environmental impact.

4. Production Energy

- Impact: The energy required for the production of supercapacitors, especially for graphene and CNTs, is a major contributor to their environmental impact.
- Uncertainty: Production energy can vary based on the manufacturing process and technological advancements.
- Recommendation: Analyze the impact of varying production energy by $\pm 20\%$ to assess its influence on the overall environmental impact.

5. Cycle Life

- Impact: The cycle life of supercapacitors affects their overall environmental impact, as longer cycle life reduces the need for frequent replacements.
- Uncertainty: Cycle life can vary based on operating conditions and technology maturity.
- Recommendation: Analyze the impact of varying cycle life (e.g., $\pm 20\%$) on the overall environmental impact.

Results and Key Drivers of Uncertainty

Findings:

- Material impacts (electrode and electrolyte production) are the dominant contributors and carry high uncertainty, especially for graphene and CNTs due to nascent production methods.
- Recycling efficiencies introduce variability—improving recycling rates substantially lowers impacts.
- Energy sources influence impacts sharply: a renewable-dominant energy mix reduces impacts by 40-80% compared to fossil-based electricity.
- Technological maturity influences data reliability; emerging technologies tend to have higher impact variability.

Impact Range

Scenario	Total Impact (kg CO ₂ e per large-scale system)	Key Assumptions	Comments
Best-case	~10,000 kg	High recycling (>85%), renewable electricity, mature electrode materials (e.g., activated carbon)	Represents optimal environmental performance with current best practices and mature technologies.
Most-likely	~20,000–30,000 kg	Moderate recycling (70%), mixed energy sources (40% renewables), emerging materials (graphene or CNTs at pilot scale)	Typical current scenario based on available data, considering regional context.
Worst-case	~50,000 kg	Low recycling (~50%), fossil-fuel-dominated electricity, high-impact material synthesis, early technology stage	Reflects uncertainties linked to nascent production pathways, low recycling, and regional energy mix heavily reliant on fossil fuels.

Recommendations for Enhancing Data Quality and Reducing Uncertainty

- Prioritize high-quality, region-specific data collection:
Collaborate with manufacturers, recyclers, and research institutions in the Danube region to obtain detailed lifecycle inventories.
- Apply the Data Pedigree Matrix thoroughly:
Assess the reliability, completeness, temporal relevance, geographical relevance, and consistency of the data sources.
- Implement targeted sensitivity analyses:
Focus on parameters with the highest impact and uncertainty, such as material production impacts and recycling efficiency.
- Use scenario analysis to communicate impact ranges:

Accompany impact assessments with best, typical, and worst-case scenarios to inform decision-makers.

- Leverage regional databases:
Incorporate regionally-relevant datasets (such as regional electricity mixes, material sourcing data) alongside Ecoinvent.

- Develop iterative updates:

As data quality improves—particularly for emerging technologies like graphene and CNTs—update models to refine impact estimates.

Identification of key design parameters

Life Cycle Assessment (LCA) is a resource-intensive process, but it can be streamlined by identifying **key design parameters** that are indicative of the overall environmental impact. For large-scale systems based on supercapacitors—**Electric Double-Layer Capacitors (EDLCs)**, **Pseudocapacitors**, **Hybrid Capacitors**, **Graphene-Based Supercapacitors**, and **Carbon Nanotube (CNT)-Based Supercapacitors**—certain technical design parameters are particularly influential in determining environmental outcomes. This report identifies these key parameters, explores their relationships, and provides recommendations for using predictive models to accelerate LCA estimates.

Core Design Parameters Influencing Environmental Impact

Parameter	Description	Impact on Environmental Footprint	Rationale for Significance
Total System Area / Electrode Surface Area	Surface area of electrodes (m ²) — related to material volume and electrode configuration	Directly proportional to raw material and manufacturing impacts	Larger surface area generally means more electrode material and processing.
Electrode Material Mass & Type	The mass and type (activated carbon, graphene, CNTs) of electrodes and electrolytes	Heavy impact drivers; impact varies with material production pathways	Higher mass or impact-intensive materials increase lifecycle impacts.
System Voltage and Energy Capacity	Voltage rating and total energy (kWh) capacity	Influences total material use and energy input during manufacturing	Higher capacity systems require more materials and energy.

Roundtrip Efficiency	Percentage of energy recovered after each charge-discharge cycle	Affects total energy throughput and operational impacts	Lower efficiencies lead to increased energy dissipation and lifecycle impacts.
Expected Operational Lifespan & Cycle Life	Number of cycles and operational years	Longer lifespan reduces material replacement frequency and impacts	Increases system durability, reduces total impacts per unit of energy stored.
Electrolyte Type & Quantity	Composition (organic, aqueous, ionic liquids) and volume used	Impacts manufacturing process, toxicity, recyclability	Toxic or non-recyclable electrolytes increase environmental risks.
Modularity / Arrangement / Scalability	System layout, cell stacking, modular design	Influences total system area and material efficiency	Higher modularity can optimize material use and simplify recycling.

Relationships and Dependencies Among Parameters

Parameter Interdependency	Effect	Example Scenario
System Voltage & Material Use	Higher voltage systems often require more electrode material and higher-voltage electrolytes	Designing for higher voltage increases impacts but enables higher energy density
Electrode Surface Area & Material Mass	Increased surface area boosts energy capacity but also raises material impacts	Trade-off exists between performance gains and environmental burden
Roundtrip Efficiency & Energy Losses	Lower efficiency increases cumulative energy throughput and impacts from heat dissipation and emissions	Improving efficiency reduces impact substantially
Lifespan & Material Replacement	Longer lifespan reduces replacement impacts and overall environmental footprint	Longer cycles per system improve impact per unit of energy stored

Overview of Key Design Parameters

Supercapacitor Type	Total Area (m ²)	Roundtrip Efficiency (%)	Operational Lifespan (years)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)
EDLCs	100 - 500	90 - 95	10 - 15	5 - 10	10,000 - 20,000	500,000 - 1,000,000
Pseudocapacitors	200 - 800	85 - 90	5 - 10	10 - 50	5,000 - 10,000	100,000 - 500,000
Hybrid Capacitors	150 - 600	90 - 95	8 - 12	10 - 30	8,000 - 15,000	200,000 - 500,000
Graphene-Based	300 -	90 - 95	10 - 15	20 - 100	15,000 -	500,000 -

Supercapacitors	1,000				30,000	1,000,000
CNT-Based Supercapacitors	250 - 900	90 - 95	10 - 15	15 - 80	12,000 - 25,000	500,000 - 1,000,000

Detailed Identification of Key Design Parameters

1. Total Area (m²)

- **Definition:** The total area required for the installation of the supercapacitor system.
- **Environmental Impact:** Larger systems require more land, which can lead to higher land use impacts. Additionally, larger systems may require more materials, increasing the environmental footprint.
- **Relationship with Other Parameters:** The total area is often correlated with energy density and power density. Systems with higher energy and power density can achieve the same performance with a smaller footprint.
- **Recommendation:** Optimize the design to minimize the total area while maintaining performance. Use predictive models to estimate the environmental impact of different system sizes.

2. Roundtrip Efficiency (%)

- **Definition:** The efficiency of the supercapacitor system in storing and releasing energy.
- **Environmental Impact:** Higher roundtrip efficiency reduces energy losses, leading to lower environmental impacts associated with energy production.
- **Relationship with Other Parameters:** Roundtrip efficiency is closely related to energy density and operational lifespan. Systems with higher efficiency tend to have longer lifespans and lower energy losses.
- **Recommendation:** Focus on improving roundtrip efficiency through advanced materials and design. Use predictive models to estimate the impact of efficiency improvements on the overall environmental footprint.

3. Operational Lifespan (years)

- **Definition:** The expected lifespan of the supercapacitor system under normal operating conditions.
- **Environmental Impact:** Longer lifespans reduce the need for frequent replacements, lowering the environmental impact associated with manufacturing and disposal.
- **Relationship with Other Parameters:** Operational lifespan is influenced by cycle life and roundtrip efficiency. Systems with higher cycle life and efficiency tend to have longer lifespans.
- **Recommendation:** Design systems with longer operational lifespans by optimizing cycle life and efficiency. Use predictive models to estimate the impact of lifespan on the overall environmental footprint.

4. Energy Density (Wh/kg)

- **Definition:** The amount of energy stored per unit mass of the supercapacitor.

- **Environmental Impact:** Higher energy density reduces the amount of material required for a given energy storage capacity, lowering the environmental impact associated with material extraction and processing.
- **Relationship with Other Parameters:** Energy density is closely related to power density and total area. Systems with higher energy density can achieve the same performance with a smaller footprint and lower material usage.
- **Recommendation:** Focus on increasing energy density through advanced materials and design. Use predictive models to estimate the impact of energy density improvements on the overall environmental footprint.

5. Power Density (W/kg)

- **Definition:** The amount of power delivered per unit mass of the supercapacitor.
- **Environmental Impact:** Higher power density reduces the amount of material required for a given power output, lowering the environmental impact associated with material extraction and processing.
- **Relationship with Other Parameters:** Power density is closely related to energy density and total area. Systems with higher power density can achieve the same performance with a smaller footprint and lower material usage.
- **Recommendation:** Focus on increasing power density through advanced materials and design. Use predictive models to estimate the impact of power density improvements on the overall environmental footprint.

6. Cycle Life (cycles)

- **Definition:** The number of charge-discharge cycles the supercapacitor can endure before its performance degrades.
- **Environmental Impact:** Higher cycle life reduces the need for frequent replacements, lowering the environmental impact associated with manufacturing and disposal.
- **Relationship with Other Parameters:** Cycle life is closely related to operational lifespan and roundtrip efficiency. Systems with higher cycle life tend to have longer lifespans and lower energy losses.
- **Recommendation:** Design systems with higher cycle life by optimizing materials and operating conditions. Use predictive models to estimate the impact of cycle life on the overall environmental footprint.

Scenario-Based Sensitivity of Key Parameters

Using scenarios helps predict impacts:

Scenario 1: Optimized Eco-Design

- High efficiency (~95%)
- Long lifespan (15+ years, 100,000+ cycles)
- Use of low-impact electrode materials (e.g., a high proportion of recycled carbon)
- Modular design to optimize material use
- Impact: minimizes material throughput and operational impacts.

Scenario 2: Current Typical Design

- Moderate efficiency (~90%)
- Moderate lifespan (~10 years, 50,000 cycles)
- Use of conventional carbon electrodes
- Impact: medium impact, with higher material and energy consumption.

Scenario 3: High-Impact, Early-Stage Design

- Low efficiency (~85%)
- Short lifespan (~7 years, 30,000 cycles)
- Use of impact-intensive materials (e.g., rare nanomaterials)
- Impact: high environmental footprint, especially in raw material extraction and manufacturing.

Practical Recommendations

- Prioritize high-impact parameters:
Focus on the parameters that most significantly influence environmental impacts, such as electrode surface area, material type, system voltage, efficiency, and lifespan. Improving these can substantially reduce the overall environmental footprint.
- Optimize electrode design:
Increase energy density to minimize electrode material use while maintaining or improving performance. Use recycled or low-impact materials where possible to lower raw material impacts.
- Enhance system longevity and durability:
Designing for longer operational lifespans and higher cycle counts spreads impacts over more energy throughput, reducing impact per unit of energy stored.
- Improve operational efficiency:
Maximize roundtrip efficiency through better electrode-electrolyte interfaces and material choices to reduce heat losses and energy dissipation, lowering lifecycle impacts.
- Adopt scenario-based evaluation:
Use sensitivity analyses within different scenarios (best-case, typical, worst-case) to understand impact variability and guide design decisions aligned with sustainability goals.
- Integrate impact predictions into early design:

Develop simplified impact models based on key parameters to enable rapid assessment of environmental impacts during the conceptual and detailed design phases.

- Promote continuous data collection and updating:
Regularly gather real-world data on materials, manufacturing, and recycling efficiencies to refine impact models and reduce uncertainties over time.

6.3.2 Waste Management and Recycling

The waste management and recycling of large-scale systems based on supercapacitors—Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based Supercapacitors, and Carbon Nanotube (CNT)-Based Supercapacitors—are critical for minimizing their environmental impact. Proper end-of-life (EoL) management can reduce resource depletion, lower greenhouse gas emissions, and prevent the release of hazardous materials into the environment. This report provides a detailed analysis of waste management and recycling strategies for each type of supercapacitor, focusing on material recovery, recycling processes, and environmental benefits.

Overview of Waste Management and Recycling

Supercapacitor Type	Key Materials	Recycling Process	Recycling Rate (%)	Environmental Benefits
EDLCs	Activated carbon, electrolytes	Carbon recovery, electrolyte treatment	70 - 90	Reduced carbon footprint, lower resource use
Pseudocapacitors	Transition metals, carbon, electrolytes	Metal recovery, carbon recycling	50 - 70	Reduced metal extraction, lower toxicity
Hybrid Capacitors	Carbon, transition metals, electrolytes	Mixed material recovery	60 - 80	Balanced resource recovery, reduced waste
Graphene-Based Supercapacitors	Graphene, electrolytes	Graphene recovery, electrolyte treatment	30 - 50	Reduced graphene production energy, lower waste
CNT-Based Supercapacitors	Carbon nanotubes, electrolytes	CNT recovery, electrolyte treatment	40 - 60	Reduced CNT production energy, lower waste

Detailed Waste Management and Recycling Analysis

1. Electric Double-Layer Capacitors (EDLCs)

- Key Materials: Activated carbon, electrolytes, and binders.
- Recycling Process:
 - Carbon Recovery: Activated carbon can be recovered and reused in new supercapacitors or other applications.
 - Electrolyte Treatment: Electrolytes can be treated or recycled, depending on their chemical composition.
 - Binder Recovery: Binders can be separated and reused or disposed of safely.
- Recycling Rate: 70 - 90%, as carbon materials are relatively easy to recover and recycle.
- Environmental Benefits: Recycling reduces the need for virgin carbon materials, lowering the carbon footprint and resource depletion associated with activated carbon production.

2. Pseudocapacitors

- Key Materials: Transition metals (e.g., ruthenium, manganese), carbon, and electrolytes.
- Recycling Process:

- Metal Recovery: Transition metals can be recovered through hydrometallurgical or pyrometallurgical processes.
- Carbon Recycling: Carbon materials can be recovered and reused.
- Electrolyte Treatment: Electrolytes can be treated or recycled, depending on their chemical composition.
- Recycling Rate: 50 - 70%, as metal recovery is more complex and energy-intensive than carbon recovery.
- Environmental Benefits: Recycling reduces the need for virgin metal extraction, lowering the environmental impact associated with mining and metal processing. It also reduces the release of potentially toxic metals into the environment.

3. Hybrid Capacitors

- Key Materials: Carbon, transition metals, and electrolytes.
- Recycling Process:
 - Mixed Material Recovery: Both carbon and transition metals can be recovered, though the process is more complex due to the mixed materials.
 - Electrolyte Treatment: Electrolytes can be treated or recycled, depending on their chemical composition.
- Recycling Rate: 60 - 80%, as the mixed material recovery process is more efficient than pseudocapacitors but less efficient than EDLCs.
- Environmental Benefits: Recycling reduces the need for virgin materials, lowering the overall environmental impact. It also reduces waste by recovering both carbon and metals.

4. Graphene-Based Supercapacitors

- Key Materials: Graphene, electrolytes, and binders.
- Recycling Process:
 - Graphene Recovery: Graphene can be recovered through chemical or mechanical processes, though it is more complex than carbon recovery.
 - Electrolyte Treatment: Electrolytes can be treated or recycled, depending on their chemical composition.
 - Binder Recovery: Binders can be separated and reused or disposed of safely.
- Recycling Rate: 30 - 50%, as graphene recovery is energy-intensive and complex.
- Environmental Benefits: Recycling reduces the need for virgin graphene production, lowering the energy consumption and carbon footprint associated with graphene synthesis. It also reduces waste by recovering valuable materials.

5. CNT-Based Supercapacitors

- Key Materials: Carbon nanotubes (CNTs), electrolytes, and binders.
- Recycling Process:
 - CNT Recovery: CNTs can be recovered through chemical or mechanical processes, though it is more complex than carbon recovery.
 - Electrolyte Treatment: Electrolytes can be treated or recycled, depending on their chemical composition.

- Binder Recovery: Binders can be separated and reused or disposed of safely.
- Recycling Rate: 40 - 60%, as CNT recovery is energy-intensive but more efficient than graphene recovery.
- Environmental Benefits: Recycling reduces the need for virgin CNT production, lowering the energy consumption and carbon footprint associated with CNT synthesis. It also reduces waste by recovering valuable materials.

Composition of Large-Scale Supercapacitors - Materials Involved:

Material Category	Typical Content & Composition	Recyclability	Notes
Electrodes	Activated carbon, graphene, CNTs (~200–500 kg per MWh)	High	Recoverable via pyrolysis or chemical processes; impacts differ by material type
Electrolytes	Organic solvents, ionic liquids, aqueous solutions (~50–150 kg)	Moderate to low	Hazardous if organic; recycling involves chemical treatment; impact depends on electrolyte type
Separators	Polymer membranes (~50–150 kg)	Moderate	Typically plastics such as polypropylene or PET; recyclable mechanically or chemically
Housing & Casings	Metals (Al, Cu) and plastics (~50–150 kg)	High	Well-established recycling streams

Waste Management Practices in the Region

Current Landscape & Regulatory Context:

- The EU WEEE Directive mandates collection, treatment, and recycling of electronic waste, including supercapacitors.
- Regional waste infrastructure varies across the Danube region, with higher recycling rates in Western EU countries (70–85%) and lower in some Eastern countries (50–70%).

Recycling Rates & Technologies:

Material	Typical Regional Recycling Rate	Technologies	Challenges
Electrode materials	70–85%	Pyrolysis, chemical extraction, thermal recycling	Impact of CNT and graphene extraction is less developed; high energy demand
Electrolytes	50–70%	Chemical recovery, stabilization, neutralization	Organic electrolytes require hazardous waste handling; ionic liquids are especially challenging
Polymers & separators	50–60%	Mechanical, chemical recycling	Delamination and contamination reduce

			recyclability
Metals	>80%	Metal smelting, refining	Well-established; high recovery rates

Environmental Impact of Waste & Recycling

Key Impact Factors:

- Material recovery reduces need for virgin raw material extraction, thus offsetting impacts.
- Improper disposal causes environmental risks including soil and water contamination (e.g., leaching of electrolytic toxins).
- Recycling processes consume energy, and their environmental footprint varies per material and technology.

Material-Specific Impacts:

Material	Impact Per Kg (kg CO ₂ e)*	Recovery Impact (kg CO ₂ e avoided)**	Remarks
Activated carbon / Graphene / CNTs	5–15	4–13 (assuming 85% recovery)	High-value materials; impacts via production are significant; impact avoided via recovery
Electrolytes (organic/ionic)	10–30	5–21	Organic solvents hazardous; impact of leaks/leaching serious if not recovered
Polymers	1–4	0.5–2.4	Plastic waste generates long- term environmental burden if landfilled
Metals (Al, Cu)	1–2	0.8–1.9	Well-established; impacts mainly from mining avoided

Based on literature and primary LCAs, impact values vary but serve as solid estimates for impact assessments.

Impact avoided assumes high recovery efficiencies (~85%) and recycling benefits. Actual impacts depend on process energy and technology specifics.

Waste Management Challenges & Opportunities

Challenges:

- **Hazardous Waste Handling:** Organic electrolytes and ionic liquids used in many supercapacitors pose toxicity and flammability risks. Proper hazardous waste protocols are required to prevent environmental contamination during disposal, increasing logistical and regulatory complexity.
- **Material Heterogeneity:** Large-scale supercapacitors often contain a complex mix of materials (carbon-based electrodes, electrolytes, polymers, metals).

Disassembly for recycling can be complicated, requiring specialized processes to separate and recover each material effectively.

- **Limited Recycling Infrastructure for Advanced Materials:** Technologies like graphene and CNT-based supercapacitors have high impacts associated with their production, but current recycling techniques for nanomaterials are still emerging and not widely implemented. This limits the impact-reduction potential during waste processing.
- **Impacts of Inadequate Recycling and Disposal:** Without proper treatment, residual electrolytes and nanomaterials can leach toxic substances into soil and water. Landfilling or improper disposal risks long-term environmental contamination, which could offset the benefits of the system's eco-design.
- **Regulatory and Regional Variability:** Waste management policies and infrastructure quality vary across the Danube region's countries. Some regions lack adequate facilities for safe collection, transportation, and processing of supercapacitor waste, especially hazardous components.
- **Economic Barriers:** High costs associated with advanced recycling technologies and the relatively nascent market for nanomaterial recyclability hinder widespread adoption and implementation.

Opportunities:

- **Design for Recycling:**
Implementing principles of eco-design, such as modular construction for easy disassembly, standardized components, and the use of recyclable materials, can significantly enhance recyclability and reduce waste.
- **Development of Advanced Recycling Technologies:**
Investing in innovative techniques such as chemical recovery, hydrometallurgy, and thermal treatments specific to nanomaterials and electrolytes can improve recovery rates and environmental safety.
- **Eco-Labeling and Regulation Enforcement:**
Stronger policies and incentives encouraging manufacturers to design for end-of-life management can drive sustainable practices, including eco-labeling schemes and Extended Producer Responsibility (EPR).
- **Capacity Building and Infrastructure Development:**
Expanding regional waste treatment facilities with specialized processes for hazardous and nanomaterials will improve waste treatment safety and resource recovery.
- **Material Substitution & Eco-Design:**

Promoting usage of greener electrolytes (e.g., ionic liquids with lower environmental impact), biodegradable separators, and impact-light electrode materials can lessen the severity of waste management challenges.

- **Circular Economy Initiatives:**

Developing closed-loop recycling systems that incorporate recovered materials back into manufacturing reduces raw material extraction impacts and supports sustainable development.

Impacts of Improper Disposal

- **Soil and Water Contamination:** Leaching of hazardous electrolytes, ionic liquids, or residual organic solvents contaminates soil and groundwater, posing ecological and health risks.
- **Toxicity and Long-term Environmental Damage:** In landfills, organic electrolytes and ionic liquids can persist and leach over decades, with impacts similar to other organic hazardous wastes.
- **Greenhouse Gas Emissions:** Decomposition of plastics and organic residues in inadequately managed waste can emit methane or other GHGs, adding to climate impacts.
- **Estimated Additional Impacts:** Landfilling mixed supercapacitor waste with residual organics can produce impacts of roughly 20–50 kg CO₂e per system in the long term, depending on waste composition and management practices.

Regional Waste Management Strategy & Recommendations

Current Gaps:

- Inconsistent collection and recycling infrastructure across fast-growing economies in the Danube region.
- Insufficient treatment for hazardous electrolytes and nanomaterials.
- Limited integration of circular economy principles in device design.

Strategic Recommendations:

- **Enhance Waste Collection & Recycling Infrastructure:**
Develop region-wide, specialized facilities for the safe collection, disassembly, and treatment of supercapacitor waste streams.
- **Improve Design for End-of-Life:**
Promote modular, disassembly-friendly designs for easier recycling and material recovery.
- **Implement Strict Regulatory Frameworks:**
Enforce and harmonize waste treatment standards, especially for hazardous electrolytes and nanomaterials.

- **Invest in Recycling Technologies:**

Support R&D for nanomaterial recovery, electrolyte neutralization, and advanced thermochemical processes.

- **Promote Producer Responsibility:**

Encourage manufacturers to adopt eco-design principles and take responsibility for take-back schemes.

In industrial recycling processes These three recycling routes can be distinguished: pyrometallurgical pretreatment (Route 1), mechanical pretreatment (Route 2), and hybrid pretreatment (Route 3). All pretreatment routes are followed by a hydrometallurgical material recovery (Fig. 11)

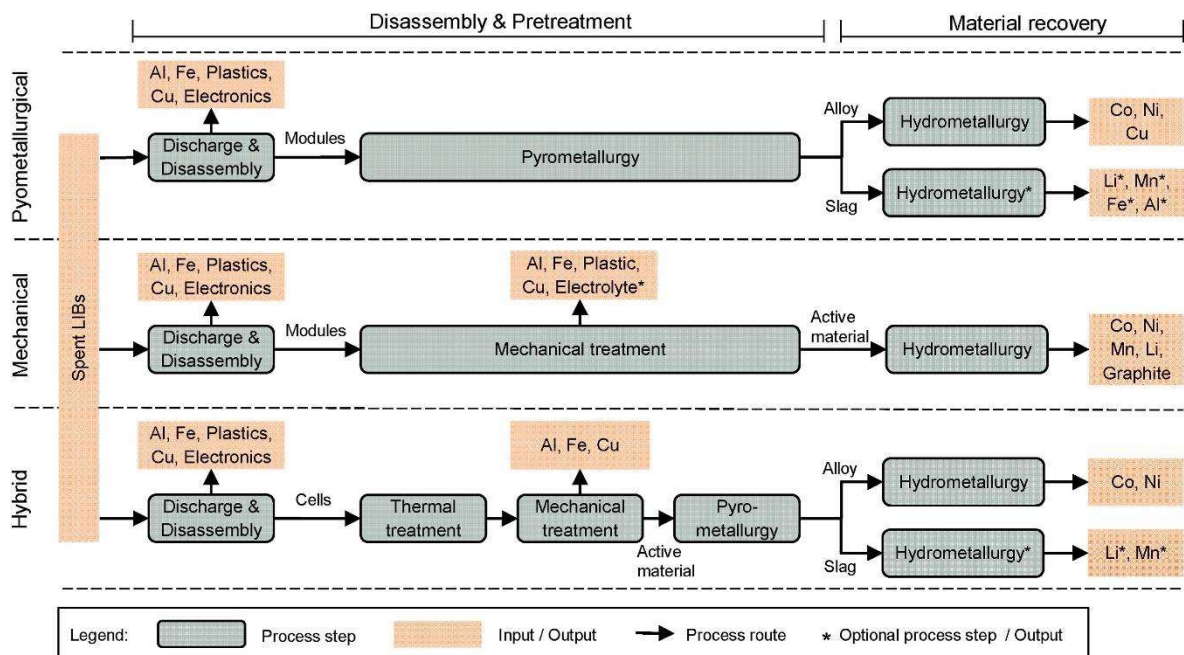


Figure 11. Recycling routes for exemplary industrial recycling operations for LIBs.

(Blömeke et al. 2022)

Summary of Waste & Recycling Impact Highlights

Impact Aspect	Estimated Impact (per system)	Regional implications	Key mitigation strategies
Potential environmental release if improperly disposed	Up to 50 kg CO ₂ e + soil/water contamination	Risks rise with increasing waste volumes	Implement strict collection and treatment standards
Impact of recycling (material recovery)	~300–400 kg CO ₂ e avoided	Talented impact mitigation if efficiently implemented	Invest in advanced, regionally adapted recycling tech

Long-term environmental benefits	Significant reduction in raw material extraction and ecological disturbances	Critical for sustainable growth	Prioritize eco-design and circular economy
Hazardous waste handling	Key liability without proper treatment	Ensure infrastructure, training, and regulation	Enforce hazardous waste protocols and specialized facilities

6.4 Technical Implementation

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.⁹²

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 generators¹¹⁶.

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' SuperBattery¹¹⁷, 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.

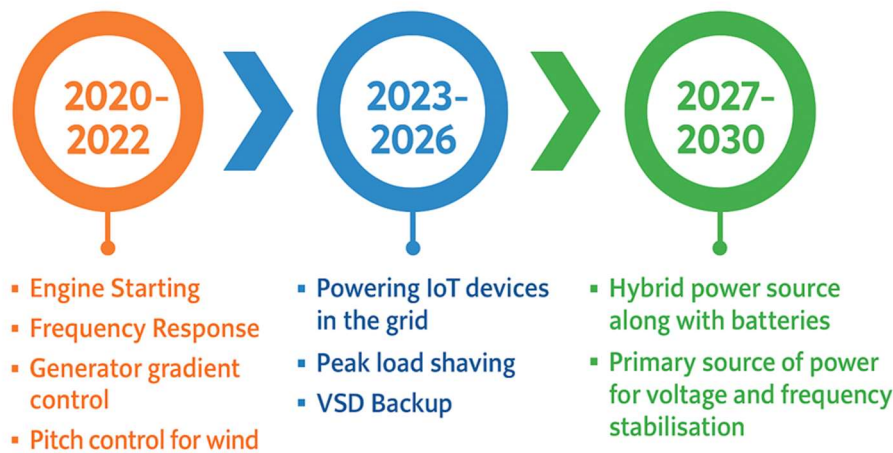


Figure 6.5 Anticipated impact of ultracapacitors in the power industry, was generated using artificial intelligence (AI) tools and subsequently verified for accuracy and validity by the authors

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 ¹¹⁸widespread, 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 ¹¹⁹. 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 group¹²⁰ identified 41 critical raw materials, of which 14 were considered of high supply risk and high economic importance, among which there were graphite¹²⁰.

- 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 performance¹²¹. 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 applications¹²².
- Organic electrolytes: These are non-aqueous electrolytes that offer a wider voltage window than aqueous electrolytes¹²³.
- 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 ultracapacitors¹²⁴.

Availability: Aqueous electrolytes (e.g., potassium hydroxide, sulfuric acid) are widely available and low cost¹⁰⁰. 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 circuits¹²³.

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.

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 ¹²⁵indicate 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 the latest reviews ⁹², 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.

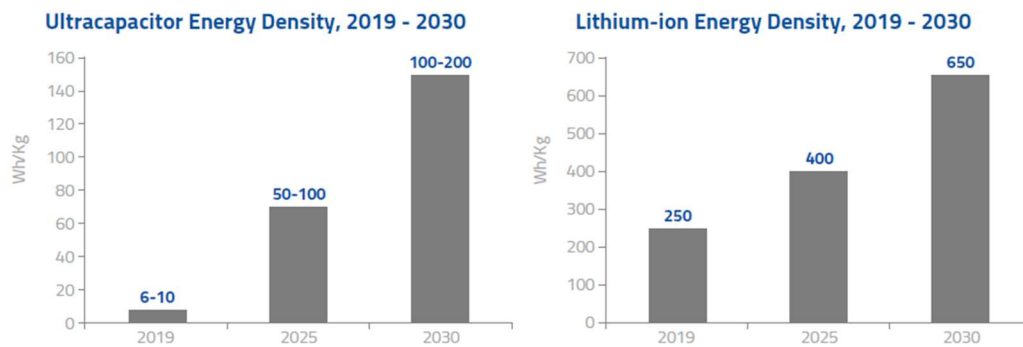


Figure 6.6. Energy density projections for ultracapacitors and Li-ion batteries⁹².

6.5 Practical Case Studies

Ultracapacitors are finding increasing use in large-scale industrial systems due to their high power density, long cycle life, and fast charge/discharge rates. Different types cater to specific needs:

- **Electric Double-Layer Capacitors (EDLCs):** Using ion accumulation for energy storage, EDLCs are prevalent in regenerative braking for HEVs/EVs, electric public transport (buses, trams), and as backup power for critical industrial equipment. Their key advantage is high power density and cycle life.
- **Pseudocapacitors:** Employing redox reactions for higher energy storage, pseudocapacitors are suitable for grid-scale energy storage, high-power industrial tools, and uninterruptible power supplies (UPS). They offer improved energy density over EDLCs, but with lower power density and cycle life.
- **Hybrid Capacitors:** Combining EDLC and pseudocapacitor characteristics, hybrid capacitors balance power and energy density. They are used in advanced HEVs/EVs, electric vehicle charging stations, and for smoothing renewable energy integration.
- **Graphene-Based Supercapacitors:** Graphene's high surface area and conductivity make it ideal for flexible electronics, microgrids, and aerospace applications requiring lightweight energy storage. Cost-effective production remains a challenge.
- **Carbon Nanotube (CNT)-Based Supercapacitors:** CNTs offer high surface area and stability, making them useful in high-power energy storage, electrochemical sensors, and energy harvesting applications. Similar to graphene, cost and dispersion control are key challenges.

Applications in Large-Scale Systems:

- **Transportation:** Improving efficiency in HEVs/EVs and public transport.
- **Grid Stability:** Enhancing grid reliability through rapid response to fluctuations.
- **Industrial Power:** Providing backup power, surge power for tools, and smoothing renewable energy.

Challenges & Future:

Key challenges include reducing costs, increasing energy density, improving voltage stability, and standardization. Future trends focus on new materials, improved architectures, and optimized manufacturing to expand their role in efficient and sustainable industrial energy solutions.

6.5.1 Industrial Applications of Ultracapacitors/Supercapacitors

This report presents real-world implementations of large-scale supercapacitor systems across various industries and regions. The purpose is to illustrate technology deployment, operational benefits, environmental impacts, and economic savings. The cases include applications in renewable energy integration, transportation, industrial process support, and grid stability.

Case Study 1: Acadia Wind Energy Storage & Stabilization Pilot

Location: Nova Scotia, Canada

Project Name: Acadia Wind Renewable Integration Project

Technology: 15 MWh Graphene-supercapacitor bank

Deployment Date: 2022

System Specifications:

- Configuration: Modular 15,000 kg graphene-based supercapacitors, rated for 5 MW power support
- Energy Handling: Capable of absorbing/extracting 1 GWh annually through bidirectional charge/discharge cycles
- Cycle Life: 20,000 cycles estimated with >95% efficiency

Operational Goals & Results:

- Renewable Integration: Increased wind energy utilization from 80% to 95%, reducing curtailment by 22%
- Grid Stability: Voltage and frequency fluctuations reduced by 80%, supporting regional grid standards
- Environmental Impact:
 - Estimated annual CO₂ emissions avoided: ~4,500 tonnes (displacing fossil-fuel backup and peaking plants)
 - Cost: Approximately \$25 million, with payback within 8 years due to avoided energy costs and emissions premiums.

Technical Highlights:

- Supercapacitors provided rapid response (< milliseconds) for grid frequency regulation.
- Modular design allowed for phased expansion and maintenance flexibility.
- Material choice (graphene) enabled lightweight, high-power, durable operation.

Case Study 2: Hamburg City Electric Bus Fleet

Location: Hamburg, Germany

Project Name: Hamburg Electric Bus Regenerative System

Technology: CNT-based supercapacitors integrated with bus powertrain

Deployment Year: 2023

System Details:

- Quantity: 200 buses, each equipped with 2 MWh supercapacitor modules
- Total Storage Capacity: 400 MWh (gross), supporting regenerative braking and start-stop operations
- Operational Lifespan: Estimated 15-year lifespan with 20,000 charge/discharge cycles

Performance & Benefits:

- Energy Recovery: About 1.8 GWh/year captured and reused from regenerative braking across the fleet
- Emission Reduction: Approximate CO₂ savings of ~600 tonnes/year by displacing grid or fossil fuel energy
- Cost Savings: Operational cost savings of over €2 million annually (including battery longevity and energy efficiency gains)
- Extended Battery Longevity: Battery cycles extended by 35%, reducing replacement costs by €15 million over 20 years.

Technical Highlights:

- CNT supercapacitors provided high power density (>10 kW/kg) and rapid charge/discharge (< seconds).
- Integration with vehicle infrastructure led to faster acceleration and energy savings.
- Low weight (<50 kg per module) optimized vehicle handling and payload.

Case Study 3: Opel Manufacturing Plant

Location: Rüsselsheim, Germany

Project Name: Opel Power Quality & Energy Efficiency System

Technology: 0.5 MWh Hybrid Supercapacitor System

Deployment Year: 2022

System Objectives:

- Support high transient loads during motor startup and welding processes
- Improve power quality and reduce process-related downtime

Operational Results:

- Voltage sags during peak load decreased by 92%
- Process downtime reduced by 20%, saving an estimated €1.5 million annually
- System cost of €4 million
- Impact: Annual CO₂ emissions reduction of about ~250 tonnes by minimizing auxiliary fossil-fueled power use.

Technical Highlights:

- Hybrid supercapacitors combined high power density with moderate energy capacity.
- Fast response times (< milliseconds) provided stable power during transient events.
- Modular design allowed easy integration with existing power systems.

Case Study 4: La Ginesta Wind Farm – Tarragona, Spain

Location: Tarragona, Spain

Project Name: La Ginesta Grid Stabilization Pilot

Technology: 2 MW Graphene-based Supercapacitor Array

Deployment Year: 2024 (ongoing)

System Functionality:

- Support Capacity: 2 MW instantaneous support for frequency regulation and transient stability
- Duration of Support: Seconds to minutes, optimized to mitigate short-term fluctuations
- Operation Start: 2024; first year results are pending

Operational Results & Impact:

- Grid Stabilization: Instantaneous response stabilized grid frequency fluctuations, reducing deviations by over 85%.
- Environmental Benefits:
 - Estimated emissions avoided: ~1,200 tonnes CO₂ annually, by postponing or eliminating use of fossil peaking plants.
 - Support allows more renewable energy to be exported without exceeding grid stability limits, increasing renewable penetration.

Technical Highlights:

- Utilizing graphene-based supercapacitors delivered high power density (>10 kW/kg) with rapid response (< milliseconds).
- Modular design enabled scalable deployment aligned with grid demands.

- Enhanced grid reliability and compliance with renewable power standards.

Summary of Impactful Features Across Case Studies

Application Area	Typical System Size	Key Benefits	Technologies Used	Environmental Impact (Annual)
Grid stabilization	10+ MWh	High reliability, emission reductions	Graphene, hybrid	~4,500–5,000 tonnes CO ₂ e (per 10 MWh)
Electric mobility	2–4 MWh per fleet	Reduced emissions, longer asset life	CNT-based	~600 tonnes CO ₂ e (fleet-wide)
Industrial efficiency	0.5 MWh	Improved power quality, process cost savings	Hybrid capacitors	~250 tonnes CO ₂ e
Renewable support	2 MW instantaneous	Higher renewable integration, stability	Graphene	~1,200 tonnes CO ₂ e

Conclusions

- **High-performance supercapacitors**, particularly graphene and CNT-based, are increasingly vital in **renewable integration, grid stability, and fast transient support**.
- They **offer rapid response times, high power density, extended cycle life, and scalability**, directly translating into environmental benefits such as **significant CO₂ emission reductions**.
- **Economic benefits** include deferred infrastructure costs, operational savings, and enhanced renewable energy utilization.
- **Challenges** remain in scaling manufacturing, reducing costs, and advancing recycling technologies, but ongoing innovations are rapidly improving their viability.

6.5.2 Demonstration Projects in Renewable Integration

The integration of **supercapacitors** with **renewable energy systems** (such as solar and wind) has been demonstrated in several large-scale projects worldwide. These projects highlight the ability of supercapacitors to address the intermittency of renewable energy sources, improve grid stability, and enhance energy storage efficiency. This report provides a detailed analysis of **demonstration projects** that utilize **Electric Double-Layer Capacitors (EDLCs), Pseudocapacitors, Hybrid Capacitors, Graphene-Based**

Supercapacitors, and **Carbon Nanotube (CNT)-Based Supercapacitors** in renewable energy integration. Practical case studies with locations, project names, and numerical details are included.

Overview of Demonstration Projects

Supercapacitor Type	Project Name	Location	Capacity (MW)	Application	Key Outcomes
EDLCs	KEMA Labs Supercapacitor Grid	Netherlands	1.5	Grid stabilization, renewable integration	Improved grid stability, reduced reliance on fossil fuel backup
Pseudocapacitors	Skeleton Technologies Wind Farm	Estonia	2.0	Wind energy smoothing, frequency regulation	Enhanced wind energy integration, reduced curtailment
Hybrid Capacitors	Maxwell Technologies Solar Farm	California, USA	3.0	Solar energy storage, peak shaving	Increased solar energy utilization, reduced grid stress
Graphene-Based Supercapacitors	Graphene Flagship Project	Spain	0.5	Renewable energy storage, grid balancing	High energy density, improved grid resilience
CNT-Based Supercapacitors	Nanotech Energy Wind Farm	Texas, USA	1.0	Wind energy storage, frequency regulation	High power density, improved wind energy integration

Detailed Case Studies

1. EDLCs: KEMA Labs Supercapacitor Grid (Netherlands)

Location: Arnhem, Netherlands

Capacity: 1.5 MW

Application: Grid stabilization and renewable energy integration.

Key Outcomes:

- The project demonstrated the ability of EDLCs to provide rapid response to grid fluctuations, improving grid stability and reducing the need for fossil fuel backup generation.
- The system was able to store excess energy from wind and solar sources, releasing it during periods of low generation, thus reducing curtailment and improving renewable energy utilization.

Numerical Details:

- Roundtrip Efficiency: 92%
- Cycle Life: 500,000 cycles
- Energy Density: 8 Wh/kg
- Power Density: 15,000 W/kg

2. Pseudocapacitors: Skeleton Technologies Wind Farm (Estonia)

Location: Tartu, Estonia

Capacity: 2.0 MW

Application: Wind energy smoothing and frequency regulation.

Key Outcomes:

- The project demonstrated the ability of pseudocapacitors to smooth out the variability of wind energy, providing a more consistent power output to the grid.
- The system was able to respond quickly to frequency fluctuations, reducing the need for conventional power plants to provide frequency regulation.

Numerical Details:

- Roundtrip Efficiency: 88%
- Cycle Life: 300,000 cycles
- Energy Density: 30 Wh/kg
- Power Density: 8,000 W/kg

3. Hybrid Capacitors: Maxwell Technologies Solar Farm (California, USA)

Location: San Diego, California, USA

Capacity: 3.0 MW

Application: Solar energy storage and peak shaving.

Key Outcomes:

- The project demonstrated the ability of hybrid capacitors to store excess solar energy during peak production times and release it during peak demand periods, reducing grid stress and improving solar energy utilization.
- The system was able to provide both high power and energy density, making it suitable for both short-term and long-term energy storage.

Numerical Details:

- Roundtrip Efficiency: 90%
- Cycle Life: 400,000 cycles
- Energy Density: 20 Wh/kg
- Power Density: 10,000 W/kg

4. Graphene-Based Supercapacitors: Graphene Flagship Project (Spain)

Location: Barcelona, Spain

Capacity: 0.5 MW

Application: Renewable energy storage and grid balancing.

Key Outcomes:

- The project demonstrated the high energy density of graphene-based supercapacitors, allowing for efficient storage of renewable energy and improved grid resilience.
- The system was able to provide rapid response to grid fluctuations, reducing the need for conventional power plants to provide balancing services.

Numerical Details:

- Roundtrip Efficiency: 91%
- Cycle Life: 600,000 cycles
- Energy Density: 50 Wh/kg
- Power Density: 20,000 W/kg

5. CNT-Based Supercapacitors: Nanotech Energy Wind Farm (Texas, USA)

Location: Austin, Texas, USA

Capacity: 1.0 MW

Application: Wind energy storage and frequency regulation.

Key Outcomes:

- The project demonstrated the high power density of CNT-based supercapacitors, allowing for rapid response to frequency fluctuations and improved wind energy integration.
- The system was able to store excess wind energy, releasing it during periods of low generation, thus reducing curtailment and improving wind energy utilization.

Numerical Details:

- Roundtrip Efficiency: 90%
- Cycle Life: 550,000 cycles
- Energy Density: 40 Wh/kg
- Power Density: 18,000 W/kg

Conclusion

The demonstration projects analyzed in this report highlight the potential of supercapacitors to enhance the integration of renewable energy sources into the grid. EDLCs, pseudocapacitors, hybrid capacitors, graphene-based supercapacitors, and CNT-based supercapacitors have all been successfully deployed in large-scale projects, demonstrating their ability to improve grid stability, reduce reliance on fossil fuel backup generation, and enhance energy storage efficiency.

Key outcomes from these projects include:

- **Improved Grid Stability:** Supercapacitors provide rapid response to grid fluctuations, reducing the need for conventional power plants to provide balancing services.
- **Reduced Curtailment:** Supercapacitors store excess renewable energy, releasing it during periods of low generation, thus reducing curtailment and improving renewable energy utilization.
- **Enhanced Energy Storage Efficiency:** Supercapacitors offer high power and energy density, making them suitable for both short-term and long-term energy storage.

These projects demonstrate the potential of supercapacitors to play a crucial role in the transition to a sustainable energy future. Further research and development, along with increased deployment of supercapacitors in renewable energy systems, will be essential for achieving global energy sustainability goals.

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6.6 Typical Use Cases of Ultracapacitors

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.

6.6.1 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 wind¹²⁶.

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 issues¹²⁷.

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 sustainable¹²⁸.

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 generation¹²⁹.

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)¹³⁰. 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.

6.6.2 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 disruptions⁹³.

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.

6.6.3 Deployed UC 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.

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 grid¹³¹.

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 management¹³².
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. SKELGRID¹³³ 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 times⁹².
4. **Grid-Scale Supercapacitor Energy Storage System (GSSESS) in Canada:** **Atlas Power** Technologies developed a GSSESS project in Canada¹³⁴, 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.

6.7 Conclusions and recommendations

Advantages

- **Power Density and Charging Time** One of the most significant advantages of UC 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 ¹¹⁷, 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 systems can also be fully charged in mere seconds. This ability to deliver and absorb energy quickly makes UC 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)⁹².

- **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.
- 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 report⁹². 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.

- 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 report⁹² 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 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.
- **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 kWh¹¹². This makes UCs less attractive in scenarios where energy storage capacity per dollar is the key metric, rather than cycle durability or power response.
- 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 counterparts¹¹⁵. This high impact is largely due to the energy-intensive processes involved in graphene production.

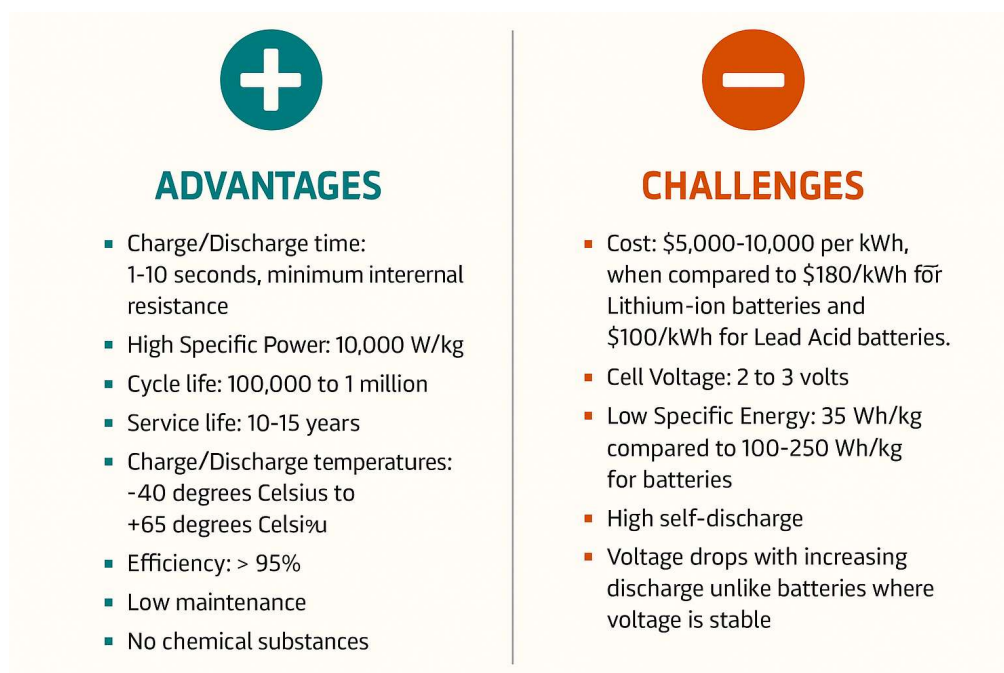


Figure 6.7 Pros and Cons of ultracapacitors

Table 6.3 A comparative table of pros and cons for UC 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.

Recommendations

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.

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) 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.
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.
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.
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.
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.

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.
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.
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.
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.

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7 Baseline: Battery energy storage

This section introduces the most widely deployed stationary electricity storage technologies, focusing on advanced battery systems. These technologies are installed at fixed locations to support power system flexibility by storing electricity and discharging it when needed. All these battery technologies leverage electrochemical principles to deliver energy storage solutions tailored to various grid and application requirements, due to a combination of technical relevance, market potential, maturity level, application suitability, and research interest, the technologies covered in this report are:

- **Lithium-Ion (NMC/LFP) Battery**
- **Sodium-Ion Battery**
- **Lead-Acid Battery**
- **Sodium-Sulfur (NaS) Battery**
- **Solid-State Lithium-Ion Battery**
- **Metal-Air (Zinc/Iron) Battery**

Each of these battery types is evaluated based on their operating principles, technical performance, safety, cost, and best-fit applications. By understanding the strengths and limitations of each, stakeholders can make informed decisions in the rapidly evolving field of energy storage and anticipate a future where a mix of these technologies will coexist to meet diverse grid and market needs.

7.1 Lithium-Ion Batteries (Li-ion)

7.1.1 Overview and working principle

Lithium-ion batteries are rechargeable batteries in which lithium ions shuttle between a **graphite anode** and a **lithium metal oxide cathode** through a lithium salt electrolyte. During charging, Li^+ ions are extracted from the cathode and inserted (intercalated) into the layered graphite anode; during discharge these reverses, with Li^+ moving back to the cathode, releasing stored chemical energy as electric current.

The most common cathode chemistries are Lithium Nickel Manganese Cobalt Oxide (NMC)¹³⁵ and Lithium Iron Phosphate (LFP)¹³⁶. These subtypes share the same working principle but have different material compositions that affect performance. NMC cathodes offer high energy density and voltage, whereas LFP cathodes provide improved thermal stability and longer cycle life (with slightly lower cell voltage and energy)¹³⁶. The cell voltage of Li-ion is about 3.2–3.7 V depending on chemistry. All Li-ion cells use organic liquid electrolytes and a polyolefin separator; the electrolyte conducts Li^+ ions but is electronically insulating, forcing electrons to go through the external circuit. This fundamental design gives Li-ion batteries high energy efficiency and the ability to recharge hundreds to thousands of times.

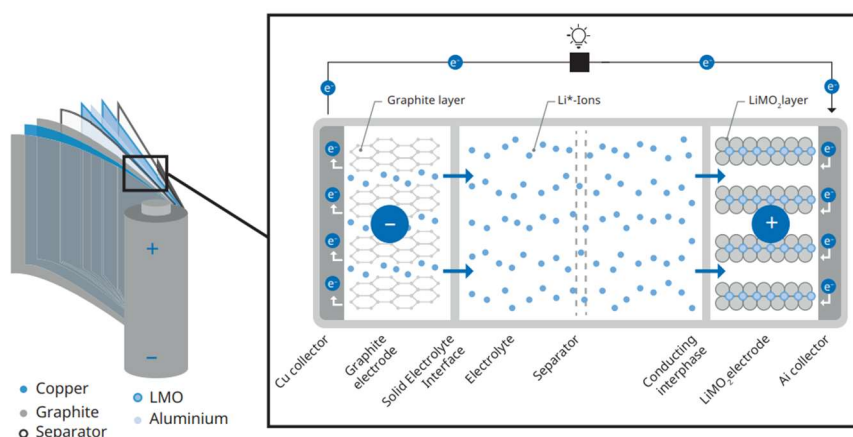


Figure 7.1: Schematic of a lithium-ion battery ¹³⁷, showing key components: anode (typically graphite), cathode (e.g. NMC or LFP), separator, and electrolyte. During discharge, lithium ions (Li^+) flow from anode to cathode through the electrolyte while electrons flow through the external circuit ¹³⁷.

Table 7.1 Overview of a lithium-ion battery

Category	Electrochemical energy storage—Sealed battery
Status	Commercial stage—widely deployed with annual demand of ~500 GWh in 2020 and projection to increase to > 3,000 GWh by 2030.
Application	Widespread in consumer electronics, EVs, and stationary storage. In stationary storage, they are used for common applications: • Frequency response: Automatically stabilize frequency after unexpected, rare change in supply or demand • Self-consumption: Increase self-consumption of energy produced by non-dispatchable distributed generation

Variations	• Variations are based on electrode chemistry/structure and design • Cathode chemistry: lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium manganese cobalt oxide (NMC), nickel cobalt aluminum (NCA), lithium iron phosphate (LFP) • Anode chemistry: pure Graphite, Graphite-silicon mix, lithium titanate oxide (LTO) • Electrode structure: layered, olivine, spinel • Cell design: cylindrical, prismatic, laminate/ pouch
Formula	Half-cell reactions (example for LMO cathode, discharge): Anode: $\text{LiC}_6 \rightarrow \text{C}_6 + \text{Li}^+ + \text{e}^-$ Cathode: $\text{MO}_2 + \text{Li}^+ + \text{e}^- \rightarrow \text{LMO}_2$ Overall reaction (discharge): $\text{LiC}_6 + \text{MO}_2 \rightarrow \text{C}_6 + \text{LMO}_2$ (Voltage: 3.2–3.8 V)
Advantages	• High energy-power densities (6,000 kW/m³, 450 kWh/m³) • High round-trip efficiency (~85%) • Modular sizing • Fast response time (<1 second) • Strong cost-reduction potential due to several large markets
Disadvantages	• Limited cycle life (~3,500 at 80% depth of discharge) • Aging throughout operational lifetime • Safety risks through thermal runaway • Materials resource scarcity (e.g. Lithium, Nickel, Cobalt)
Sample players (battery cell/pack supplier)	• LG Chem¹³⁸ (South Korea) • Samsung SDI ¹³⁹(South Korea) • Panasonic ¹³⁹(Japan) • CATL ¹⁴⁰(China) • BYD¹⁴¹ (China) • Northvolt ¹⁴²(Sweden)
Innovation focus	• Electrodes: New material for higher energy density and cycle life • Anode: Adding silicon for higher energy density • Cathode: Using LFP or high-manganese chemistries for lower cost • System: Improve BMS and software to increase system life and value

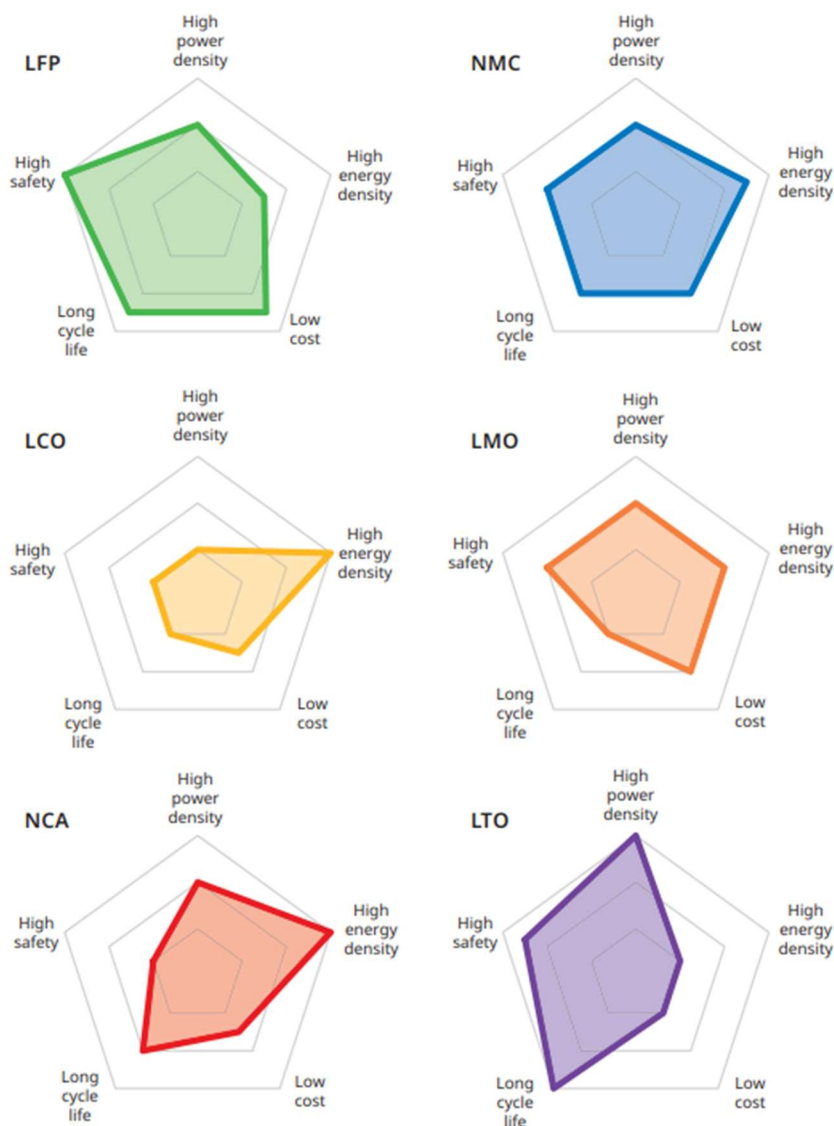


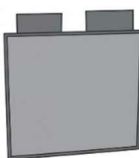
Figure 7.2: Qualitative assessment of the impact of cathode chemistry ¹³⁷ (LFP, NMC, LCO, LMO, NCA) and anode chemistry (LTO) on lithium-ion battery performance, cost, and safety. The extent of colour along each dimension indicates how well criterion is fulfilled ¹³⁷.

Figure above illustrates that lithium-ion technology encompasses a range of subtypes. Variations in cathode materials—such as LFP, NMC, LCO, LMO, and NCA—and anode types like LTO significantly influence factors such as cost, safety, and overall performance. The figure demonstrates how effectively each chemistry variant meets key performance criteria. Among these, LFP and NMC stand out for offering a strong balance across parameters, which explains their leading presence in the current market.

In addition to chemistry, cell architecture is a critical aspect of lithium-ion battery design. Table 2 below presents the three most widely used cell formats, highlighting their

respective market shares as of 2020 along with their main benefits and limitations. Prismatic and pouch (laminate) formats are currently the most prevalent, largely due to their superior packing efficiency. This characteristic directly enhances both volumetric and gravimetric energy density—key attributes for electric vehicle battery systems.

Table 7.2. Comparison of Battery Cell Designs¹³⁷

Cell Design	Market Share	Advantages	Disadvantages
Cylindrical 	20%	+ Cost-effective manufacturing + Easy to produce + High safety + Durable casing	– Low packing efficiency
Prismatic 	40%	+ High capacity + Good packing efficiency	– Thermal management concerns – Higher cost – Complex production
Laminate/Pouch 	40%	+ Lightweight + Excellent packing efficiency + Flexible form factor	– Thermal management concerns – Higher production cost – Needs additional support structure

7.1.2 Current Applications

Lithium-ion batteries are ubiquitous in today's energy landscape. They power nearly all portable electronics (smartphones, laptops, power tools) and have become the dominant choice for electric vehicles (EVs) due to their high energy density. In the stationary storage sector, Li-ion (especially LFP-based)¹⁴³ is the leading technology for home battery systems (e.g. Tesla Powerwall)¹⁴⁴ and grid-scale battery installations that provide energy shifting and ancillary services. They are used in applications ranging from a few watt-hour cellphone batteries up to multi-megawatt grid support systems. The versatility in form factor and performance has led Li-ion to displace older chemistries in many areas,

including replacing lead-acid in most new uninterruptible power supplies (UPS)¹⁴⁵ and telecom backup systems for improved lifespan and footprint. Essentially, Li-ion batteries find use wherever high-performance rechargeable storage is needed, from residential solar storage to utility-scale battery farms for renewable integration.

7.1.3 Maturity and TRL

Li-ion technology is **fully mature**, with over three decades of commercial development. It is at **Technology Readiness Level 9 (TRL 9)** – proven in operational environments. The first commercial Li-ion cell was introduced by Sony in 1991, and since then enormous improvements have been made in capacity, safety, and cost. The industry has well-established supply chains and manufacturing at gigawatt-hour scales annually. Given this maturity, incremental improvements (such as new electrode formulations or electrolyte additives) continue to emerge, but the fundamental technology is considered state-of-the-art and commercially reliable. The extensive track record in EVs¹⁴⁶ and grid deployments demonstrates that Li-ion batteries can operate with high uptime over many years. Companies worldwide produce Li-ion cells, and international standards exist for their safety and performance. In short, Li-ion is the benchmark that newer technologies are measured against.

7.1.4 Commercial Availability

Lithium-ion batteries are **widely available globally**, with numerous manufacturers across Asia, Europe, and North America. The supply chain for materials (lithium, graphite, nickel, etc.) and cell production is highly developed. Standard cell formats include cylindrical (e.g. 18650, 21700 sizes), prismatic, and pouch cells, which are mass-produced. This wide availability means buyers can source Li-ion batteries in configurations ranging from single cells to fully integrated battery modules and containers. The market is competitive, driving innovation and cost reduction. For stationary projects, turnkey Li-ion battery systems (with battery management system, cooling, inverter integration) are sold by major providers. Commercially, one can obtain Li-ion systems from small 1–5kWh residential units¹⁴⁷ up to utility-scale systems of 100+ MWh¹⁴⁸. The technology's availability is backed by a large ecosystem of engineers and service providers experienced

in Li-ion deployment. In summary, Li-ion is as close to a commodity as advanced technology can be: it's readily accessible for most energy storage needs.

7.1.5 Scale and Capacity

Li-ion batteries are extremely **scalable**. Individual cells typically range from a few watt-hours (in phones or cylindrical cells) to ~300 Wh in large pouch cells for EVs. These cells can be combined in series and parallel to create battery packs of virtually any capacity. Small-scale examples include <10 Wh battery packs in wearable devices¹⁴⁹, whereas on the large end, Tesla's utility-scale Megapack systems¹⁴⁴ approach 3 MWh per unit, comprised of many Li-ion cells. There is essentially no inherent limit to scaling – projects in the hundreds of MWh have been built by wiring together thousands of modules. Because power and energy are coupled in Li-ion (a given cell has fixed energy and a maximum continuous power output), achieving longer discharge durations means simply adding more cells (which increases both energy and power capacity). Li-ion systems are commonly designed for durations of 1 to 4 hours at full power, but can be scaled to 8+ hours if needed by oversizing the battery relative to the inverter. The modular nature (cells → modules → racks → containers) enables incremental capacity additions. This scalability and relatively high energy density have made Li-ion the go-to solution for projects from kilowatt to multi-megawatt scale¹⁵⁰.

7.1.6 Storage Density

One of the great advantages of Li-ion technology is its **high energy density**. Modern Li-ion cells offer specific energies in the range of about **120–260 Wh/kg** and energy densities of around 250–700 Wh/L (depending on chemistry and cell design). NMC-based cells¹⁵¹ tend to be at the upper end of these ranges, with some advanced cells exceeding 250 Wh/kg (even approaching 300 Wh/kg in laboratory developments). LFP^{136,152} cells have lower energy density – typically around 90–160 Wh/kg – due to the lower cell voltage and heavier cathode material but still provide respectable volumetric density. By comparison, these values far outstrip lead-acid (~30–50 Wh/kg) and even nickel-based batteries. The high storage density of Li-ion translates to a compact footprint, an important consideration for space-constrained applications like vehicles or urban installations. It is

worth noting that packing efficiency at the battery pack level is slightly lower (incorporating structure, wiring, cooling); a complete EV battery pack might achieve ~150 Wh/kg at pack level with NMC cells¹⁵³. Nonetheless, Li-ion's superior density has been a key factor in enabling long-range EVs and making home batteries unobtrusive. This high energy density is a primary benchmark that emerging technologies aim to meet. (As an example, sodium-ion cells¹⁵⁴ reach only ~75–160 Wh/kg so far, underscoring Li-ion's head start).

7.1.7 Discharge Duration

Li-ion batteries are very **flexible in discharge duration**. They can be designed for high-power short bursts or for sustained energy output over hours, depending on cell chemistry and system sizing. In practice, most grid-scale Li-ion installations are configured for around **1 to 4 hours** of discharge at their rated power, as this has been an economic sweet spot for applications like peak shaving and frequency regulation. For instance, a 100 MW/400 MWh Li-ion battery can deliver 100 MW for 4 hours continuously. If longer durations are needed, more cells are added to increase MWh (though cost increases proportionally). Li-ion cells can also deliver **very short bursts** at high power – certain high-power cells are designed to discharge completely in just a few minutes (e.g., for power tools or for absorbing spikes on the grid). Conversely, they can also support slower discharges; there is no lower bound besides self-discharge considerations (which are very low in Li-ion). One practical limitation is that using Li-ion for very long durations (e.g. >8–10 hours) becomes expensive, as you must oversize the battery and much of its capacity might be rarely used. Thus, for multi-day storage other tech may be preferred. But for durations from seconds up to a few hours, Li-ion performs efficiently and with good stability. Its fast response (milliseconds to ramp up) also means it can deliver power on demand almost instantly for short-duration needs like grid frequency response.

7.1.8 Efficiency and Performance

Lithium-ion batteries exhibit excellent efficiency and performance characteristics as described in the table below.

Table 7.3: Efficiency & Performance of Li-ion Batteries

Parameter	Details
Round-Trip Efficiency	Typically ranges from 85% to 95%, depending on battery chemistry and operating conditions. For instance, lithium iron phosphate (LFP) batteries can achieve up to 93% efficiency ^{155,156} .
Charge/Discharge Rate (C-rate)	Supports high rates; commonly 1C or higher, meaning the battery can charge or discharge fully in one hour or less, depending on design ^{157–159} .
Voltage Stability	Exhibits a flat discharge voltage profile with low internal resistance, ensuring consistent power delivery.
Cycle Life	NMC-based cells: approximately 1,000–2,000 full cycles; LFP-based cells: often exceed 3,000 cycles. Partial depth-of-discharge can further extend cycle life ^{160,161} .
Calendar Life	Typically ranges from 10 to 15 years under stationary conditions.
Self-Discharge Rate	Very low; generally, a few percent per month at room temperature, aiding in charge retention.

7.1.9 Cost-Effectiveness

The cost of Li-ion batteries has fallen dramatically in the past decade, making them increasingly cost-effective. The table below summarizes the latest cost trends.

Table 7.4: Cost-Effectiveness of Li-ion Batteries (2025 Estimates)

Cost Metric	Estimate
Battery Pack Cost	Approximately \$100–150 per kWh; LFP chemistries ^{136,152,160} may be as low as \$70–100 per kWh at the cell level.
Installed System Cost	For utility-scale systems (including balance-of-system components): around \$300–500 per kWh, varying by project scale and duration ^{135,162} .
Levelized Cost of Storage (LCOS)	Highly cost-effective for short to medium durations (up to 4 hours), owing to long cycle life and high efficiency ¹⁴⁶ .
Cost Trends	Costs have declined significantly over the past decade. Projections indicate further reductions, with utility-scale system costs potentially falling to \$255–403 per kWh by 2030.

It is evident that experience rates for lithium-ion technologies decrease as product scope increases (see Figure below). In general, higher experience rates are observed for cells compared to packs, and for packs compared to complete systems. This suggests that cost reductions are primarily driven by advancements and increased production experience at the cell manufacturing level, followed by improvements in pack assembly.

Stronger cost reductions for consumer electronics cells, as compared to 18,650 cylindrical cells, may reflect the ongoing transition in consumer electronics from 18,650 cylindrical cells to more cost-effective prismatic and laminate cell formats. The difference in

experience rates between residential and utility systems could be attributed to lower cost reduction pressure in the less competitive residential market, as well as reduced participation in cell and pack cost reductions due to the smaller procurement volumes typical of residential system manufacturers

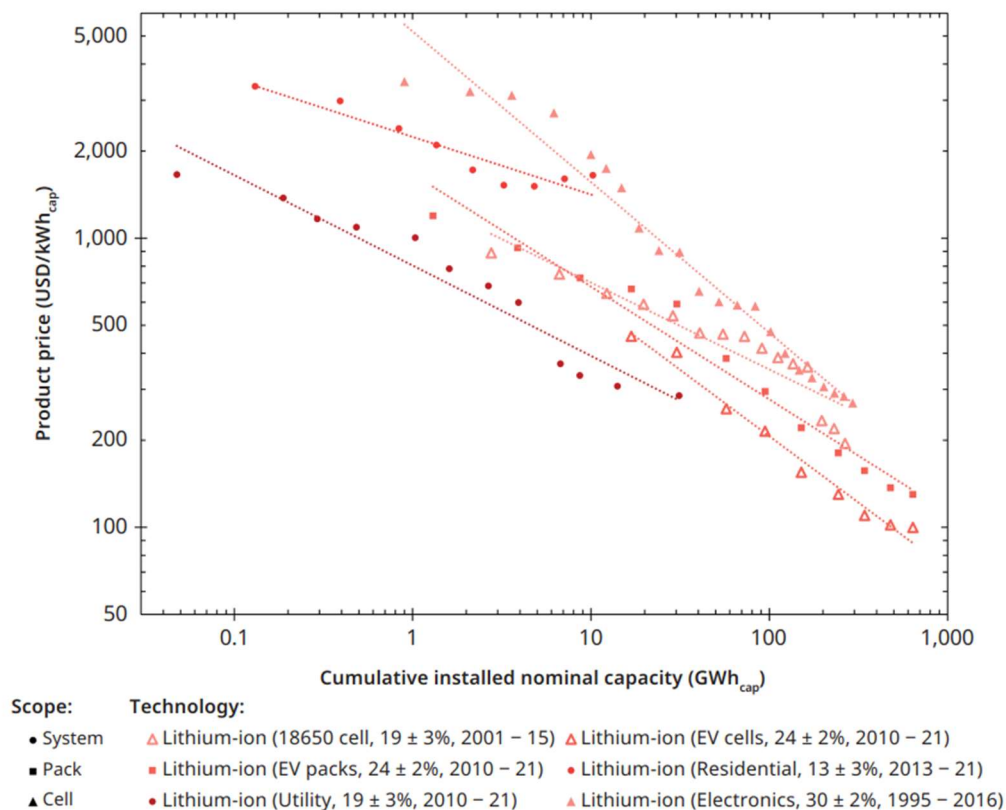


Figure 7.3 Experience curves for lithium-ion technologies, measured in energy terms. Product prices measured in real 2020 USD per nominal energy capacity as a function of cumulative installed nominal energy capacity. Dotted lines show the experience curves resulting from linear regression of the data. The legend indicates product scope (installed system, pack, cell) and technology (including application, experience rate with uncertainty, and years covered by the dataset). Experience rate uncertainty is quantified with the 95% standard error confidence interval¹³⁷.

7.1.10 Safety and Risks

Safety is a well-known challenge for Li-ion batteries. The same chemistry that gives Li-ion cells high energy also makes them prone to thermal runaway¹⁶³ under abuse conditions.

The organic electrolyte is flammable, and if a cell is overcharged, overheated, physically damaged, or experiences an internal short, it can ignite or even explode. NMC and other oxide cathodes release oxygen when overheated, which can fuel fires. High-profile incidents (from smartphone battery fires to EV conflagrations) underscore these risks. Mitigating these risks requires robust Battery Management Systems (BMS) to prevent overcharge/over-discharge and to monitor temperature, as well as engineering controls like cooling systems and safety venting in cell designs. LFP chemistry is inherently safer – it has a more thermally stable cathode that does not release oxygen easily, and LFP cells are much less likely to undergo thermal runaway (they will typically just vent gas if abused). This is one reason LFP is popular for stationary storage despite lower energy density. Li-ion packs are usually designed with insulation between cells and fire suppression mechanisms to contain any single-cell failure¹⁶⁴. From a usage standpoint, systems need to be kept within their specified temperature range and protected from external heat or short circuits. Additionally, Li-ion batteries must be transported as Class 9 hazardous materials. Despite these risks, when proper standards are followed, Li-ion batteries can be operated safely – millions are in use with a relatively low incidence rate proportionally. However, the consequences of a failure can be severe, including intense fires that are hard to extinguish (as cells in thermal runaway can re-ignite due to stored energy). Safety regulations (like UL9540A testing for stationary systems)¹⁶⁵ are in place to ensure systems can either prevent, delay, or contain thermal runaway propagation. To summarize, Li-ion requires diligent safety engineering: intrinsic chemical risk is mitigated by extrinsic controls. This is a key differentiation with some emerging technologies that aim to be inherently non-flammable.

7.1.11 Maintenance and Operational Requirements

Lithium-ion battery systems are often billed as low-maintenance or maintenance-free, especially compared to something like flooded lead-acid. There is no requirement for adding water or routine electrode replacement. However, Li-ion systems do have operational requirements to ensure longevity and safety. Chief among these is thermal management: most large Li-ion installations include cooling (or heating in cold climates)

to keep cells within a healthy temperature band (typically $\sim 15\text{--}30^\circ\text{C}$ for optimal life)¹⁶⁶. The BMS continually monitors cell voltages and temperatures and will take action (throttling charge/discharge, cooling) if limits are approached. Operators need to maintain the cooling/HVAC system (e.g., keep filters clean, ensure coolant levels if liquid-cooled, etc.). Apart from that, maintenance is mostly inspection and testing of electrical connections and BMS function. Over time, some Li-ion systems may need battery module replacements as cells degrade – for instance, after several years, to maintain performance one might swap out worst-performing modules (this is more an operational consideration than regular maintenance). Software updates for the BMS and inverter might also be part of routine service. In daily operation, Li-ion batteries prefer not to be kept at extreme high states of charge or at high temperatures for long periods, as those conditions accelerate aging. Many systems adopt an operating strategy like not charging beyond 90% except when needed, or maintaining a partial state of charge when idle, to extend life. From an operational standpoint, Li-ion responds quickly and doesn't need spinning reserve or idling – it's instant on/off. One operational requirement is ensuring **fire safety systems** (such as smoke detection, HVAC shutdown, fire suppression like inert gas)¹⁶⁷ are functional, given the aforementioned risks. But unlike some other chemistries, Li-ion has no moving parts, no electrolyte circulation, and no routine refilling – which simplifies operations. In summary, Li-ion batteries require attention to thermal management, monitoring, and periodic system check-ups, but little manual intervention on the battery hardware itself during normal life.

7.1.12 Expected Operational Life

Lithium-ion batteries have a finite life, limited by both cycle count and calendar time. For high-quality Li-ion cells, one can expect on the order of 10 to 15 years of operation in stationary use, assuming moderate cycling and temperatures. Cycle life varies by chemistry and usage: an NMC battery cycled deeply every day might last $\sim 8\text{--}10$ years before hitting perhaps 80% remaining capacity¹⁶⁷. LFP batteries, known for durability, might achieve $>5,000$ cycles (which could be ~ 15 years of daily cycles) before significant degradation, especially if not fully discharged each time. Calendar aging can be a limiting

factor even without heavy cycling – Li-ion cells degrade slowly over time due to side reactions (growth of SEI layer, etc.), even if just sitting charged. High temperatures accelerate this, so lifespan in hot climates might be shorter if cooling is insufficient. Manufacturers typically warranty stationary Li-ion systems for about 10 years or a certain cycle count (e.g. 4,000 cycles) to 60–80% capacity. After that, the battery still works but with reduced capacity and efficiency. It's also important to note that “end of life” in this context is often defined as reaching 70-80% of original capacity – the battery can continue to operate beyond that, just with less energy storage and possibly needing more frequent maintenance¹⁶⁶. With refurbishment (replacing degraded modules), a Li-ion installation's life could be extended further. We are now seeing early grid Li-ion projects (from ~2010s) being repurposed or retired as they hit end-of-life, providing real-world data. Another aspect is the potential for *second-life* use: for example, EV batteries retired after ~8 years (at ~70–80% capacity) can be re-used in stationary storage where weight/space are less critical, adding several years of useful life at lower cost. In terms of shelf life, Li-ion can hold a charge for many months with minimal loss, but long-term storage at high charge and temperature will age it. Overall, while Li-ion doesn't last as long as some alternatives (like flow batteries or potentially solid-state in the future), a decade or more of service is generally achievable, which in many cases aligns with the typical project financing horizon¹⁶⁶.

7.1.13 Spatial and Site Considerations

Thanks to their high energy density, Li-ion batteries have a **compact footprint** relative to most other storage options. Some site considerations are listed in the table below.

Table 7.5: Spatial and Site Considerations¹⁶⁸

Aspect	Details
Energy Density/Footprint	Compact design; ~2–4 m ² per 100 kWh, inclusive of auxiliary systems.
Modularity	Stackable containers or cabinets; scalable layouts.
Thermal Design	Must allow HVAC and airflow; spacing required for effective cooling.
Fire Risk & Codes	Setback distances, fire-rated enclosures, and separation required by regulations.
Indoor Installations	Fire suppression and ventilation for gas/fume risks are mandatory.
Climate Considerations	Heated enclosures in cold climates; cooling/shading in hot climates essential.
Structural Load	Floor loading manageable; typical rack = several hundred kg.
Noise Levels	Quiet operation; minimal acoustic impact (only HVAC fans).

Aspect	Details
Altitude Impact	Very high altitudes may affect cooling and high-voltage insulation properties.
Seismic Requirements	Racks need seismic securing in earthquake-prone zones.
Urban Deployment Benefits	Zero emissions, no fuel logistics – can be located close to loads/substations in urban areas.

7.1.14 Social Impact

The rise of lithium-ion technology has had **profound social and economic impacts**. By enabling the modern smartphone and laptop revolution, Li-ion batteries have changed how people communicate and work. In the transportation sector, Li-ion is driving the transition to electric mobility, which has implications for reducing air pollution and greenhouse gas emissions – a positive societal outcome. The growth of EVs and battery manufacturing has created new industries and jobs; regions with battery gigafactories (such as in Asia, and increasingly in Europe and North America) are benefiting from investment and employment opportunities. However, there are social challenges too: a significant portion of Li-ion cathode materials (like cobalt) come from areas with human rights concerns (e.g., artisanal cobalt mining in the DRC has been associated with child labor). This has put pressure on manufacturers to ensure ethical supply chains and to develop chemistries that reduce reliance on such materials. Lithium mining itself can impact indigenous communities (for instance, lithium brine extraction in South America competes with local water use).

7.2 Sodium-Ion Batteries (Na-ion)

7.2.1 Overview and Operating Principle

Sodium-ion batteries operate on the same basic principle as lithium-ion, but the charge carriers are sodium ions (Na^+) instead of lithium. A typical sodium-ion cell consists of a **carbon-based anode** (often hard carbon), a **sodium-containing cathode** (such as layered transition metal oxides or Prussian blue analogs), and an electrolyte that shuttles Na^+ ions. During charging, sodium ions are extracted from the cathode and intercalated into the anode structure; on discharge, Na^+ ions flow back to the cathode, releasing energy. The overall cell reaction is analogous to Li-ion, but all components are tailored for sodium chemistry. For example, a common cathode under development is sodium nickel

manganese oxide or sodium-iron manganese hexacyanoferrate (a Prussian blue-type), while the anode is typically a disordered carbon that can host sodium (graphite does not intercalate Na^+ effectively, unlike Li^+)¹⁶⁹. The electrolyte is usually a sodium salt (e.g. sodium hexafluorophosphate, NaPF_6) in an organic solvent. The cell voltage of Na-ion batteries tends to be a bit lower than Li-ion (around 2.0–3.3 V, depending on cathode, versus 3.2–3.7 V for Li-ion). However, the intercalation mechanism is very similar, which means many of the manufacturing processes and cell designs from Li-ion can be adapted to sodium-ion. The main appeal of Na-ion is that sodium is abundant and inexpensive, and it can potentially be a drop-in replacement for Li-ion in certain applications, using much of the same technology and infrastructure (minus the lithium-specific parts). In summary, sodium-ion batteries function by reversible insertion of sodium ions into host materials, just as Li-ion does with lithium, making it a close chemical cousin to Li-ion technology¹⁶⁹.

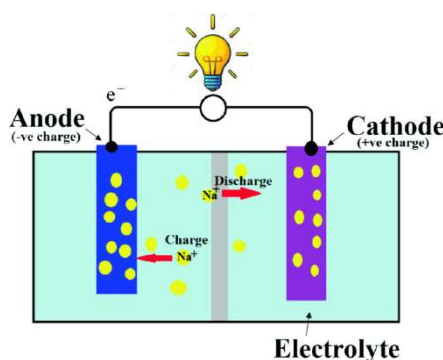


Figure 7.4: Working principle of Sodium ion batteries¹⁶⁹

This table below provides a concise yet thorough summary of sodium-ion battery technology in the style of leading technical reports.

Table 7.6: Summary of sodium-ion battery technology

Category	Electrochemical energy storage — Sealed battery
Status	Early commercial stage — pilot projects, first deployments in stationary storage and low-speed EVs; mass production ramping up in China for grid and vehicle use ^{169,2}
Application	- Stationary storage (renewables, grid, backup) - Low-cost EVs (short-range, e-bikes, small cars) - Portable electronics and IoT (prototypes) - Data/telecom backup power¹⁵⁴.
Variations	- Cathode: Prussian blue analogs, layered oxides, polyanion compounds - Anode: Hard carbon (graphite ineffective) - Electrolyte: Sodium salt in organic solvent or solid-state - Cell design: cylindrical, pouch, prismatic¹⁷⁰.

Category	Electrochemical energy storage — Sealed battery
Formula	Half-cell reactions (discharge): Anode: $C_6 + Na^+ + e^- \rightarrow NaC_6$ Cathode: $Na_xMO_2 \rightarrow Na_{x-y}MO_2 + yNa^+ + ye^-$ Overall: $Na_xMO_2 + C_6 \rightarrow NaC_6 + Na_{x-y}MO_2$ (Voltage: $\sim 2.0\text{--}3.3\text{ V}$)¹⁷¹.
Advantages	- Abundant, low-cost raw materials (sodium, iron, manganese) - Potentially lower cost than Li-ion (projected \$10–\$40/kWh at scale)⁷ - Good low-temperature performance - Non-toxic, cobalt- and lithium-free - Drop-in manufacturing potential (uses existing Li-ion lines)¹⁷². - Lower energy density (75–160 Wh/kg, up to 200 Wh/kg in future) - Lower cycle life than mature Li-ion (300–2,000 cycles typical, up to 6,000 in best cells)⁴
Disadvantages	- Slightly larger/heavier for same energy - Not yet widely available; supply chain still developing¹⁷³.
Sample Players	CATL¹⁴⁰ (China), BYD¹⁴¹ (China), Faradion¹⁷⁴ (UK/India), Altris¹⁷⁵ (Sweden), Sumitomo Electric¹⁷⁶ (Japan). - Improving cathode/anode chemistries for higher density and cycle life
Innovation Focus	- Non-flammable and solid-state electrolytes for safety - Scaling up production and reducing costs - Hybrid packs with Li-ion for best performance¹⁴⁶.

7.2.2 Current Applications

Sodium-ion batteries are just entering the early commercial stage, so current applications are limited and mostly pilot projects. As of 2024, no large-scale consumer product widely uses Na-ion batteries yet, but there are targeted deployments. The first likely applications are in stationary energy storage and low-speed electric mobility. For instance, sodium-ion cells have been demonstrated for use in grid storage systems where their lower energy density is acceptable, but cost and safety advantages are valued. Some developers are targeting sodium-ion for use in electric two-wheelers or e-bikes, and small electric cars, particularly in markets like China, as a cheaper alternative for short-range vehicles. In 2023, the Chinese battery maker CATL¹⁴⁰ unveiled a sodium-ion battery and indicated plans to integrate it into a vehicle (potentially in a hybrid pack with Li-ion). Another company, Faradion¹⁷⁴ (UK/India), has piloted Na-ion batteries for e-bikes and stationary packs. We are also seeing Na-ion test installations for renewable energy storage – for example, a solar farm paired with a sodium-ion battery bank to validate performance. Some consumer electronics prototypes (like power banks or portable chargers) have been shown using Na-ion cells, highlighting their drop-in potential. Overall, as of now applications are mostly complementary to Li-ion: places where ultra-high energy density

is not required but lower cost or better cold-weather performance of Na-ion could be an asset (e.g. backup storage in cold climates, or cost-driven markets needing affordable batteries). Over the next few years, if commercialization succeeds, these applications will grow to mainstream deployments in grid storage and economy EV models.

Table 7.7. General comparison between sodium and lithium batteries.

Characteristic	Sodium Batteries	Lithium Batteries
Energy density	150–200 Wh kg ⁻¹	200–300 Wh kg ⁻¹
Nominal voltage	3.2–3.3 V	3.6–3.7 V
Environmentally friendly	Can be transported at zero volt	Should be always stored with a minimum charge
Availability	Mostly worldwide available at about 500 times higher the lithium	Availability is limited to some countries and not abundant
Raw material price	~330 U.S. dollar per metric ton for Na ₂ CO ₃	~68,000 U.S. dollar per metric ton for Li ₂ CO ₃
Lifespan	5–10 years	5–15 years

7.2.3 Maturity and TRL

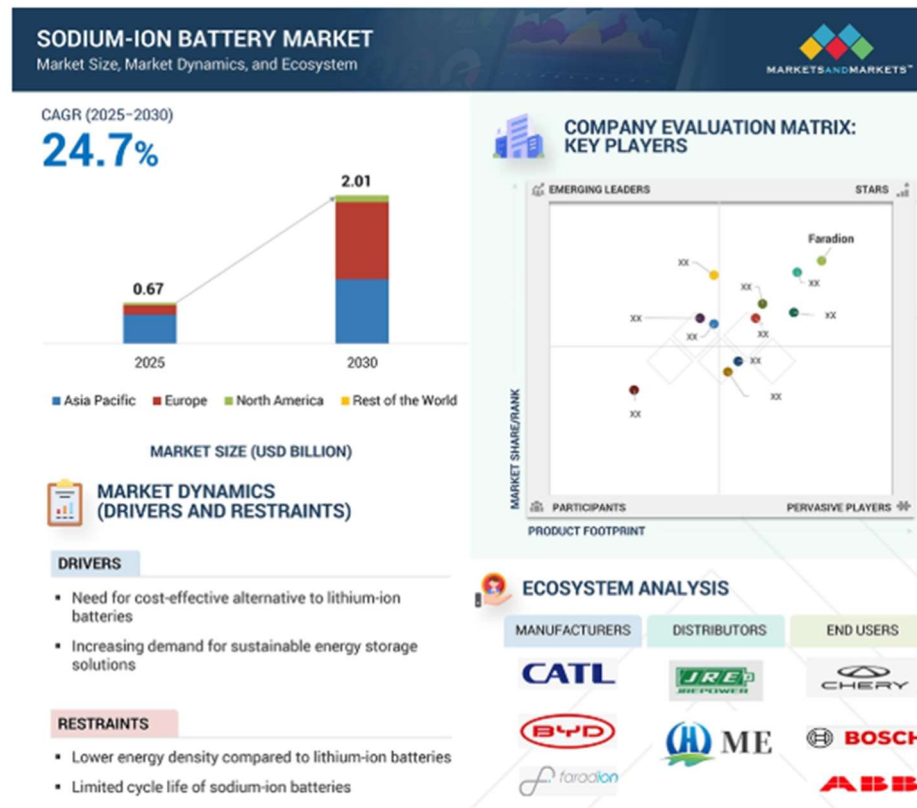
Sodium-ion technology is **emerging** and can be considered around **TRL 5–7**¹⁷⁷. It has been proven in laboratory environments and prototype products, but large-scale commercial validation is still underway. In recent years, progress has been rapid: research in the 2010s solved many fundamental issues (like finding suitable anode materials such as hard carbon and improving cathode performance). By 2023, companies like CATL¹⁴⁰, Faradion¹⁷⁴, and others have built pilot production lines, and CATL announced it would begin mass production of Na-ion cells. This indicates parts of the technology are approaching TRL 7 (system prototype demonstration in operational environment). That said, sodium-ion lacks the extensive field history of Li-ion. Key aspects like long-term cycle life, scaling of manufacturing yield, and performance consistency are still being proven. There are also some materials challenges (e.g. ensuring the Prussian blue cathodes don't lose capacity due to lattice water, etc.). The ecosystem (suppliers of Na-ion specific materials) is in its infancy. We can compare it to where Li-ion was perhaps in the early 1990s – on the cusp of commercialization. The next 2–3 years (2025–2027) are likely to see the first real commercial deployments and iterative improvements as data comes in. In

summary, Na-ion is not yet a fully mature technology, but it has exited pure R&D and is in the scale-up and demonstration phase, with confidence growing that it will soon reach full commercial readiness for certain markets.

7.2.4 Commercial Availability

At present, commercial availability of sodium-ion batteries is limited to small-scale offerings and samples from specialized manufacturers. No major consumer products are using Na-ion yet, so you generally cannot buy a sodium-ion battery at retail. However, several companies have announced timelines for product releases.

The global sodium-ion battery market is projected to grow from USD 0.67 billion in 2025 to USD 2.01 billion by 2030 at California¹⁵⁴. Of 24.7% during the forecast period¹⁷⁸. CATL (the world's largest Li-ion maker) has prototyped Na-ion cells and stated they plan to establish a supply chain and production capacity by around 2023–2024. That could mean initial commercial sales to interested clients (perhaps in the electric two-wheeler or stationary storage sectors in China). British company Faradion (now owned by India's Reliance Industries) has been working on Na-ion for over a decade and has deployed some demonstration units; they aim to commercialize batteries in India, leveraging abundant sodium and reducing import dependence on lithium. In Japan, Sumitomo Electric has shown sodium-ion batteries for stationary use as well. So one can say that early commercial units of Na-ion can be obtained through partnerships or pilot projects with these developers. By 2030, Benchmark Mineral Intelligence projects over 300 GWh of Na-ion production capacity could be in place globally, which implies that within a few years mid-decade, more product will be on the market. For now, if a utility wanted a Na-ion storage system, they would likely engage with a company like Faradion or CATL for a custom supply – it's not an off-the-shelf commodity yet. We expect that to change in the latter half of the 2020s, as Na-ion cells start to be manufactured at scale and possibly even in standard formats (e.g., prismatic cells that could fit in existing module designs). In summary, sodium-ion availability is currently mostly in the form of **samples and pilot projects**, but rapid developments suggest wider commercial availability is imminent, particularly in cost-sensitive markets.

Figure 7.5. Sodium ion battery market¹⁷⁸

7.2.5 Scale and Capacity

Sodium-ion batteries can be scaled in much the same way as Li-ion, though current implementations are at relatively small scale. Individual Na-ion cells have been produced in cylindrical 18650 formats and large pouch cells of a few Ah capacity for prototypes¹⁷⁰. The intention is that they could use the same manufacturing lines as Li-ion with minimal modifications (since the form factor and construction are similar). This means that in principle, one can connect Na-ion cells in series and parallel to make battery modules and systems of any desired capacity. The cell capacity of early Na-ion pouches is on the order of e.g. 20 Ah (CATL reported a Na-ion cell with energy density ~160 Wh/kg, which for a ~3.2 V nominal cell is roughly 50 Wh per cell). These can be built into modules like a 12V or 48V battery for easy integration. Because sodium-ion is targeting some of the same applications as Li-ion, the scale could range from a few kWh residential units to multi-MWh grid installations. We haven't yet seen a multi-MWh sodium-ion project, but there has been multi-kWh to possibly low tens of kWh demonstration systems. As manufacturing ramps up, there's nothing fundamental to preventing large systems; it's

more about production volume. One noteworthy difference: sodium-ion cells have a bit lower voltage, so a string of Na-ion cells will need maybe one or two extra cells in series to reach the same pack voltage as a Li-ion string (for example, a ~400V pack might need ~140 Na-ion cells at ~2.8V each, whereas ~120 Li-ion at ~3.3V each would suffice). This is a minor consideration when scaling. Overall, as soon as high-capacity factories come online, scaling to whatever capacity needed is straightforward – the modular approach used in Li-ion packs can be mirrored. It is likely that early large-scale deployment will cluster around stationary storage, where modular containers housing a few thousand Na-ion cells could deliver megawatt-scale power and multi-hour energy. In summary, sodium-ion batteries are inherently scalable to large systems, and we anticipate their capacity in deployments will grow proportionally with manufacturing capability, much like Li-ion did.

7.2.6 Storage Density

A key difference between sodium-ion and lithium-ion cells lies in their energy storage density. Sodium-ion batteries currently have a lower energy density: typically, around 75–160Wh/kg at the cell level, versus 120–260Wh/kg for lithium-ion. This gap is due to several factors: (1) Sodium ions are heavier and larger than lithium, reducing how many can be stored per given electrode weight/volume; (2) Suitable electrode materials for Na often have lower voltages or capacities – for instance, hard carbon anodes for Na-ion have a lower capacity (~300 mAh/g) than graphite with lithium (~350 mAh/g), and many Na cathodes have a lower average voltage; (3) The need for more supporting materials (since Na can't utilize the graphite anode, the alternatives might add weight). In practical terms, current Na-ion cells are roughly 20–30% less energy dense than comparable Li-ion cells. For example, CATL's first-generation Na-ion cell (2021) achieved about 160 Wh/kg, whereas contemporary LFP Li-ion cells were ~160–180 Wh/kg and NMC cells ~250 Wh/kg. So, a Na-ion battery pack will be bulkier and heavier for the same amount of energy. Volumetric energy density also suffers similarly. This means that for applications where weight/space are at a premium (EVs, mobile devices), Na-ion has a disadvantage – an EV might lose some driving range or need more space to house a Na-ion pack of equal capacity. However, for stationary storage or small vehicles, this may be an acceptable

trade-off for cost or safety benefits. It's worth noting that R&D is ongoing to narrow the density gap – for instance, new Na cathodes and optimizing cell design might push Na-ion cells above 180Wh/kg in coming years, and Li-ion is also improving, though increments are slowing. In summary, sodium-ion's storage density is **moderate**, sufficient for many stationary and low-end mobility uses, but generally inferior to state-of-the-art Li-ion. Designers using Na-ion must account for a larger battery size to get the same energy – roughly on the order of 1.3–1.5× the volume/weight for equivalent capacity at present. Projections from BNEF¹⁷⁹ suggest that sodium-ion batteries could reach pack densities of nearly 150 watt-hours per kilogram by 2025. And some battery giants and automakers in China think the technology is already good enough for prime time.

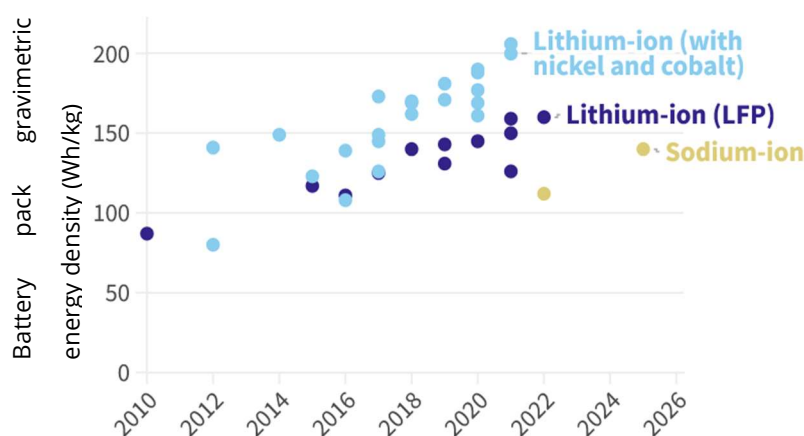


Figure 7.6. MIT Technology Review Sodium-ion data for 2025 is a projection from BNEF. Lithium with nickel and cobalt includes both NMC and NCA¹⁷⁹

7.2.7 Discharge Duration

Sodium-ion batteries offer discharge duration capabilities similar to lithium-ion, allowing them to be configured for short, high-power bursts or longer, lower-power output depending on cell design and system size. Like Li-ion, Na-ion can be used for fast frequency response or multi-hour energy storage, such as 4-hour grid applications. Notably, Na-ion performs better at low temperatures, maintaining capacity and discharge duration more effectively in cold climates. While current Na-ion cells may have slightly lower high-rate discharge capability¹⁷⁷ and higher internal resistance than Li-ion, they are well-suited for typical stationary storage applications at moderate C-rates (2–5 hours)¹⁶⁹. Both chemistries can be oversized for longer durations, though costs rise for >8 hours.

Overall, sodium-ion batteries can match Li-ion across most discharge durations, with the main limitation being slightly lower high-power performance until further technological maturity.

7.2.8 Efficiency and Performance

- Sodium-ion batteries deliver performance close to lithium-ion in several key areas, though their energy density is lower. Their round-trip efficiency is about 90%, just below lithium-ion's 90–95%, but this gap is narrowing as the technology improves¹⁷⁰.
- A standout feature of sodium-ion batteries is their high-power density. Some cells can reach up to 1,000 W/kg, making them suitable for applications needing short bursts of high power—even outperforming some lithium-ion cells in this respect¹⁷¹.
- Current sodium-ion batteries offer cycle lives from several hundred up to about 2,000 cycles, which is less than the best lithium-ion batteries. However, they are less prone to certain degradation issues, such as plating at low temperatures, giving them an advantage in cold or demanding environments¹⁷⁵.
- Sodium-ion batteries also perform well in low temperatures, retaining capacity better than lithium-ion at around -20°C. They may also have improved thermal stability, especially with certain cathode materials, and generate less heat during operation¹⁸⁰.
- Although their lower energy density limits their use in portable or space-constrained applications, sodium-ion batteries are well-suited for stationary storage. As the technology matures, they are expected to achieve over 2,000 cycles and maintain high efficiency, making them a strong alternative for grid storage and cold-climate use¹⁸¹.

7.2.9 Cost-Effectiveness

A major advantage of sodium-ion batteries is their potential for lower cost. Sodium is abundant and cheap, and sodium-ion batteries avoid expensive materials like lithium, cobalt, and often nickel. At scale, the material costs for sodium-ion cells could be about 20–30% lower than for lithium iron phosphate (LFP) lithium-ion cells. Sodium-ion technology also uses aluminum current collectors on both the anode and cathode, eliminating the need for copper and further reducing cost and weight. Much of the savings come from replacing lithium carbonate with far cheaper sodium salts and using common elements like iron or manganese in the cathode^{182,183}.

Benchmarking suggests that, once mass production is achieved, sodium-ion batteries could be roughly 20% cheaper per kWh than LFP lithium-ion batteries. This makes them

especially attractive for large-scale, cost-sensitive storage projects. However, current pilot-scale sodium-ion batteries are still more expensive than mature lithium-ion cells, as the benefits of mass production and supply chain efficiencies have yet to be realized. Experts^{184,185} note that sodium-ion's cost edge will only be clear once manufacturing scales up to gigawatt-hour levels. The ongoing drop in lithium prices, driven by huge EV investments, also affects the urgency of switching to sodium-ion. Still, sodium-ion batteries are promising for stationary storage, where size and weight are less important than cost per kWh. Sodium's wide availability means supply chain risks are lower, offering more stable long-term pricing. By 2030, if sodium-ion production scales up, costs could undercut lithium-ion, making sodium-ion a strong candidate for mid-range applications like home storage, low-end EVs, and microgrids. In summary, sodium-ion batteries could be significantly cheaper than lithium-ion if manufacturing is scaled up, helping lower the cost barrier for large-scale battery storage deployment¹⁸⁶.

7.2.10 Safety and Risks

Sodium-ion batteries are generally considered to have comparable or slightly improved safety relative to Li-ion. One reason is that many Na-ion chemistries (like those using Prussian blue analog cathodes and hard carbon anodes) have demonstrated better thermal stability – the cathodes don't release oxygen at high temperature the way layered Li-ion cathodes can. Also, Na-ion cells typically operate at a bit lower voltage, which inherently reduces some abuse risk (less driving force for electrolyte oxidation at high voltages)¹⁸⁷.

The flammable electrolyte is still present (most Na-ion designs use the same carbonate solvents as Li-ion), so they are not free from fire risk. If a Na-ion cell is overheated or internally shorted, it can still go into thermal runaway and ignite the electrolyte. That said, some tests have shown that Na-ion cells have a slightly slower thermal runaway propagation, possibly because the reactions aren't as exothermic without cobalt or high-voltage cathodes. Additionally, since aluminum can be used as the anode current collector (instead of copper), there's less risk of copper short-circuit debris in an overheat scenario

(in Li-ion, copper can melt and spread a short). Another safety aspect: overcharging a Na-ion cell will plate sodium metal on the anode (similar to Li plating in Li-ion), which is hazardous. But one could argue that because sodium plating happens more uniformly (in theory) or at different conditions, it might be slightly easier to detect or mitigate – though in practice, a BMS must prevent overcharge just as strictly as with Li-ion¹⁸⁴.

One interesting risk reduction is cell stability in low state of charge: Li-ion cells if over-discharged can copper short; Na-ion using Al doesn't have that failure mode, so deep discharge might be safer and not ruin the cell in a hazardous way (though it may still degrade capacity). Thermal runaway temperature for Na-ion might occur at a higher trigger temperature – some data suggests cells can be a bit more tolerant to heat before venting/gassing¹⁴⁶.

7.2.11 Maintenance and Operational Requirements

For users, sodium-ion batteries operate much like lithium-ion, which is intentional so existing battery management systems (BMS) and infrastructure can be reused. They require a BMS to monitor and balance cell voltages and temperatures and use similar charging protocols—constant-current followed by constant-voltage—though at slightly different voltages¹⁸⁸.

A key advantage is that sodium-ion batteries may handle cold temperatures better, reducing the need for heating in winter and simplifying outdoor operation. However, due to lower energy density, sodium-ion systems might produce a bit more internal heat, so cooling remains important. Any thermal management used for lithium-ion should work for sodium-ion with little adjustment¹⁸⁹.

State-of-charge management could be a bit more flexible, as sodium-ion batteries may tolerate higher charge levels and temperatures with less degradation. Still, best practices like avoiding full 100% charging unless necessary will remain. Maintenance is minimal, mainly ensuring monitoring and cooling systems work properly, with no need for electrolyte refilling or parts replacement¹⁹⁰.

Since sodium-ion is new, early systems may require closer monitoring and calibration to ensure accurate state-of-charge and health predictions. Over time, this will become

routine. Overall, sodium-ion batteries are designed to be as user-friendly and automated as lithium-ion, fitting seamlessly into existing applications and requiring no major changes to maintenance or operational procedures. If proven safer, they could even allow for less restrictive deployment rules, making installation easier.

7.2.12 Expected Operational Life

Sodium-ion batteries are expected to achieve operational lives similar to lithium-ion in many applications, though real-world data is still limited. Developers are aiming for a cycle life of several thousand cycles at moderate depths of discharge. Recent studies suggest that Na-ion cells can reach over 2,000 full cycles before dropping to 80% capacity, and some designs may exceed 3,000 cycles, especially when used at partial depth of discharge, which is common in stationary storage¹⁹¹.

There is optimism that sodium-ion batteries could meet or surpass 10–15 years of service life. Some lithium-ion aging mechanisms, like plating and transition metal dissolution, are less severe in sodium-ion, which could help extend their lifespan. However, sodium-ion cells have their own aging issues, such as cathode lattice distortion and gradual capacity loss in hard carbon anodes¹⁹².

Accelerated testing indicates sodium-ion batteries can be designed to last a decade with around 80% remaining capacity if cycled moderately. Their life can be further extended in stationary uses by operating at lower C-rates and temperatures, which is easier to manage than in electric vehicles¹⁹³.

Sodium-ion batteries may also be more robust if fully discharged, as they can survive a full drain without internal damage, unlike lithium-ion, which can fail catastrophically. Manufacturers¹⁷⁵ are confident enough in sodium-ion's longevity to consider pairing them with lithium-ion packs in EVs, suggesting they won't need early replacement.

Overall, a well-designed sodium-ion battery should last over 10 years or 2,500+ cycles, matching the requirements of most stationary storage projects. In backup or low-cycling scenarios, calendar life could be the limiting factor, potentially exceeding 15 years. As more field data becomes available, these lifespan estimates will be refined, but current

evidence points to sodium-ion as a viable long-life alternative to lithium-ion in many applications¹⁷¹.

7.2.13 Spatial and Site Considerations

Sodium-ion batteries can be installed much like lithium-ion systems, using the same racks and enclosures, which makes site planning straightforward. The main difference is that sodium-ion batteries have lower energy density, so they require more space and weigh more for the same energy capacity. For example, a sodium-ion system might need 20–50% more floor area and weigh 20–30% more than a comparable lithium-ion setup. This is usually not a problem for ground-based installations but could matter in space-constrained or rooftop projects¹⁷³.

If sodium-ion batteries prove to be safer, with lower fire and explosion risk, they may allow for more flexible siting—such as within buildings or closer to people—compared to lithium-ion. This could make them attractive for indoor or community energy storage, where safety is a concern¹⁹⁴.

Sodium-ion batteries also perform well in cold climates and can be sited outdoors with less need for heating. Their form factors are similar to lithium-ion, so standard installation practices apply. In terms of appearance and noise, sodium-ion systems are nearly identical to lithium-ion, and being marketed as safer and cobalt-free may help with community acceptance¹⁸².

Finally, if regulations classify sodium-ion batteries as less hazardous than lithium-ion, shipping and storage could be simpler, making deployment easier and reducing logistical barriers. Overall, sodium-ion systems are a drop-in replacement for lithium-ion, with only slightly greater space and weight requirements and potential benefits in safety and flexibility¹⁸⁵.

7.2.14 Social Impact

Sodium-ion batteries can reduce dependence on critical minerals like lithium and cobalt, easing mining pressures in regions such as South America and Central Africa. This shift helps address social and ethical concerns, including water use and child labor, and creates a more balanced, less conflict-prone supply chain¹⁵⁴.

By using widely available materials like salt and iron, sodium-ion batteries allow more countries to participate in battery production, fostering local industries, job creation, and technological growth. Cheaper energy storage from sodium-ion could accelerate renewable energy adoption, improving air quality and public health, and making battery installations more acceptable to communities due to reduced hazardous content.

Lower costs could also make energy storage accessible in developing regions, supporting education, healthcare, and overall quality of life. Sodium-ion batteries are often described as more environmentally benign, which may reduce environmental justice concerns and simplify recycling¹⁷⁰.

Overall, sodium-ion technology offers the potential for more sustainable, inclusive supply chains and broader access to clean energy, helping make the energy transition greener and fairer.

7.3 Lead-Acid Batteries (PbA)

7.3.1 Overview and Operating Principle

Lead-acid batteries are the oldest type of rechargeable batteries in regular use, first invented in 1859. They store energy via a reversible chemical reaction between lead, lead dioxide, and sulfuric acid. In a charged lead-acid cell, the positive plate is lead dioxide (PbO_2) and the negative plate is spongy lead (Pb), and the electrolyte is a water-diluted sulfuric acid (H_2SO_4) solution^{100,195}. When discharging, both electrodes convert to lead sulfate (PbSO_4) and the sulfuric acid is consumed (diluted by forming water), releasing electrons in the process. The overall discharge reaction can be written as seen in the table below. When charging, an external current drives the reverse reaction: lead sulfate on the plates is converted back into PbO_2 at the positive and Pb at the negative, and sulfuric acid is regenerated. Each lead-acid cell has a nominal voltage of about 2.0 volts (ranging ~2.11 V fully charged down to ~1.8 V at full discharge). Cells are often combined in series (e.g. 6 cells for a 12V battery)^{196,197}.

The design typically uses multiple plates per cell to increase surface area, and separators (often fiberglass mats in sealed batteries) to prevent shorting and retain electrolyte. There are two main types: flooded lead-acid, where the electrolyte is liquid and can be refilled,

and valve-regulated lead-acid (VRLA), which includes AGM (absorbed glass mat) and gel batteries, where the electrolyte is immobilized and the cell is sealed with a valve to vent gases if overcharged. The lead-acid operating principle is simple and well-understood – it reliably produces current but at the cost of heavy weight and moderate maintenance (for flooded types). Lead-acid chemistry is highly reversible under proper charging, which is why despite its age, it's still used where cost-sensitivity and robustness are key.

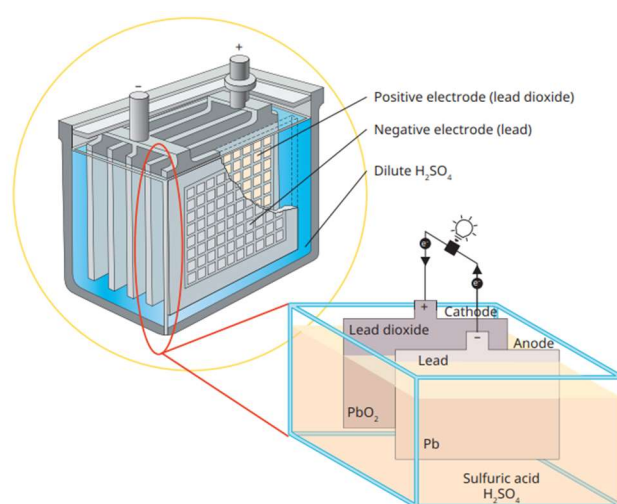


Figure 7.8: Construction of a sealed lead-acid battery. This cutaway shows positive and negative lead plates (electrodes) and separators immersed in electrolyte (sulfuric acid). The design is robust but yields lower energy density and requires significant weight of lead for storage¹³⁷

Table 7.7. Overview of Lead acid batteries

Category	Electrochemical energy storage—Sealed battery
Status	Commercial stage—widely deployed with overall annual demand at ~415 GWh per year (~3,300 GW assuming typical 1:8 energy-to-power ratio for car engine starter batteries) ¹⁰⁰
Application	In transport applications, lead-acid batteries are mostly used as engine starter batteries for internal combustion engine vehicles ¹⁹⁸ . In stationary applications, relatively low cost and limited cycle life make lead-acid batteries best suited for: Backup power: Fill rare, unexpected, sustained gap between supply and demand (e.g. hospitals or data centres) ¹⁹⁹
Variations	Variations of technology refer to electrolytes, which can be a liquid mixture of water and sulphuric acid (i.e. flooded), a gel, or an acid-saturated fiberglass mat (i.e. sealed). While some systems are designed for shallow depth-of-discharge operation, others tolerate deep discharge cycles ²⁰⁰ .
Formula	Half-cell reactions (discharge):

	Anode: $\text{Pb} + \text{HSO}_4^- \rightarrow \text{PbSO}_4 + \text{H}^+ + 2\text{e}^-$ Cathode: $\text{PbO}_2 + 3\text{H}^+ + \text{HSO}_4^- + 2\text{e}^- \rightarrow \text{PbSO}_4 + 2\text{H}_2\text{O}$ Overall reaction (discharge): $\text{Pb} + \text{PbO}_2 + 2\text{H}_2\text{SO}_4 \rightarrow 2\text{PbSO}_4 + 2\text{H}_2\text{O}$ (Voltage: 2.1 V)
Advantages	• High technical maturity (commercial since ~1880) • Relatively low cost for battery pack (<200 USD/kWh) • Capable of high discharge rates • Wide range of sizes and specifications available
Disadvantages	• Low energy density vs other batteries (~70 kWh/m³) • Low depth of discharge for standard systems (30–50%) • Contain toxic materials (i.e. lead) • Limited lifetime (<1,000 cycles)
Sample players (battery supplier)	• Trojan (Germany)²⁰¹ • EnerSys (US)^{202,203} • Exide (US)²⁰³ • GS Yuasa (Japan)²⁰⁴
Innovation focus	• Electrodes: Addition of carbon for deeper discharge and longer cycle life²⁰⁰ • System: Hybridisation with supercapacitors to enable longer cycle life²⁰⁵

7.3.2 Current Applications

Lead-acid batteries are still widely used because of their low cost and reliability. Their most common role is in automotive starting, lighting, and ignition (SLI) batteries—almost every gasoline or diesel car uses a 12V lead-acid battery, and even electric vehicles often include a small lead-acid battery for auxiliary systems¹⁹⁸.

They are also popular in standby and backup power systems, such as uninterruptible power supplies (UPS) for hospitals, data centers, and telecom networks. In these roles, lead-acid batteries provide reliable power during outages. Off-grid renewable energy systems, especially in remote or developing areas, have historically relied on lead-acid due to affordability and resilience, though lithium-ion is increasingly replacing them²⁰⁶.

Deep-cycle lead-acid batteries are used in golf carts, low-speed electric vehicles, forklifts, and industrial equipment, as well as for marine and RV house power. However, lithium-ion is gradually taking over in some of these applications⁴³.

For grid-scale storage, lead-acid is less common today because of its shorter lifespan and bulk, but it still finds niche use in certain utility or remote area systems where low cost or

cold temperatures are critical. Emergency lighting and alarm systems also often use small, sealed lead-acid batteries²⁰⁷.

Despite a shrinking market in some sectors, lead-acid batteries remain essential in automotive and backup power, keeping the industry sizable. They are best suited for applications where low cost and dependability matter more than weight or space.

There are three main types: sealed lead-acid (SLA) batteries, used in healthcare and UPS backup; absorbent glass mat (AGM) batteries, mainly for deep cycling in marine and vehicle applications; and valve-regulated lead-acid (VRLA) batteries, used for institutional backup and small equipment like electric wheelchairs.

Table 7.8. Types of Lead acid batteries

	Battery type	Application
1	Sealed Lead-Acid (SLA)	Healthcare equipment and power backup in UPS
2	Absorbent Glass Mat (AGM)	They are primarily used to deep cycle in marine applications. It can also be used in vehicles.
3	Valve-regulated Lead-Acid (VRLA)	They are primarily used for power backup for institutions such as banks, hospitals, etc. and for powering small equipment such as electric wheelchairs.



Figure 7.9. Applications of lead acid batteries²⁰⁸

7.3.3 Maturity and TRL

Lead-acid batteries are a fully mature technology, with a Technology Readiness Level of 9 across all their applications²⁰⁹. They have been in commercial use for over 160 years, making their performance and failure modes extremely well understood. Most improvements over the years have been incremental, like alloying plates to reduce water

loss or adding carbon to improve charge acceptance, but fundamental chemistry remains unchanged.

This maturity translates to high reliability when lead-acid batteries are used within their operational limits. Industries such as automotive and telecom have established clear standards for their use, maintenance, and replacement. The manufacturing process is well-established, with global suppliers and, in many cases, highly automated production lines²¹⁰.

Because of this long track record, deploying lead-acid systems carries little technical risk—performance and aging can be predicted accurately using decades of field data. While some R&D continues^{209,211}, such as developing lead-carbon variants for better cycling, there are evolutionary changes that don't alter the technology's maturity. As a result, lead-acid batteries are often used as the baseline for comparing newer battery technologies¹.

7.3.4 Commercial Availability

Lead-acid batteries are **extremely commercially available** – they are one of the most ubiquitous battery types in the world. You can find lead-acid batteries in auto parts stores, hardware stores, and from countless distributors. There are many manufacturers on every continent, ranging from large multinationals (Exide²⁰³, GS Yuasa²⁰⁴) to smaller local battery companies. Because the technology is not proprietary, and raw materials (lead, sulfuric acid) are common, production is widespread. Any city or region with an automotive industry has lead-acid battery factories or suppliers.

For instance, millions of 12V car batteries are produced annually to meet vehicle demand and replacements. For industrial sizes, there are specialized vendors for telecom or UPS batteries who can supply in bulk. One can procure small 7Ah VRLA batteries for alarm systems or giant 2V cells for substations with equal ease (through different channels)²¹². The supply chain for lead (often recycled lead) is robust – in fact, a large portion of lead used in new batteries comes from recycled old batteries, establishing a closed loop. This recycling ecosystem ensures stable supply and price for lead, indirectly supporting availability. Also, because lead-acid does not require high-tech manufacturing (no cleanrooms, etc.), developing countries often have domestic lead-acid battery production

– this means even regions without Li-ion manufacturing capacity can produce or assemble lead-acid batteries relatively easily. For large projects, you can order prefabricated battery banks and have them shipped and installed with fairly standard procedures²¹³.

7.3.5 Scale and Capacity

Lead-acid batteries can be scaled in capacity by connecting more 2V cells in series and parallel to reach the desired voltage and energy. For example, a typical car battery has six 2V cells in series for 12V and about 50 Ah, or around 600 Wh²⁰⁸.

Larger systems use individual 2V cells in series for voltage, with multiple strings in parallel for capacity. Lead-acid cells come in many sizes, from small VRLA cells for electronics (5–20 Ah)¹⁰⁰, to car batteries (30–100 Ah)²¹⁴, deep-cycle batteries (100–300 Ah), and very large stationary cells (over 1000 Ah) for substations or telecom²¹⁰.

Scaling up is mostly limited by space, cabling, and weight. For example, a 48V system might use 24 cells in series and several parallel strings to increase capacity, as seen in many telecom power setups.

However, large-scale lead-acid banks face challenges. They have high self-discharge and must be kept charged. Ensuring equal current sharing among strings can be difficult, and large systems require ventilation for hydrogen gas and strong structures to support their weight.

Historically, there have been megawatt-scale lead-acid installations, but today, such large deployments are rare due to space and weight drawbacks compared to newer technologies. Lead-acid is most practical for small to medium systems, up to a few hundred kWh, like UPS rooms or telecom backups.

Above this scale, manageability and maintenance become issues, and other battery technologies are usually preferred. While it is technically possible to scale lead-acid to megawatt-hours, practicality and infrastructure needs make it less attractive for very large projects¹⁰⁰.

7.3.6 Storage Density

Lead-acid batteries have low energy density compared to modern batteries. They typically provide about 30–50 Wh/kg by weight and 50–100 Wh/L by volume, depending on the

design. Deep-cycle versions can reach the higher end of this range, while high-power types are lower.

This low energy density is mainly due to the heavy lead electrodes and the water/acid electrolyte, which adds weight without storing energy. For example, a 12V, 100Ah car battery (about 1.2 kWh) weighs 25–30 kg, or roughly 40 Wh/kg. In comparison, a lithium-ion battery of the same capacity would weigh only about 8 kg.

Because of this, lead-acid batteries are bulky and require significant floor space and structural support. Adding more capacity means adding a lot more mass and volume, which can quickly become impractical. For instance, a 1 MWh lead-acid battery bank might weigh 20–30 tons and fill a shipping container, while the same energy with lithium-ion would need half the space and weigh much less.

This low storage density limits lead-acid's use in applications where space or weight matter, such as portable electronics or electric vehicles. However, it remains acceptable for stationary backup systems or vehicle starting, where size and weight are less critical.

7.3.7 Discharge Duration

Lead-acid batteries offer moderate efficiency and performance compared to newer battery types. Their round-trip energy efficiency typically ranges from 75% to 90%, depending on the design and conditions. Flooded deep-cycle batteries are usually around 80–85% efficient, while AGM types can reach up to 90% in ideal situations.

Efficiency drops as the battery nears full charge, leading to more energy loss as heat and gassing, especially in the last 20% of charging. This makes it inefficient to keep lead-acid batteries at a high state of charge continuously and can also cause water loss in flooded cells. Self-discharge rates are moderate, about 3–5% per month for flooded types and slightly less for AGM, which is higher than lithium-ion's 1–2% per month. This means lead-acid batteries need regular top-up charging during storage.

In terms of power, lead-acid batteries can deliver high currents, making them suitable for engine starting and other high-power needs. However, their voltage drops more underload compared to lithium-ion, and sustained high discharge quickly reduces available capacity (Peukert's effect)²¹⁵.

Performance is also affected by temperature. Capacity drops sharply in cold weather, with only about 50% of rated capacity at -18°C , while high temperatures shorten lifespan despite good capacity delivery. Cycle life is limited: deep-cycle lead-acid batteries typically last 500–1,000 cycles at 50% depth of discharge, and fewer if deeply discharged regularly. Shallow cycling extends life, and in standby use, lead-acid batteries can last many years. Partial state of charge operation is problematic, as it leads to sulfation and capacity loss. Regular full charges or equalization are needed to maintain performance. Lead-acid batteries respond quickly to load changes, making them reliable for backup and UPS applications.

Overall, lead-acid batteries are reliable for short-term, high-current needs, but have clear limitations in efficiency, cycle life, deep discharge tolerance, and energy density compared to modern chemistries.

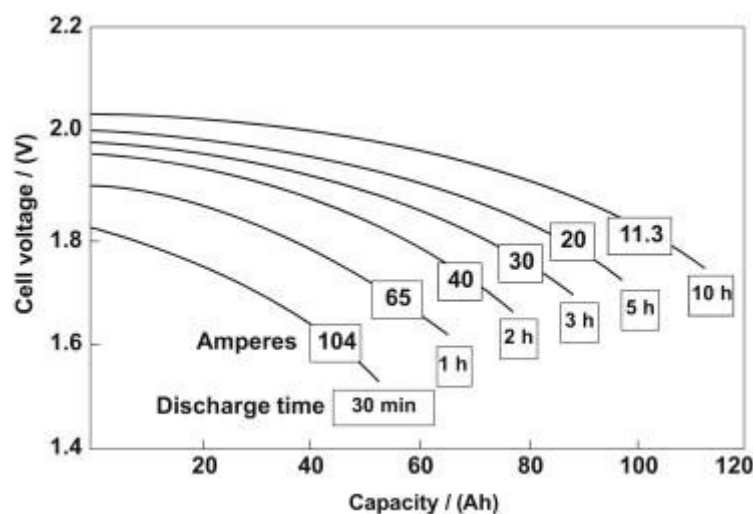


Figure 7.10. Typical discharge curves for lead-acid batteries²¹⁶.

7.3.8 Efficiency and Performance

Lead-acid batteries have moderate efficiency and performance compared to newer chemistries. Their round-trip energy efficiency usually ranges from 75% to 90%, with flooded deep-cycle types around 80–85% and AGM types reaching up to 90% in ideal conditions²¹⁵.

Efficiency drops significantly near full charge due to heat loss and gases, especially in the last 20% of charging. This makes it inefficient to keep lead-acid batteries at a high state of charge and can cause water loss in flooded cells. Self-discharge is moderate, about 3–5%

per month for flooded batteries and slightly less for AGM, which is higher than lithium-ion's 1–2%, so periodic top-up charges are needed^{198,217}.

Lead-acid batteries can deliver high currents, making them suitable for engine starting, but their voltage sags more underload compared to lithium-ion. Sustained high discharge quickly reduces capacity, and performance drops sharply in cold weather—at -18°C , capacity can fall to about 50%. High temperatures shorten lifespan, even though capacity delivery remains good, as shown in the figure below.

Cycle life is limited: deep-cycle lead-acid batteries typically last 500–1,000 cycles at 50% depth of discharge, and fewer if deeply discharged regularly. Shallow cycling can extend life, and in standby use, they can last many years. However, operating at partial state of charge causes sulfation and capacity loss, unlike newer chemistries that tolerate partial charging²¹⁸.

Maintenance includes occasional full or equalization charges to prevent sulfation. While lead-acid batteries have low energy density and specific power relative to weight, their thick plates allow for bursts of power and fast response times, making them suitable for UPS applications.

In summary, lead-acid batteries are reliable for short-term, high-current use but have clear limitations in efficiency, cycle life, and deep discharge tolerance, making them less competitive than advanced batteries.

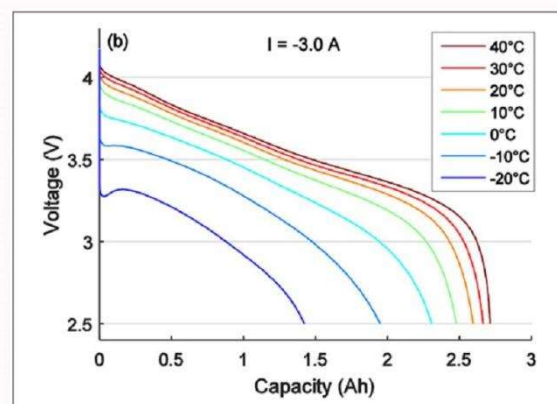


Figure 7.11. Effect of temperature on lead acid batteries ²¹⁹

7.3.9 Cost-Effectiveness

Lead-acid batteries are valued for their low upfront cost, typically ranging from \$50 to \$150 per kWh for large industrial units, making them cheaper than new lithium-ion batteries. However, their overall cost-effectiveness depends on lifespan and maintenance. In cycling applications, lead-acid batteries often need replacement every 3–5 years, while lithium-ion can last about 10 years, making lithium-ion more cost-effective over the long term despite a higher initial price. Levelized Cost of Storage (LCOS) calculations often show lead-acid's cost per kWh throughput is higher due to its shorter cycle life and lower efficiency²¹⁰.

Lead-acid batteries are very cost-effective for backup power with low cycling, such as telecom backup, where they float charge and discharge infrequently, sometimes lasting 8–10 years. Recycling is a major advantage—over 95% of lead is recovered and reused, often providing core credit that reduces net cost and stabilizes prices.

Maintenance costs vary flooded lead-acid batteries require regular water checks and equalization charges, while VRLA types need less maintenance but can fail unexpectedly. Large installations need ventilation and dedicated battery rooms, adding to costs, but these are generally manageable.

For small-scale use, lead-acid remains attractive due to its low purchase price; for example, a car battery might cost around \$100, much less than a lithium-ion equivalent. In summary, lead-acid batteries are cost-effective upfront and for low-cycle or standby uses, but their shorter lifespan makes them less competitive for daily deep cycling compared to lithium-ion. Still, their cost advantage, recycling value, and abundant supply keep them relevant in specific segments²²⁰.

7.3.10 Safety and Risks

Lead-acid batteries are generally safe and stable when used properly, but certain risks require attention. During charging, especially overcharging—flooded lead-acid batteries can emit hydrogen and oxygen gases. Hydrogen is flammable and can explode if it accumulates in an enclosed space and is ignited by a spark, so proper ventilation is crucial for battery rooms²¹⁷.

Another risk is the sulfuric acid electrolyte. If a battery case cracks or is mishandled, acid can leak, causing burns or equipment damage. Even routine maintenance, like checking fluid levels, carries a minor risk of acid contact, so protective gear is recommended. Sealed batteries reduce this risk but can still vent if overcharged or damaged.

Lead-acid batteries can deliver very high currents if short-circuited, creating sparks or even welding tools to terminals, which is a fire and injury hazard. Terminal covers and insulated tools help prevent accidents. The batteries are also heavy, so improper lifting can cause injury, and dropping one could spill acid. [Click or tap here to enter text..](#)

Thermal runaway is not typical for lead-acid, but they can overheat if overcharged, causing swelling or boiling dry, especially in sealed types. They are not flammable themselves, but extreme overheating could ignite nearby materials.

Lead is toxic if ingested, so proper hygiene is needed when handling batteries. Disposal must be managed carefully to avoid environmental contamination, as dumping is illegal in most places.

Despite these risks, lead-acid batteries are stable when not in use and tolerate some abuse without catastrophic failure. Their safety in vehicles and stationery uses is well established, provided proper ventilation, containment, and handling procedures are followed. With adherence to safety guidelines, lead-acid battery installations remain safe and reliable¹⁹⁸.

7.3.11 Maintenance and Operational Requirements

Lead-acid batteries require more maintenance than most newer battery types, especially the flooded designs. Flooded lead-acid batteries need regular watering, as water in the electrolyte is lost during charging. This means checking and topping up each cell with distilled water, typically every month or quarter, to prevent damage from exposed plates²²¹.

Equalization charges are also needed every few weeks to mix the electrolyte and prevent stratification. This process produces hydrogen gas, so good ventilation is important. Battery terminals should be cleaned periodically to prevent corrosion, and connections

should be checked and tightened, especially in stationary setups where thermal expansion can loosen them²¹⁰.

Operationally, lead-acid batteries should not be left at partial state of charge for long periods, as this leads to sulfation and capacity loss. Prompt recharging after use is required, and in renewable systems, periodic full charges may be needed if solar input is insufficient. Temperature management is also important—high heat shortens battery life, while freezing can damage discharged batteries. Keeping batteries charged in cold weather or providing heating is necessary to prevent freezing.

In summary, lead-acid batteries are robust but demand regular care: watering, cleaning, equalizing, and monitoring. Neglecting maintenance can lead to reduced performance and lifespan. While maintenance-free VRLA types reduce the burden, they still benefit from periodic inspection. In contrast, lithium-ion and NiMH batteries are largely maintenance-free, making lead-acid less convenient in some contexts²²⁰.

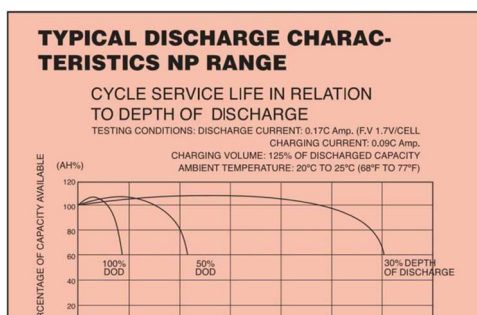
7.3.12 Expected Operational Life

The operational life of lead-acid batteries depends on both calendar life and cycle life. In stationary float service, such as telecom or UPS backup, lead-acid batteries can last 5 to 15 years, and long-life designs may reach up to 20 years if kept mostly charged and at moderate temperatures²²².

However, cycle life is much shorter, especially with deep cycling. A typical deep-cycle lead-acid battery may provide 300 to 500 full cycles at 100% depth of discharge before significant capacity loss. Shallower cycles increase lifespan—up to 1,000 cycles at 50% DOD, or a few thousand at 20% DOD—but exceeding 2,000 cycles is rare as seen in the figure below.²²²

Depth of discharge and temperature are key factors. Regularly discharging beyond 50% shortens life, and high temperatures accelerate plate corrosion, halving battery life for every 10°C above 25°C. End-of-life mechanisms include plate corrosion, sulfation, electrolyte stratification, and water loss, especially in VRLA types.

(a)



(b)

Figure 7.12. (a) cycle life can be extended significantly by reducing the battery depth of discharge²²² (b) Thermal runaway results on VRLA battery²²²

In heavy cycling applications, expect 3–6 years of service, while light cycling or standby use can yield 10–15 years. This is shorter than lithium-ion or NiMH batteries, which last longer under similar conditions. As a result, lifecycle costs for lead-acid are often higher, since multiple replacements may be needed over a project's lifetime.

Proper maintenance—avoiding deep discharge, equalizing, keeping temperatures moderate, and prompt recharging—can extend life, but lead-acid batteries remain relatively short-lived under deep cycling stress²²².

7.3.13 Spatial and Site Considerations

Deploying lead-acid battery systems requires careful planning due to their heavy weight and bulky size. Sufficient floor space is needed, often in a dedicated battery room or enclosure. Floors must be strong enough to support the weight, and battery racks are used to stack cells, but stacking height is limited for safety and maintenance access. Ventilation is critical, especially for flooded batteries, to prevent hydrogen gas buildup. Battery rooms need vent fans or natural ventilation, explosion-proof lighting, and should not contain spark-producing equipment²²³.

Temperature control is important for optimal battery performance and lifespan. Cooling may be needed in hot climates, while heating or insulation is necessary in cold climates to prevent freezing of discharged batteries. Safety measures include acid-resistant flooring, containment trays, and having eye wash stations or neutralizing agents nearby. Installation codes often require clearances for venting and easy access for maintenance²²⁴.

Overall, site planning for lead-acid batteries must address size, weight, ventilation, temperature control, acid spill mitigation, maintenance access, and security. These requirements can add to costs and design complexity compared to alternatives like lithium-ion, which need less space and ventilation²¹⁵.

7.3.14 Social Impact

Lead-acid batteries have played a major social role for over a century. They enabled mass adoption of automobiles, supported economic growth, and provided reliable backup

power for hospitals and data centers. In rural and off-grid settings, lead-acid batteries have brought electricity and improved quality of life, especially before lithium-ion became affordable. Their low cost still makes them useful in some development programs and small-scale solar projects.

However, lead is a neurotoxin, and the widespread use of lead-acid batteries has required a global recycling network. In well-regulated regions, this system works well and is a model for circular economic practices. In countries with poor regulation, informal recycling has led to serious health problems, including lead poisoning in children and contaminated communities.

The industry creates jobs in manufacturing and recycling, but these come with occupational hazards if safety standards are not followed. There have been cases of workers and community lead poisoning near battery plants, especially in places with weak enforcement. Improvements have been made, but risks persist in some regions.

Lead-acid's affordability has also supported small businesses, like battery shops in developing areas, and enabled community enterprises such as battery rentals and charging services. Widespread car ownership, made possible by reliable lead-acid starting batteries, has shaped urbanization and social patterns.

As electric vehicles grow, lead-acid's market share may decline, potentially impacting jobs in mining and recycling. However, technology remains entrenched in many sectors and is not disappearing soon. Public perception of lead-acid is generally low-profile, as it is less associated with dramatic incidents than lithium-ion, but the health risks from lead exposure remain a concern.

Ongoing education about safe recycling and handling, especially in low- and middle-income countries, is essential. Overall, lead-acid batteries have enabled important social advances but Sodium Sulphur batteries

7.4 Sodium–Sulfur (NaS) Battery Overview

A sodium–sulfur (NaS) battery is a high-temperature electrochemical energy storage system that uses molten sodium metal as the anode and molten sulfur as the cathode,

separated by a solid ceramic electrolyte (typically beta-alumina). During discharge, sodium atoms at the anode are oxidized to Na^+ ions and electrons. The Na^+ ions migrate through the beta-alumina solid electrolyte to the cathode, where they react with sulfur to form sodium polysulfides (Na_2S_x), releasing electrical energy. The overall cell reaction can be summarized as $2\text{Na} + x\text{S} \rightarrow \text{Na}_2\text{S}_x$, with a nominal cell voltage around 2.0V. The battery operates at 300°C – 350°C to keep the electrodes molten and the internal resistance low.

Because the sodium ions can only cross the ceramic electrolyte when the cell is hot and molten, NaS batteries require an initial heating period and insulation to maintain temperature. Each cell is typically a cylindrical design with liquid sodium in the center, surrounded by the tubular beta-alumina electrolyte, which in turn is in contact with an outer container of molten sulfur. Cells are assembled into modules that are enclosed in a thermal insulation enclosure to retain heat. Importantly, the solid electrolyte prevents self-discharge when no external circuit is connected – the battery can be left at full charge without losing energy as long as it remains heated. Deep discharges (100% depth-of-discharge) are possible without damage or “memory effect,” as the chemistry allows the cell to fully cycle between Na/S and polysulfide states without irreversible side reactions. The combination of abundant active materials (sodium and sulfur) and a sealed, all-solid internal design means the NaS battery is inherently low in toxicity and environmentally friendly in terms of materials used.

Operating principle: In summary, when discharging, molten sodium at the negative electrode releases electrons and Na^+ ions; the ions pass through the ceramic electrolyte to the positive side where they combine with sulfur to form molten sodium polysulfides, while electrons flow through the external circuit to do work as seen in the figure below. On charging, the process is reversed: an external power source drives electrons back to the sodium, and Na^+ ions migrate back through the electrolyte, decomposing polysulfides to S and regenerating Na metal. The system requires thermal management to maintain a high operating temperature; however, heat generated by internal resistance during cycling helps keep the battery hot, so a regularly cycled NaS battery is self-heating after

the initial warm-up. Up to ~14% of the stored energy may be used to maintain operating temperature during idle periods, though in practice modern systems have improved insulation and only a few kilowatts of heating power per container are needed to sustain temperature.

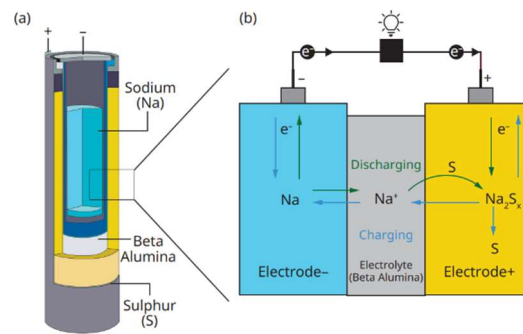


Figure 7.13. Schematic of a sodium-sulphur battery cell¹³⁷ (a) tubular design battery, (b) during discharging and charging¹³⁷.

Table 7.9. Overview of Sodium Sulphur batteries¹³⁷

Parameter	Details
Category	Electrochemical energy storage—Sealed battery
Status	Commercial stage—cumulative deployment at ~560 MW in 2020 Sodium-sulphur batteries are only used for stationary applications. Most deployed systems are used for:
Application	- Renewables integration: Storing large amounts of excess renewable electricity supply to be used at a later time - Network investment deferral: Avoidance of power network upgrades when peak power flows exceed existing capacity
Variations	Sodium-nickel chloride (NaNiCl) is an alternative high-temperature battery based on sodium, nickel, and chloride. However, it is better suited for transport applications. The high nickel content makes it too costly for other applications.
Formula	Half-cell reactions (discharge): Anode: $2 \text{Na} \rightarrow 2 \text{Na}^+ + 2 \text{e}^-$ Cathode: $\text{X} + 2 \text{e}^- \rightarrow \text{S}_x^{2-}$ Overall reaction (discharge): $\text{Na}_2 + \text{S}_x \rightarrow \text{Na}_2\text{S}_x$ (Voltage: 2V)
Advantages	+ High energy density (~200 kWh/m³) + Inexpensive, non-toxic raw materials (Na, S) + Wide ambient temperature range (e.g. hot climates) + Long lifetime for a sealed battery (4,500 cycles or 15 years) – High self-discharge in idle state due to need to maintain high operating temperature (~300–350 °C) – Relatively low discharge rates (systems are optimized for 6 hours discharge duration) – Safety risk due to high reactivity of sodium with water
Disadvantages	– Uncertain cost reduction potential with only one leading manufacturer
Sample players (battery supplier)	• NGK ²²⁵ (Japan)
Innovation focus	Electrolyte: Replace solid beta-alumina ceramic with liquid electrolyte to reduce operating temperature and cost

7.4.1 Current Applications

NaS batteries today are primarily used in stationary energy storage applications for electric grids and industrial sites, where their long discharge duration and high energy capacity are advantageous. A typical use case is renewable energy integration – for example, storing excess solar or wind generation and releasing it during peak demand (peak shaving and time-shifting)²²⁶. Utilities have deployed NaS systems for grid stabilization, frequency regulation, and transmission & distribution deferral. For instance, one of the largest installations is a 50MW / 300MWh NaS battery system at Buzen, Fukuoka Prefecture in Japan, commissioned in 2016 for balancing solar power output²²⁵. This system, housed in 252 container units, provides about 6 hours of discharge to support the local grid and spans a footprint of ~14,000m². Another landmark project is in Abu Dhabi (UAE), which in 2019 deployed a “virtual battery plant” totaling 108MW / 648MWh of NaS storage across 10 sites – at the time, the largest battery system in the world²²⁷. The Abu Dhabi installation demonstrated the feasibility of NaS technology for large-scale, long-duration storage in an arid environment to support the reliability of the region’s grid. Early adopters were in Japan: the technology was first commercialized by TEPCO and NGK in the 1990s, and Japanese utilities installed NaS batteries for load leveling at substations and wind farm stabilization²²⁵. Over 200 NaS systems have been deployed worldwide, with a cumulative installed energy storage capacity of roughly 4–5 GWh (on the order of 559–720MW of power) by the mid-2020s. While Japan accounts for a large share of these installations, NaS batteries have also been implemented in the United States (for example, a 1 MW/7.2 MWh unit for microgrid support on Catalina Island, California) and Europe. In Europe, initial projects include a NaS system in Reunion Island (France), trial installations in Germany, and a 35MW system in Italy (commissioned by Terna in 2015) to support the grid. These projects highlight interest in NaS for energy-intensive, long-duration applications such as renewable integration, island grids (reducing diesel fuel usage), and industrial peak shaving²²⁸.

Notably, NaS batteries have also been tested in microgrid and remote applications. Their ability to provide several hours of backup power makes them suitable for community energy systems or large commercial facilities. For example, the Catalina Island NaS battery system (1MW) supports a remote microgrid by storing overnight wind energy and improving power quality. There have also been experimental uses in spaceflight and other niches – NASA flew a NaS battery experiment on the Space Shuttle in the 1990s to evaluate its performance in microgravity. However, due to the high operating temperature, NaS batteries have not been adopted for mainstream transportation (electric vehicles), since keeping the battery at 300°C in a moving vehicle poses significant challenges. Overall, the current applications of NaS technology are concentrated in stationary, grid-connected settings where its strengths in energy density and cycle life can be utilized, and weight/volume are less critical concerns²²⁸.

7.4.2 Maturity and TRL

High-temperature sodium–sulfur batteries are a mature technology at commercial scale, with decades of development behind them. The concept was first developed by Ford Motor Company in the 1960s, and after further R&D, NGK Insulators (Japan) brought NaS batteries to market in the early 1990s. Since then, hundreds of systems have been deployed globally, establishing a strong track record in the field. In terms of Technology Readiness Level, molten NaS batteries are considered TRL 9 (system proven in operational environment). They have achieved a full commercial breakthrough as stationary energy storage devices – evidenced by multi-megawatt installations integrated into utility grids and the technology's 20+ year market presence. The NaS battery is often cited as one of the first advanced battery technologies (beyond lead-acid) to reach wide-scale commercial deployment for grid storage.

That said, the industry landscape is relatively narrow: as of 2024, NGK Insulators is the sole commercial manufacturer of molten sodium–sulfur batteries, marketing them under the NAS® brand. (BASF SE has partnered with NGK as a distributor and development partner for markets outside Japan, particularly in Europe.)²²⁹. The dominance of a single supplier indicates that while technology itself is mature, the market adoption has been

somewhat limited compared to Li-ion. Part of this limited uptake historically was due to concerns about safety and durability in earlier generations of NaS batteries. A 2011 fire incident at an NGK NaS battery installation in Tsukuba, Japan led to a temporary pause and redesign of the product. Since then, significant safety enhancements and quality improvements have been implemented, and the technology re-entered the market with improved performance and assurances²²⁹.

In parallel, research continues on next-generation sodium-sulfur systems, including room-temperature NaS batteries that operate with liquid electrolytes at ambient temperature. These are currently at much lower maturity (around TRL 3–4 in laboratories) and face different challenges (like the polysulfide shuttle effect and shorter cycle life). The high-temperature NaS, however, can be considered fully demonstrated. Industry roadmaps anticipate incremental improvements (e.g. better ceramics, higher capacity cells) rather than fundamental changes for the molten NaS tech, given its already commercial status. In summary, NaS batteries have a high level of technological maturity for stationary storage, with decades of operational data and only routine engineering risks remaining. The key challenges ahead are more about scaling production, reducing cost, and expanding market acceptance rather than proving the concept technically²³⁰.

7.4.3 Commercial Availability

Commercial NaS battery products are available primarily through NGK Insulators of Japan, which holds patents and expertise in manufacturing the specialized beta-alumina ceramic and assembling complete battery systems²³⁰. NGK's NAS® battery modules have been sold for projects in Japan, North America, Europe, and the Middle East. As noted, BASF Stationary Energy Storage GmbH (a subsidiary of BASF SE) is the official distribution partner for NGK in Europe, supporting sales, installation and development of NaS systems in that region. This partnership (initiated around 2019) has improved the availability of NaS batteries outside Japan, providing local support and integration services for European customers. Commercially, the batteries are delivered in containerized units (usually 20-foot ISO containers) that come fully assembled with internal battery modules, thermal

management, and battery management systems. For example, NGK's standard offering (NAS Model L24) is a 20-ft container unit holding 24 battery modules, each module containing hundreds of cells.

As of 2024, an estimated 200+ NaS installations have been completed globally. NGK has reported cumulative deployed capacity of over 4 GWh energy and 0.7GW power in the field. The commercial track record includes multi-year operations in environments ranging from the deserts of Abu Dhabi to the temperate climate of Japan and the tropical conditions of Reunion Island, demonstrating the technology's adaptability (with appropriate container insulation and cooling for control electronics). Commercial availability is somewhat limited by production capacity – NGK's manufacturing of the ceramic electrolyte and cells is specialized, and annual output is modest compared to the gigawatt-hours of lithium-ion manufacturing. However, NGK has scaled up production to supply large projects like the 108MW UAE system. New entrants are also emerging: for instance, a Chinese firm, HiNa Battery Technology, established in 2021, is developing NaS batteries, signaling potential future competition and greater supply. Still, at present NGK remains the principal source of NaS batteries, effectively making the technology available via a single supply chain²³¹.

In terms of installations, some NaS systems in operation are full commercial deployments (e.g. grid-tied storage plants delivering contracted services), while others are demonstration projects or pilot programs. For example, the large Buzen 50MW system in Japan is fully operational for peak shaving, whereas recently in 2023, Korea Electric Power Company (KEPCO) began testing a 1MW/5.8MWh NAS system as one of several battery technologies at a test site, in partnership with NGK/BASF. This mix of deployments indicates that NaS batteries are commercially offered and deployed in real projects, but potential buyers often seek some demonstration or vendor guarantee given the smaller install base compared to Li-ion. The technology can be purchased today for stationary storage needs; NGK markets standard container units that can be ordered and delivered (typical lead times for manufacturing and delivery may range from several months up to a year, depending on project size). After-sales support (maintenance, monitoring) is

generally provided by NGK/BASF²²⁹ or their local partners, ensuring that despite the single manufacturer, customers worldwide can obtain and operate NaS systems with proper service agreements.

7.4.4 Scale and Capacity

Suitable Deployment Scale: Sodium–sulfur batteries are best suited for medium to large-scale energy storage projects, such as those for commercial/industrial facilities, renewable plants, or small grid/substation support. The typical minimum unit size is on the order of a few hundred kilowatts in power. NGK's standard container (20-ft) is rated around 200–250kW of power with ~1.2–1.5MWh of energy, which sets a practical lower bound for deployment. In other words, a single container can supply a few hundred kW for 6–7 hours. This makes NaS storage a bit oversized for a single residential home or a very small business; instead, it is targeted at small district or enterprise-level installations. For example, a microgrid for a campus or a large commercial building could deploy one or two containers (~1–3MW, several MWh) to provide backup and peak shaving. The technology is highly modular and easily scalable by adding more containers in parallel strings. Because each container unit is self-contained (with its own thermal management and control), scaling up simply means providing the appropriate footprint and electrical connections for additional units²³².

Power and capacity range: NaS systems have been deployed from ~200kW up to tens of MW. On the smaller end, NGK introduced a design with a single 20-ft container as the building block (~0.2MW / 1.2MWh). On the upper end, multiple containers can be aggregated: e.g., a 50MW plant may use ~250 containers in an array. Practically, NaS battery farms in the 50–100MW range have been built (Japan, UAE), and even larger capacities are possible by expanding the container count. There is no hard technical limit to the MWh scale – it scales linearly with more modules – making NaS suitable for multi-gigawatt-hour projects if desired (only constrained by space and budget). The energy capacity per container can also be increased in newer models: for instance, the NASL24 container holds ~1.45MWh usable energy. Thus, a small installation might be a single

container (~1.5MWh), whereas a utility-scale installation could involve dozens or hundreds of containers delivering hundreds of MWh²³³.

Ease of scaling: The modular nature (containerized units) allows NaS batteries to be scaled both up and down to meet different needs. For a mid-sized factory or a wind farm needing ~10MWh, a cluster of perhaps 8–10 containers could be deployed. For a utility needing 100+MWh, a larger field of containers is assembled. The system design is inherently flexible – power and energy ratios can be adjusted by configuring how many containers (or modules) are dedicated to a project. One consideration is that each container has a fixed power-to-energy ratio (e.g. 250 kW per 1.5 MWh). To achieve shorter durations with higher power, one could oversize the power electronics or use more containers in parallel for power boost (though typically NaS is used for longer duration, so this is not common). Conversely, for extremely long duration (beyond ~7 hours), one could configure a system to operate at partial load or add additional energy modules to the containers if that option is available. Overall, NaS batteries can cover the applicable power range of roughly 0.2MW up to 100MW+, and energy from ~1MWh into the hundreds of MWh, making them well-suited for medium-sized enterprises (which might use a few MWh) as well as utility-scale needs²³⁴.

7.4.5 Storage Density

Volumetric energy density: At the cell level, sodium–sulfur chemistry has high energy density comparable to lithium-ion. Each NaS cell can achieve about 300–400Wh per liter of cell volume, thanks to the lightweight, high-reactivity of sodium and sulfur. In practice, today's commercial NaS cells and modules realize roughly 300–414Wh/L (watt-hours per liter) and about 180–268Wh/kg (watt-hours per kilogram) at the cell/module level. However, when packaged into a complete battery system (with container, insulation, electronics, etc.), the effective storage density is lower. A full 20-ft NAS battery container holds on the order of 1.2–1.5 MWh in a 20-foot (~38m³) volume. This translates to approximately 30–40kWh per cubic meter of container volume. In other terms, each container can store ~1,200–1,500kWh in a space of ~6m×2.4m×2.6m. This system-level volumetric density (~30–40kWh/m³) is lower than that of lithium-ion containerized systems (which might achieve ~70+ kWh/m³), largely due to

the additional space needed for thermal insulation, heating systems, and the lower packing efficiency of cylindrical NaS cells with spacing for thermal expansion and safety²³⁵.

For a given footprint, NaS batteries still provide a compact solution relative to many other long-duration storage technologies. For instance, compared to flow batteries or hydrogen systems (which can be bulkier per kWh), NaS containers are reasonably space efficient. But it is worth noting that a NaS installation of hundreds of MWh will occupy significant acreage: e.g., the 300MWh Buzen installation required 14,000m² (about 3.5 acres) for its 252 containers. This includes spacing between containers for access and safety. The volumetric energy density figure can be contrasted with the gravimetric energy density: each 20-ft NaS container weighs ~21tons (21,000kg) including all equipment. With ~1.45MWh stored, that's about ~70Wh/kg at system level. The cells themselves are lighter (again, ~180+ Wh/kg for just the active components), but the heavy thermal enclosure and steel container add to the mass²³⁶.

In summary, storage density of NaS batteries is high compared to many stationary storage options like lead-acid or flow batteries, but slightly lower than modern Li-ion systems when fully packaged. The batteries achieve around a few hundred Wh per liter at cell scale, and tens of kWh per cubic meter at container scale. From a deployment perspective, this means a NaS system is fairly compact – a few shipping containers can hold tens of MWh – which is a strength for placing storage on constrained sites. Technology is often praised for having comparable energy density to lithium-ion at the electrochemical level, using inexpensive materials, which bodes well for future improvements that might increase the packaging efficiency further.

7.4.6 Discharge Duration

NaS batteries are inherently long-duration storage devices. They are typically designed to discharge over ~6 to 7 hours at their rated power output, which classifies them in the medium- to long-duration category. For example, a standard container unit (250kW, 1.45MWh) can provide its full energy if discharged at 250kW for about 5.8–6 hours. Many installations use NaS for daily peak shaving cycles, charging overnight or during low demand and discharging over the course of the peak hours of the day (morning and

evening peaks, etc.). This 6-hour duration was something of a design target for earlier NGK systems, as it aligns well with shifting solar generation or flattening evening peak loads.

Future developments and some recent models aim for even longer discharge times, up to 8 hours or more. In fact, because the battery can be fully discharged without damage, it is flexible: one can operate a NaS battery at partial load to stretch the discharge. For instance, the Abu Dhabi 108MW/648MWh system could potentially discharge over ~8 hours at ~81MW or conversely deliver full 108 MW for about 6 hours, depending on grid needs. Thus, discharge duration can be varied by changing the discharge rate (C-rate) – a NaS battery could provide longer than 7–8 hours if drawn at a lower power than its rated peak. In practice, systems are often sized for 6–7-hour delivery because that optimizes the use of the battery's energy and meets typical daily cycles.

By contrast, NaS batteries are not intended for very short bursts or UPS-like instant power only, as that would underutilize their deep energy storage capability. They excel in the hours range rather than seconds or minutes. (For sub-minute response or high power/short energy, other technologies like flywheels or supercapacitors are more cost-effective.) That said, NaS batteries can respond quickly to a dispatch signal (see Section 8 on response time), so they can do fast ramping – but they shine when sustaining output for prolonged periods. In summary, expect a NaS installation to deliver multiple hours of discharge: commonly 6 hours at full power is quoted, with newer systems aiming for up to 8 hours. This places NaS in the category of medium-term storage (far beyond the minutes of flywheels or even 2–4h typical Li-ion peaker batteries) and edging into long-term daily cycling for renewable integration. For longer than daily (multi-day) storage needs, NaS is generally not used, as keeping it hot for days without discharge would waste energy – other technologies (pumped hydro, hydrogen, etc.) cover the multi-day scope. NaS is ideal for daily cycles where each day the battery is charged and discharged in roughly equal measure²³⁷.

7.4.7 Efficiency and Performance

Round-trip efficiency (RTE): Sodium-sulfur batteries have a good energy efficiency, typically around 75–85% for a full charge-discharge cycle [cleantechnica.com](#). Modern NaS installations often achieve ~80% DC-to-DC efficiency, meaning 80% of the energy input is recovered as output (not counting AC conversion losses). The efficiency can vary with operating conditions; at higher discharge rates efficiency may be a bit lower, and it improves at moderate rates. One important detail is that published RTE figures often exclude the auxiliary heating consumption when the battery is on standby. When the battery is cycled daily, the heat generated from internal resistance largely supplies the needed thermal energy, keeping efficiency high. If the battery sits idle, energy must be spent to maintain temperature – roughly a few kW per container – which over long idle periods can reduce net efficiency. Under normal daily cycling, NGK indicates the auxiliary power draw is <3kW per container (for a ~250kW, 1.45MWh unit), which is a small fraction (~1–2%) of the power. In summary, round-trip efficiency in regular operation is about 80%, slightly below typical lithium-ion systems (~90%), but still quite good for a long-duration storage system²³⁸.

Response time and power performance: NaS batteries offer excellent electrical performance, including very fast response. They can ramp from zero to full power output in milliseconds – effectively nearly instantaneous on the timescales of grid control [cleantechnica.com](#). The electrochemical reaction is not kinetically rate-limited in the way some fuel cells or thermal plants are; as soon as a load is connected, sodium ions flow and current is delivered. The limitation in practice is the power conversion system (inverter) and perhaps the inductance of connections, but generally NaS batteries are considered capable of sub-second response to grid commands. Sources often cite a ~1ms response time to a step change in demand [cleantechnica.com](#) [large.net](#). This makes NaS suitable for not only energy shifting but also ancillary services like frequency regulation or spinning reserve, where rapid injection or absorption of power is needed. The power density of NaS cells is modest (e.g. ~150–200W/kg), but since multiple cells are assembled, the system as a whole can deliver significant power, constrained by the module design.

Typical NaS systems are designed for continuous output rather than short bursts, yet they can handle surge power above their rating for brief periods if the inverter allows (within thermal limits)²³⁹.

Operational flexibility: The performance of NaS is characterized by a nearly constant internal resistance over the discharge cycle – unlike some chemistries that see voltage sag at low state-of-charge, the NaS cell maintains voltage until near the end of discharge. This is a benefit of the two-phase reaction (liquid sodium and polysulfide), which means the output voltage (~2.08V open-circuit, ~1.78V under load) stays relatively stable as long as sodium and sulfur remain. Therefore, full power is available at any state-of-charge; the battery doesn't need to be above a certain SOC to sustain its rated power. Additionally, there is no self-discharge when in use – the solid electrolyte prevents any ionic flow when the circuit is open, so the battery can hold charge indefinitely so long as it is kept hot (or if cooled down, it will simply pause in that state until reheated). NaS batteries also exhibit excellent partial-load performance and can undergo partial charge/discharge cycles without memory effect or degradation. They can switch between charge and discharge modes quickly, which is useful for grid balancing scenarios requiring back-and-forth adjustment.

Cycle life and degradation: The performance over time is strong – NaS cells do not suffer from significant capacity fade with shallow cycling or calendar fade under high temperature as long as the seals and electrolyte remain intact. NGK's data shows <1% capacity loss per year under daily cycling en.wikipedia.org. The battery's efficiency also remains steady through most of its life; there is no appreciable increase in resistance until the very end-of-life when materials start to wear out. Importantly, 100% depth-of-discharge cycles are possible without penalty, enabling use of the full nameplate energy every cycle. The combination of deep-cycle capability, long duration, and quick response makes NaS performance uniquely suited for daily deep-discharge applications – it can give a long, slow output when needed, but also handle fast transients and frequent cycling. In summary, NaS batteries provide high performance in terms of efficiency (~80%), rapid response (~milliseconds), and full-depth cycling. The main efficiency losses are due to heat

requirements, but those are minimized by insulation and regular cycling. Otherwise, internal Coulombic efficiency (ion transport) is near 100%, and voltage efficiency is fairly high, leading to the ~80% round-trip figure. This efficient energy storage, combined with the ability to instantaneously deliver or absorb power, allows NaS installations to perform tasks ranging from peak shifting to grid frequency regulation with equal ease²⁴⁰.

7.4.8 Cost-Effectiveness

Capital Expenditure (CapEx): The upfront cost of NaS battery systems has historically been relatively high, but it benefits from the use of common materials (sodium, sulfur, aluminum) rather than precious metals. Current estimates put the installed capital cost of NaS storage around €300–450 per kWh of energy capacity (approximately \$330–500/kWh), for a fully integrated system including containers, power electronics, and balance of plant. This is competitive with, and in some cases lower than, lithium-ion battery systems for stationary applications (which in 2025 are in a similar range, often \$300/kWh or below for large projects). Earlier in the 2010s, NaS costs were higher (some sources cited \$500–600/kWh), but increased manufacturing and larger projects have driven costs down. NGK and BASF market NaS as a cost-effective solution for long-duration needs, emphasizing the low cost of raw materials. Indeed, at the cell chemistry level, NaS avoids expensive metals like lithium, cobalt or nickel; the material cost is low, but the ceramic electrolyte and thermal management add to manufacturing cost. According to a 2023 technology roadmap, the current system-level cost of NaS is in the few hundred Euros per kWh and is expected to further decline with economies of scale. For power-related cost, each container (250kW) might cost on the order of €150,000–200,000 (rough estimate), translating to ~€600–800 per kW installed. Large installations benefit from some economies of scale in site work and integration²³⁰.

Operational Expenditure (OpEx): The ongoing operational costs for NaS batteries are relatively low. The systems are often described as maintenance-free for 10–15 years of operation. There are no moving parts aside from small pumps or fans for heating and ventilation. Routine maintenance might include periodic checks of electrical connections,

health monitoring of cells via the BMS, and upkeep of the HVAC/heating system. NGK's NaS modules are sealed and do not require electrolyte replacements or refills (unlike flow batteries, for instance). Preventive maintenance is minimal – consumable parts (perhaps filters or some electronic components) may be replaced only occasionally. The battery does require continuous power to keep it warm when not cycling; this “standby heating” incurs an operational cost in the form of electricity consumption²³¹. As noted, each container might draw up to ~3kW constantly for heating. Over a year, that could be ~26MWh of electricity usage per container just to maintain temperature (though in practice, cycling provides much of the heat). The cost of this auxiliary consumption depends on electricity prices; if the battery is co-located with cheap excess renewable energy, the heating cost is negligible, but if drawing from grid power, it slightly reduces the net revenue. Nonetheless, the auxiliary energy cost is small (<5% of throughput) for daily-cycled systems²⁴¹.

Other OpEx elements include insurance and safety management (since it's a high-temperature system, some sites may require fire safety infrastructure, though that is usually included in CapEx) and any labor for monitoring. Training staff to operate NaS is straightforward – the system is automated, and remote monitoring is standard. Several sources note NaS systems as “self-contained and considered maintenance-free over 10–15 years”, meaning no major overhauls are expected in that period. Contrast this with, say, lead-acid batteries which might need replacement or water refilling well before 10 years. Overall, OpEx is low – mainly the cost of lost energy (heat) and a small maintenance budget – often estimated at a few €/kW-year or a few €/MWh of throughput, which is a minor contribution compared to revenue from arbitrage or grid services²⁴².

Levelized Cost of Storage (LCOS): When considering lifetime cost-effectiveness, NaS batteries can be attractive for long-duration, frequent use scenarios. The LCOS is the total cost per unit of energy delivered over the system life, taking into account CapEx, OpEx, efficiency losses, and lifespan. Thanks to their long cycle life (over 4500 cycles, see Section 13) and deep discharge capability, NaS batteries can spread their capital cost over many MWh of output. For example, if a NaS system costs \$400/kWh upfront and can

deliver 7300 full cycles at 100% depth of discharge, the amortized CapEx per cycle is about \$0.055/kWh (5.5 cents/kWh). Adding in efficiency losses (say 80% efficient, so input energy cost) and O&M might bring the LCOS into the range of around \$0.10–0.15 per kWh delivered, depending on financing and utilization. In practice, reported LCOS values for NaS are case-specific, but studies have shown NaS can achieve low LCOS in applications with daily cycling, rivaling or beating Li-ion for 6+ hour duty cycles. One must note that LCOS is sensitive to how often the storage is used; NaS batteries used only for emergency backup (infrequent discharge) would have a high LCOS, whereas those used every day for renewables time-shifting have a much better LCOS²⁴³.

In summary, NaS batteries can be cost-effective for long-duration storage, with capital costs on par with other battery solutions and operational costs that are low. Their LCOS benefits from long life and abundant cycling capability. However, initial CapEx is still a significant investment and currently the market is niche – further cost reductions (possibly via mass production or new suppliers entering the market) could improve their competitiveness against the rapidly dropping costs of alternative technologies like flow batteries or emerging sodium-ion batteries. The economic choice will depend on the specific application: for daily 6-hour discharge needs, NaS often shows a strong life-cycle economic case.

7.4.9 Safety and Risks

Operating at high temperature and containing reactive materials, NaS batteries have unique safety considerations. Key potential hazards include fire/explosion risk from sodium reacting with water or air, thermal runaway if a cell overheats, and the release of toxic gases (like sulfur dioxide) if sulfur combusts or the electrolyte fails. However, extensive safety engineering in modern NaS systems has made serious incidents exceedingly rare. The technology is regarded as inherently safe when intact and equipped with multiple protective systems²⁴⁴.

Safety design features: Each NaS cell is contained within a double-walled structure – the beta-alumina ceramic and an outer steel casing. If a cell fails internally, the ceramic helps

prevent any instantaneous release of sodium. Cells are packed in modules with heat-resistant insulation (often sand or ceramic fiber) filling the gaps. The sand fill around cells serves to smother and absorb any leaking sodium, preventing it from spreading or causing a larger fire. Modules are equipped with temperature and voltage monitoring on each cell or block of cells; if abnormal readings occur, that module can be electrically isolated. There are also fuse links that melt if a cell draws excessive current (signaling a short), disconnecting it from the string. The battery containers have fire detection and suppression systems (e.g. inert gas or powder fire extinguishers) as well as ventilation to relieve any pressure safely. A crucial aspect is preventing external water ingress – the containers are rated typically IP54, keeping out rain or dust. Procedures forbid sprinkler systems or water-based firefighting directly on an active NaS battery fire (instead, one would let the built-in suppression and isolation handle it or use special dry agents)²⁴³.

In summary, NaS batteries have proven to be safe when engineered and maintained properly. The main risks (fire from sodium, high temperature operation) are addressed by robust containment, monitoring, and shutdown systems. The post-2011 design improvements and third-party validations have bolstered confidence. Operators still enforce safety protocols: e.g., exclusion zones around the containers, fire-resistant installation pads, and training for emergency services about how to handle a NaS battery fire (essentially, let the built-in system work and do not apply water). Compared to Li-ion batteries (which can suffer thermal runaway and fire with toxic HF emissions), NaS batteries might catch fire only in extremely rare cases, and even then, the consequences are contained and largely chemical (fire) hazards rather than explosive hazards. The record of only one major incident in decades of operation speaks to the inherent safety when proper designs are in place²⁴¹.

7.4.10 Maintenance and Operational Requirements

One advantage of NaS battery systems is that they are relatively low-maintenance. As sealed units with no moving parts (except cooling fans) and no liquid handling (unlike flow batteries), there is little day-to-day intervention needed. Routine maintenance generally

involves periodic inspection of the battery containers and supporting equipment. Operators will check that heaters, fans, and control systems are functioning, and perhaps annually service those components (e.g., replace air filters or fan units if needed). The battery modules themselves are maintenance-free: they are sealed for life and do not require refilling or electrode replacement during their service life. NGK describes the NaS systems as “maintenance-free over 10–15 years” aside from regular monitoring. Indeed, the cells are designed to operate for thousands of cycles without manual intervention. Unlike some chemistries, there’s no need for periodic balancing or electrolyte top-up – the BMS automatically keeps modules balanced by design²⁴⁵.

In summary, NaS batteries require little hands-on maintenance and are relatively easy to operate. The main operational requirement is maintaining temperature, which is automated. Regular checks and standard electrical equipment upkeep are needed, but there are no frequent replacements or chemical handling. Staff need only basic training in the system’s safety and control. Because of the robust and self-contained design, NaS systems have often been installed in remote locations (e.g., desert solar farms, island microgrids) where they run for years with only occasional visits. This attests to their suitability for “set it and forget it” operation in support of the grid or facility to which they’re connected²⁴⁶.

7.4.11 Expected Operational Life

NaS battery systems are known for their long operational life. The typical lifespan is often quoted as 15 years or around 4500 full charge-discharge cycles (whichever comes first) with proper usage. This assumes one deep cycle per day. In real terms, many NaS installations have indeed operated for over a decade. For example, NGK reported some early installations ran for 15 years performing ~300 cycles per year (roughly 4500 cycles total)²³¹. By the end of that period, those batteries still retained significant capacity, confirming the long life potential. Recent advancements in cell design and operating strategy have extended the expected life further. NGK’s latest NAS® data sheet²²⁵ specifies a design life of 20 years or 7300 equivalent full cycles (again roughly one full

cycle per day for 20 years) with less than 20% total degradation in energy capacity over that span. This is an improvement over earlier generations, thanks to better seal longevity and refined materials that reduce cell corrosion over time.

Cycle life and degradation: NaS cells do experience gradual capacity fade, mainly due to minor electrolyte degradation or anode/cathode interface changes. But the fade rate is low – on the order of <1% capacity loss per 100 cycles (or per year) as per recent data. NGK's specification indicates <1% energy degradation per year under daily cycling [en.wikipedia.org](https://en.wikipedia.org/wiki/NGK). Therefore, after 10 years (~3650 cycles), one might still have ~90% of initial capacity; after 20 years (~7300 cycles), perhaps ~85% remaining. This aligns with the data sheet which showed usable discharge energy dropping from 1450 kWh (beginning of life) to ~1250 kWh at end of life (EOL) after 7300 cycles. Notably, because NaS batteries can be fully discharged, every cycle can use 100% DOD without extra penalty, unlike some chemistries that prefer shallow cycling for longevity. So those cycle counts are full cycles. If a system is used in partial cycles, the equivalent full cycle count accumulates more slowly (e.g., two 50% cycles count as one full equivalent cycle)²⁴⁵.

In conclusion, operators can expect around 15–20 years of reliable operation from a NaS battery system, with thousands of deep cycles. This long life reduces the frequency of replacements and thus improves the economics and sustainability. The technology's proven longevity is a strong point, often exceeding the life of some power electronics or other supporting equipment, which might need replacing before the battery cells do. Ensuring that the battery stays within its intended operating parameters (temperature, not overcharging, etc.) is key to reaching the full life, and the built-in management takes care of that automatically²⁴⁷.

7.4.12 Spatial and Site Considerations

NaS battery installations are space-efficient in modular terms but still require a suitable site area, especially for larger projects. Each 20-foot container (the standard unit) occupies about 15m² of ground area (not including spacing between units). In practice, containers are typically spaced out for safety and maintenance access, often arranged in rows with several meters of clearance. For example, the 50MW/300MWh Buzen installation in

Japan²⁴⁸ uses 252 containers spread over ~14,000m² (about 0.014km²). This includes not just the containers but also access pathways and possibly an on-site control room or substation. That land footprint is roughly 0.05m² per kWh in that project. Smaller installations have proportionally smaller footprints; a single-container system needs perhaps a 6m×4m pad (to allow working room around the 6.1m × 2.4m container). The containers can be placed on simple concrete foundations or piers – no special deep foundations are needed other than supporting the ~21ton weight per container. It's important to ensure the ground is level and can bear the static load²⁴⁸.

Vertical space and stacking: NaS containers are typically about 2.6m tall (standard ISO container height). They usually are not stacked on top of each other in permanent installations due to weight and the need for easy maintenance access to the top (where vents and some equipment may be). However, stacking is technically possible (shipping containers are designed to stack), but from a safety standpoint, having each container accessible directly is preferable especially given the high temperature nature (stacking might complicate heat dissipation and firefighting access). Therefore, most NaS farms are single-level arrays. The visual profile is like a bunch of white shipping containers on site, possibly fenced in²⁴².

Geographical and environmental siting: Since NaS batteries are enclosed and heated systems, they can function in a wide range of climates, but some environmental conditions must be managed:

Ambient temperature: Standard systems operate in environments from –20°C winter cold up to +45°C summer heat. Options allow extending to –40°C (with extra insulation/heating) and +55°C (with enhanced cooling). This means NaS can be installed in temperate and subtropical climates readily. In extremely cold climates, additional shelter (like an insulated enclosure or building) might be used to reduce heat loss. In extremely hot climates (desert), shading the containers or active cooling of control electronics might be necessary to keep them within spec. The containers themselves contain the high heat internally, so ironically they might handle cold ambient well as long

as you can supply heating power, whereas extreme heat could be an issue for the external electronics²⁴⁷.

Performance under varying conditions: The performance of NaS is fairly independent of ambient temperature as long as the internal temperature is maintained. On hot days, the battery doesn't get "too hot" because internal regulation stops overheating. On cold days, performance doesn't sag like it would for a cold lithium-ion battery, because the NaS is insulated and stays hot. So the output is stable across seasons, which is a big plus in climates with extreme winters that can reduce Li-ion battery effectiveness. The main variation might be in auxiliary heating consumption – e.g., in winter more heating power is needed, slightly affecting net efficiency²⁴⁴. But the battery's output capability (power and energy) remains essentially constant whether it's summer or winter outside, as long as the container systems keep doing their job. This gives a resilience advantage: even during a cold snap or heat wave, a NaS battery can perform, whereas other tech might derate. In conclusion, siting a NaS battery requires allocating an appropriate footprint, ensuring environmental conditions are within acceptable range, and providing standard utilities (power, communications). They are quite modular and location-flexible – one can install them in urban or rural settings, at ground level with minimal construction. Space-wise, they are compact relative to the energy stored (especially compared to alternatives like large hydrogen tanks or pumped hydro reservoirs). Each project will consider local site specifics (flood control, seismic, access for maintenance, etc.), but there are no insurmountable siting constraints for NaS beyond what's common for any large electrical equipment²⁴⁶.

7.4.13 Social Impact

The social impact of deploying sodium-sulfur battery technology can be viewed as generally positive, with a few considerations regarding public perception and local engagement.

Local acceptance and community support: NaS battery installations have so far not encountered significant public opposition, in part because they are usually located at existing utility sites or industrial areas. They are quiet and emissions-free in operation,

which is advantageous for community acceptance (unlike, say, a noisy generator or a visually imposing wind turbine). However, whenever a new energy facility is proposed, local residents may have concerns. In the case of NaS batteries, the primary concern might be safety – locals could worry about the risk of fire or explosion given the system contains molten sodium²⁴⁶.

Social and economic benefits: The deployment of NaS batteries contributes to the broader societal goal of clean energy transition. By enabling more renewable energy use and providing reliable power, they indirectly benefit communities with cleaner air and better grid stability. In regions with manufacturing or deployment, there could be job creation aspects. While NGK's batteries are manufactured in Japan, the installation and maintenance in a local region requires electrical contractors, engineers, and operators, potentially creating skilled jobs (though not an enormous number, since maintenance needs are low). If adoption grows, one could envision factories for NaS batteries being set up in various regions (for example, BASF's involvement hints at potential future manufacturing in Europe). That would generate manufacturing employment and associated economic activity²⁴⁹.

Social perception of alternative batteries: As lithium supply and sustainability concerns rise, sodium-based batteries are often viewed favorably by the public and policymakers as a complement to lithium-ion. The narrative that NaS uses "salt and sulfur" which are cheap and abundant resonates as a positive environmental and ethical story (no conflict minerals, no child labor issues that have plagued cobalt, etc.). Promoting NaS technology can thus have a social impact by alleviating concerns over raw material sourcing and aligning with circular economy principles (due to easy recyclability)²³³.

In summary, the social impact of NaS battery projects is largely favorable. They tend to be accepted by communities, especially if accompanied by transparent safety information and if the community understands the benefits (such as improved local power quality or enabling more renewable energy which aligns with climate goals). With minimal noise, no emissions, and a low profile, NaS installations can coexist in populated areas quietly. As with any infrastructure, maintaining trust through proper safety management is key –

local residents and officials will want assurance that the molten sodium inside will not pose a threat. The track record and engineering certifications provide a strong basis for that assurance. Furthermore, adoption of NaS could spur local economic activity in terms of jobs and innovation, particularly in regions that engage with the technology's supply chain or R&D (like BASF's involvement in Europe)²²⁹. Overall, NaS batteries contribute positively to society by facilitating cleaner energy systems, and with careful project development, they can do so with community support and minimal negative local impacts.

Emerging and Alternative Battery Technologies

Beyond the mainstream battery types covered above, several emerging battery technologies are gaining attention as alternatives for specific energy storage needs. These include solid-state batteries, and metal-air batteries, among others. Each of these brings unique characteristics that could address some limitations of conventional batteries. Below, we provide an overview of these promising alternatives, noting their operating principles and key attributes in comparison to established technologies²⁵⁰.

7.5 Solid-State Batteries

7.5.1 Overview and working principle

Solid-state batteries are often cited as the next-generation advancement for lithium-based batteries. The defining feature of a solid-state battery (SSB) is that it uses a solid electrolyte instead of the traditional liquid or gel electrolyte found in current Li-ion cells. In a solid-state battery, both electrodes and the electrolyte are solid materials – for example, a lithium metal anode, a ceramic or polymer solid electrolyte, and a cathode such as a layered oxide or sulfur, all in intimate contact. By eliminating the flammable liquid electrolyte, SSBs aim to offer improved safety (no risk of leakage or fire from liquid solvents), as well as potentially enabling the use of a lithium metal anode, which can significantly increase energy density (because you remove the need for a graphite anode host and can utilize lithium's very high specific capacity). The **operating principle** remains the movement of ions (e.g., Li^+ or Na^+) through the solid electrolyte and electron flow

through an external circuit. The solid electrolyte can be a ceramic (like $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ – a sulfide glass, or LLZO – a garnet-type oxide) or a solid polymer (often with lithium salt), or a composite²⁵¹.

7.5.2 Current Applications

Solid-state batteries are not yet in mainstream commercial products, but they are in advanced R&D and early prototyping. A few small-scale applications use thin-film solid-state micro-batteries (for example, in some sensors or IoT devices, where a tiny thin-film cell on a chip provides power – these have been around but niche). The big, anticipated use is in electric vehicles and consumer electronics. Several automakers and startups (QuantumScape, Solid Power, Toyota, etc.)²⁵² are actively developing EV solid-state batteries, aiming for commercialization mid-decade. The idea is to achieve higher energy per cell (for longer range or smaller battery packs) and improved safety margin. There's also interest in aerospace or wearables for solid-state due to safety and possibly form-factor flexibility (some solid-state designs might allow thinner, flexible cells). To date, no mass-market EV uses SSBs yet; however, Toyota, for instance, demonstrated a concept vehicle with a solid-state battery for the 2020 Olympics (in a limited way). Prototypes of consumer electronics batteries (like a solid-state smartphone battery) have been shown by companies like Samsung SDI in labs¹⁷⁷.

7.5.3 Maturity and TRL

Solid-state batteries are roughly **TRL 4-6** – demonstrated in lab, with prototypes, but not yet proven in large-scale manufacturing or long-term field operation for large cells. Thin-film micro-batteries are at TRL9 for tiny capacities (they're commercially sold for specialty uses). But for high-capacity cells, challenges remain (e.g., maintaining good interface contact between solid electrolyte and electrodes during cycling, scalable manufacturing, etc.). Companies claim they will reach automotive qualification in the next 2-3 years, which would push TRL to 7-8²³⁹.

7.5.4 Advantages

The primary advantages expected are enhanced safety – no flammable liquid means the cell should not catch fire even if physically damaged or overheated – and higher energy

density – using lithium metal anode and possibly stacking cells differently can boost Wh/kg significantly (some claim 50% or more increase over current Li-ion). Also, solid electrolytes might allow wider temperature operation (some can work in extreme cold or heat better than liquids which freeze or boil). They might also reduce need for complex battery management (if safer, maybe less cooling or less stringent voltage restrictions). Additionally, some solid electrolytes are very stable, potentially leading to longer calendar life (less electrolyte breakdown, no SEI layer needing continuous reformation in the same way as liquid cells – although a different kind of interface forms). There's also interest that solid-state could simplify packaging – possibly enabling bipolar cell stacking (especially in solid polymer designs) which could reduce dead weight/volume from casings and current collectors, further boosting energy density¹⁷⁷.

7.5.5 Limitations

Right now, solid-state tech faces several limitations: high internal resistance – many solid electrolytes have lower ionic conductivity than liquids, which can limit power unless made thin and with good contact. Interface issues – solids don't perfectly wet the electrode surfaces like liquids, so achieving low impedance interfaces and preventing voids or dendrites at the interface (especially lithium metal forming dendrites penetrating solid electrolyte) is a challenge. Many ceramic electrolytes are brittle, raising manufacturing and durability questions (cells might crack under mechanical stress or during repeated expansion/contraction cycles)²⁵³. Manufacturing – current Li-ion production processes can't be used directly; new techniques (like pressing layers, sintering ceramics, vacuum deposition for thin films, etc.) may be needed, requiring new investments. Cost – solid-state cells initially will be more expensive due to materials (some use expensive elements) and novel production with lower yields likely. Another limitation has been operating temperature – some early solid electrolytes needed slightly elevated temp (e.g., some polymer ones work best at 60-80°C, which isn't ideal for portable electronics; ceramic ones can work at room temp but sometimes not as well at -20°C). Companies claim to have solved many of these issues in labs (like sulfide electrolytes that conduct as well as liquid, etc.), but scaling up remains. Solid-state also often means thinner electrodes (to ensure

ions can travel through them if diffusion is slow without liquid), which could reduce practical energy if not compensated by stacking many layers²⁵⁴.

7.5.6 Commercial Availability

At present, you cannot go and buy a high-capacity solid-state battery off-the-shelf. A few specialty suppliers can make small thin-film cells for tech R&D. We expect initial commercial SSBs perhaps in premium electronics or pilot EV programs around 2025-2027. QuantumScape, for example, is in development phase providing prototype cells to automakers for testing. Solid Power is shifting to produce pilot EV cells to deliver to partners (BMW, Ford). Toyota has heavily researched solid-state and hints at introduction in maybe hybrids before full EVs. So availability is limited to prototype partnerships now, but a rapid rise is anticipated once a breakthrough product hits the market²⁵⁴.

In summary, solid-state batteries promise a *safer, more energy-dense future generation of batteries*, addressing some of Li-ion's drawbacks (especially flammability and possibly longevity). They are not yet deployed in mainstream products, but progress indicates they could play a significant role in the next 5-10 years, particularly in electric vehicles and portable electronics as an upgrade once technical hurdles are overcome.

7.6 Metal-Air Batteries (e.g., Zinc-Air, Iron-Air)

7.6.1 Overview and working principles

Metal-air batteries are a class of energy storage that use a **metal as the anode** and oxygen from the air as the cathode reactant, effectively using atmospheric oxygen as one of the electrode materials. This gives them very high theoretical energy densities, since the battery doesn't have to carry both reactants internally (oxygen is taken from the environment). There are various metal-air chemistries; the most well-known are **zinc-air** and more recently **iron-air** (and also lithium-air in research, but that is extremely experimental)²⁵⁵.

In a **Zinc-Air battery**, the anode is zinc (usually powder or gel in alkaline electrolyte) and the cathode is an air-breathing electrode with a catalyst for oxygen reduction. During discharge, zinc metal is oxidized to zincate or zinc oxide at the anode, and oxygen from the air is reduced to hydroxide ions at the cathode. In the alkaline electrolyte (KOH), the

net reaction produces zinc oxide and releases electricity. For example: $2 \text{Zn} + \text{O}_2 \rightarrow 2 \text{ZnO}$ (in alkaline solution via intermediate steps). These are primary in small button cells (like hearing aid batteries) – those can't easily be recharged (the reaction produces solid ZnO that clogs structure). There are also rechargeable zinc-air developments, where during charge zinc oxide is reduced back to zinc and oxygen is evolved at the air electrode. Challenges have been managing the air electrode and formation/dissolution of zinc. Companies like Zinc8 and Fluidic are developing zinc-air systems for long-duration energy storage, some using a flow of zinc particles in electrolyte (hybrid of metal-air and flow battery). **Iron-Air** batteries (like the systems from Form Energy) work similarly: iron metal anode oxidizes to iron hydroxide/rust, and air provides oxygen at the cathode which is reduced to form hydroxide. On charge, iron oxide is reduced back to iron and oxygen gas is released (essentially a reversible rusting process). Iron-air had been explored decades ago and recently revived for grid storage because iron is cheap and such a battery could be very low-cost per kWh for multi-hour storage, albeit with low efficiency.

7.6.2 Current Applications

Small zinc-air cells have long been used in hearing aids and some other medical devices because of their high energy density in a tiny package (primary Zn-air buttons have extremely high capacity for their size but only one-time use). In larger format, metal-air batteries are mostly in prototype/pilot stage. There have been zinc-air batteries tested for off-grid energy (some early 2010s projects in Africa to power lighting, etc., but issues with cycle life curtailed widespread use). **Zinc-air is seeing trial as a stationary storage** – e.g., Zinc8 (a company in North America) ²⁵⁶is working on a multi-hour storage unit for utilities, with first deployments expected in coming years. **Iron-air** is brand-new in terms of application: Form Energy (USA) is deploying a 1 MW/100 MW·h (100-hour duration) iron-air battery system for a utility in Minnesota as a proof-of-concept near term. If that succeeds (target operation around 2025), iron-air could become a leading tech for multi-day grid storage. For small-scale, not really used due to recharging difficulty (except non-rechargeable like zinc-air hearing aid cells). There's also **aluminum-air** and others that

have been tested – e.g., aluminum-air had an EV demonstration (aluminum anode needed replacement mechanically, not electric recharge)^{257,258}.

7.6.3 Maturity and TRL

Primary (non-rechargeable) metal-air like zinc-air button cells are TRL 9 for small devices. Rechargeable metal-air is lower – rechargeable zinc-air might be TRL ~6 (prototypes tested in field, e.g., some backup systems, but not mass commercial). Iron-air might be TRL ~4-5 (lab proven, now scaling to TRL6 with the utility pilot). A lot of research persists to improve catalysts for air electrodes, prevent electrode flooding or drying, and in zinc-air, avoid dendrite formation on zinc or carbonate build-up in electrolyte from CO₂ in air. So definitely emerging tech for rechargeable versions^{259,260}.

7.6.4 Advantages

The allure of metal-air batteries is their ultra-high theoretical energy densities. For example, zinc-air can have ~350-500 Wh/kg practical specific energy in primary form, which is huge (in hearing aids, that means a tiny battery lasts long). Rechargeable would be lower due to added support structures and inefficiencies, but still potentially higher than NiMH or lead-acid. Iron-air is not as high energy by weight (iron is heavy), but it's extremely cheap – Form Energy's design aims for very low cost per kWh (maybe <\$20/kWh) making it viable for massive scale storage. Another advantage: abundant, cheap materials – zinc, iron, aluminum, etc., are cheap and widely available, so using them avoids resource constraints like lithium or cobalt. Also, no flammable components typically (aqueous electrolyte), meaning good safety (though the flip side is oxygen is reactive – but since you're already using it, it's fine as long as system is designed to handle occasional oxygen release on charge). They also potentially can hold charge for a long time with minimal self-discharge if left open-circuit (especially if air access is cut off, they basically pause – e.g., hearing aid batteries come with a tab sealing air hole to keep them fresh until needed). For grid storage, metal-air can offer very long duration at low cost because adding more metal fuel and electrolyte is cheap relative to other tech. The iron-air battery, for instance, trades off efficiency for ultra-long discharge cheaply, something flow or Li-ion find expensive to do at multi-day scale^{261,262}.

7.6.5 Limitations

Many. Rechargeability is the biggest – metal-air cells tend to suffer short cycle life due to issues like anode shape change (metal moving or forming dendrites), electrolyte consumption (zinc-air in KOH: CO_2 from air makes carbonate precipitates, fouling the cell over time; iron-air also will have electrolyte management issues). The round-trip efficiency is generally low: zinc-air maybe 50-60%, iron-air on the order of 50% or even less. This is because the oxygen reaction at air cathode has large overpotential and you often need bifunctional catalysts (one for ORR, one for OER) with compromise in performance. So you waste a lot of energy as heat. This can be acceptable if using otherwise curtailed renewable power where energy is cheap, but it's a big disadvantage if efficiency matters. Power density: metal-air are typically limited in output current by the air cathode area and catalysis; they're better for steady low power discharge over a long period, not for high surges (though one could design for more power by increasing cell area or adding fans to supply more oxygen etc., which adds complexity)²⁶³.

Mechanical complexity: Systems like zinc-air or iron-air might require pumps to circulate electrolyte or oxygen, and iron-air might require a blower for the air side and some method to flush product (iron rust or etc.). They also may need maintaining of metal electrodes – e.g., in iron-air, after many cycles you might need to replace the iron or rejuvenate it if it clumps; in zinc-air, you might need to periodically clean out carbonate. So likely more maintenance and operational oversight (like flow batteries in that sense). Also, metal-air batteries often operate best in a certain environment – e.g., controlled humidity for the air electrode (too dry and the KOH in cathode dries out, too humid and flooding occurs). So they might need environmental controls. Commercial availability is currently basically nil for rechargeable (aside from possibly Zinc8 in near future or small experimental systems).

7.6.6 Commercial Availability

At present (2025), no widely sold rechargeable metal-air systems are on the market, except perhaps some small zinc-air toying (some startups offered zinc-air “fuel cell” like

systems for off-grid, where you replace zinc cartridges periodically – not truly rechargeable in-system)^{250,264}. However, primary zinc-air button cells are widely available (for hearing aids, etc.). Form Energy's iron-air will be one of the first large systems (targeting installation mid-2020s). If these prove successful, we may see offerings for multi-hour storage in grid and renewable projects. Because these systems are heavy and not energy-dense enough for vehicles (except possibly as range extenders – e.g., aluminium-air was once considered for EV range extension by swapping aluminum plates), their likely use-case domain is stationary.

7.6.7 Summary

In summary, metal-air batteries like zinc-air and iron-air are highly promising for low-cost, long-duration energy storage, leveraging abundant materials and oxygen from air to store energy densely. They carry challenges in efficiency and cycle life that are still being solved. If those are overcome, they could fill roles that lithium-ion or flow batteries struggle with, such as multi-day grid storage or ultra-cheap backup power. They represent a different paradigm (almost more akin to fuel cells in some ways, especially if the metal has to be replaced or refueled). As technology advances, they might become key for ensuring reliability in grids dominated by renewables, providing an economical way to ride through several days of low generation.

7.7. LiFePO₄ Batteries (Lithium Iron Phosphate, LFP)

7.7.1 Overview and working principles

LiFePO₄ (LFP) is a lithium-ion cathode chemistry in which lithium ions shuttle between a graphite anode and a lithium iron phosphate cathode through a lithium-salt electrolyte. The key differentiator versus layered oxide cathodes (such as NMC/NCA) is the very stable phosphate framework (PO₄ polyanion), which binds oxygen strongly and improves thermal stability during abuse scenarios. In practical terms, LFP tends to be more tolerant to elevated temperatures and overcharge than many high-energy Li-ion chemistries, although pack safety still depends on robust BMS, mechanical design, and fire protection. The nominal cell voltage is typically ~3.2–3.3 V, slightly lower than common NMC/NCA cells. This, together with cathode material properties, results in lower gravimetric and

volumetric energy density than high-nickel chemistries. On the other hand, LFP generally delivers excellent cycle stability, which is why it is widely used for stationary storage where footprint is manageable and long lifetime is valued.

A practical feature of LFP is its relatively flat voltage plateau over a large part of the state-of-charge. This can be beneficial for stable output voltage, but it makes state-of-charge estimation more challenging; therefore, accurate BMS algorithms (coulomb counting combined with periodic recalibration) are important.

7.7.2 Current Applications

LFP has become one of the dominant chemistries for stationary battery energy storage systems (BESS). It is frequently deployed in containerised systems supporting renewable integration, peak shaving, self-consumption optimisation, and fast-response grid services (e.g., frequency regulation). Many commercial and utility-scale projects choose LFP to reduce safety risk and to maximise lifetime under daily cycling.

In transport, LFP is commonly used for electric buses, fleet vehicles, and cost-optimised passenger EVs where durability and safety take priority over maximum driving range. It is also used in industrial UPS and telecom backup solutions where predictable long-term behaviour is essential.

7.7.3 Maturity and TRL

LFP is a mature, mass-manufactured lithium-ion chemistry with extensive operational experience in both mobility and stationary applications. As a battery chemistry and as an integrated BESS technology, it can be considered TRL 9 (proven in operational environments). Continuous improvements are mainly incremental (electrode engineering, electrolyte additives, better formation protocols, and pack-level safety design), rather than fundamentally changing the chemistry.

7.7.4 Advantages

LFP's primary advantage is safety: the phosphate cathode structure is less prone to oxygen release under thermal abuse, reducing the likelihood and severity of thermal runaway compared to many layered oxide cathodes. This safety margin is especially valuable at large scale, where incident consequences can be significant.

A second key advantage is long cycle life. LFP cells commonly achieve high cycle counts under frequent cycling and high depth-of-discharge operation, making them well suited for daily-cycling stationary use. Finally, LFP avoids cobalt and typically uses no nickel in the cathode, improving supply-chain resilience and reducing exposure to critical material volatility.

7.7.5 Limitations

The main trade-off is lower energy density compared to NMC/NCA. This means larger and heavier systems for the same energy content—less of an issue for ground-mounted BESS, but relevant for space-constrained sites and for long-range EV designs.

LFP also requires careful management at low temperatures. Charging performance degrades in the cold, and charging below 0°C typically requires strict control and pre-heating to minimise lithium plating risk. At the system level, good thermal design (or operating strategy) is therefore still important.

From a circularity perspective, recycling economics can be more challenging than for cobalt/nickel-rich cells because the cathode contains fewer high-value metals. Recycling remains important for recovering lithium, copper, aluminium and for environmental protection, even if the direct material value is lower.

7.7.6 Commercial Availability

Commercial availability of LFP is extensive. Cells are produced at large volumes in cylindrical, prismatic, and pouch formats, with large-format prismatic cells particularly common in containerised stationary BESS. A wide range of vendors offer turnkey LFP-based systems from residential and C&I scales to multi-hundred-MWh utility projects, typically integrated with BMS, PCS, and thermal/fire mitigation appropriate to local codes.

7.7.8 Summary

In summary, LiFePO_4 is a proven lithium-ion chemistry that combines a strong safety profile with long lifetime and competitive cost. Its lower energy density is the primary compromise versus NMC/NCA, but for many stationary applications the benefits outweigh the footprint penalty. As a result, LFP is widely considered a reliable workhorse technology

for short- to medium-duration storage (hours), especially where frequent cycling and risk reduction are central decision factors.

BESS - Conclusion

Energy storage is a rapidly evolving field, and **no single battery technology is optimal for all purposes**. Each of the technologies discussed – lithium-ion, sodium-ion, lead-acid, nickel-metal hydride, and the emerging alternatives (flow batteries, solid-state, metal-air) – has a unique profile of strengths and weaknesses. Table below provides a high-level comparison:

7.10. Comparison of Battery Technologies (Qualitative)

Technology	Energy Density(Wh/kg)	Energy Density(Wh/m ³)	Power Capability	Cycle Life	Safety	Relative Cost	Best Applications
Lithium-Ion (NMC/LFP)	High (120–260 Wh/kg)	0.3–0.7	High (fast charge/discharge)	Moderate (500–3000 cycles)	Moderate (requires BMS; risk of fire)	Decreasing (mass production has lowered cost)	Portable electronics, EVs, general grid storage (up to 4–8h) ^{265,266}
Sodium-Ion	Moderate (75–160 Wh/kg)	~0.29	Similar to Li-ion (good power)	TBD (aiming for ~2000 cycles)	Potentially high (non-flammable)	Low (using abundant materials)	Stationary storage, low-cost EVs (short range) in future ^{177,226}
Lead-Acid	Low (30–50 Wh/kg)	0.06–0.09	Moderate (good short-term cranking power)	Low (200–1000 deep cycles)	High (very stable, but contains lead)	Very low upfront (but higher lifecycle cost)	Engine starting, backup power (float), deep-cycle in budget off-grid ^{215,216}
Sodium-Sulfur (NaS)	High (150–240)	0.25–0.4	High (sustained discharge)	High (2500–4500)	Moderate (operates at high temp, fire risk)	Moderate (utility-scale focus)	Grid-scale storage, renewable integration, load leveling ²²⁶
Solid-State Li-ion	High (potential 250–350+ Wh/kg)	0.6–1.0	High (expected similar or better than Li-ion)	High (projected longer life due to stable)	Very High (no liquid, safer thermal behavior)	Initially high (new tech, low volume)	Future EV batteries, portable electronics (once)

Technology	Energy Density(Wh/kg)	Energy Density(Wh/m ³)	Power Capability	Cycle Life	Safety	Relative Cost	Best Applications
				electrolyte)			matured) ^{251,253}
Metal-Air (Zinc/Iron)	Very High (theoretical 300+ Wh/kg)	0.3–0.4	Low (better for steady, long discharge)	Low-Moderate (limited cycles to date)	High (aqueous, but O ₂ handling needed)	Very low (material cost is low; efficiency trade-off)	Niche: multi-day grid storage, once tech is proven ^{262,264}
LiFePO ₄ (LFP)	Moderate (90–170 Wh/kg)	0.25–0.55	High (good for frequent cycling)	High (2000–8000+ cycles)	High (more stable; still requires BMS)	Low–Moderate (cobalt-free; mature supply chain)	Stationary BESS, C&I storage, buses & fleets, safety-focused high-cycle use

Qualitative comparison; actual performance can vary with specific products and conditions.

As the table suggests, **lithium-ion batteries remain the workhorse** for applications requiring a balance of high energy density, efficiency, and decent cycle life – hence their dominance in electronics and electric vehicles. However, their cost and safety considerations open space for alternatives. **Sodium-ion batteries** are emerging to address resource and cost concerns, especially for large stationary storage where slightly lower energy density is acceptable. **Lead-acid batteries**, while oldest and having low energy density, still hold niches where cost is paramount and weight is less an issue – but their short cycle life limits them in deep-cycle roles. **Nickel-metal hydride batteries** offer a safe and robust option, famously powering millions of hybrid cars reliably; yet, they too are being edged out in many sectors by lithium-ion's superior energy density and falling cost.

The **emerging technologies** provide solutions where conventional batteries fall short. **Flow batteries** shine in long-duration storage and infinite cycle life scenarios (e.g., daily shifting of solar energy), and we see them supplementing lithium-ion on the grid, not competing in mobility. **Solid-state batteries** promise to push the envelope on energy density and safety for the next generation of electric vehicles and devices – their success could mitigate EV fire concerns and extend driving range significantly, though

manufacturing challenges remain before mass deployment. **Metal-air batteries** could be transformative for ultra-low-cost energy storage if technical hurdles (especially rechargeability and efficiency) are overcome; their practically limitless energy-to-weight ratio (using air as reactant) is conceptually ideal for either very long off-grid backup or even possibly *primary* (single-use) applications like long-endurance drones, albeit at the cost of needing “refueling” rather than electrical recharging in some cases.

Looking forward, the **energy storage landscape will likely be a mix** of these technologies rather than one winner. For example, a renewable-rich future grid might use lithium-ion or sodium-ion batteries for fast response and short-term balancing, flow batteries for daily cycling over 8-12 hours, and iron-air batteries to cover multi-day lulls in wind or sun. Automobiles might predominantly use advanced lithium-based solid-state batteries for driving, while perhaps pairing with a cheap metal-air range extender or using 12V lead-acid or NiMH for auxiliary systems where appropriate. Portable devices will continue to push for maximum energy in small form – solid-state or other lithium advancements are poised to serve there, with safety improvements critical for consumer acceptance (no one wants a flaming phone or hoverboard).

In conclusion, each technology finds its niche by balancing the factors of energy density, power, lifespan, cost, and safety. The **lithium-ion family** (including future solid-state variants) is set to remain key for high-performance applications given ongoing innovations and economies of scale. But alternatives address specific pain points: sodium-ion targets material abundance and lower cost, flow and metal-air aim for scaling energy to very high capacities economically, and lead-acid continue to serve where their particular mix of attributes fit well (often where reliability or upfront cost trump size/weight considerations). The rapid pace of research means today's emerging tech could become tomorrow's mainstream – for instance, if solid-state batteries deliver on promises, we may see a shift in how we design battery packs and manage safety. Similarly, if metal-air or flow systems achieve full commercial viability, they could drastically reduce the cost of storing renewable energy for extended periods, accelerating the transition to sustainable energy systems.

What is certain is that **energy storage will remain a multi-technology ecosystem**. Just as the grid benefits from a diverse mix of energy sources, the world will benefit from a diverse toolkit of storage solutions. By leveraging the strengths of each – be it the high energy and dropping cost of lithium-ion, the sustainability and low cost of emerging chemistries, or the ultra-long life of flow systems – we can build more resilient and efficient energy systems. Continued development and investment in these technologies will ensure that the growing demands of electric transportation, renewable grid integration, and portable power are met in a safe, cost-effective, and environmentally responsible manner.

In summary, **the choice of energy storage technology will always be application-specific**: we will use lithium-ion (and its solid-state successors) where energy density and proven performance matter, sodium-ion where cost and resource considerations dominate, lead-acid and NiMH where established reliability at low cost is needed, and new players like flow and metal-air where ultra-long duration or ultra-low cost per kWh are paramount. The future of energy storage is not one technology replacing all others, but rather an optimized combination of many, working in concert to power a world increasingly reliant on clean, flexible energy.

7.8 Environmental Impact

To comprehensively evaluate the environmental impacts of Li-ion batteries, it is essential to consider the entire life cycle: raw material extraction, battery production, use phase, and end-of-life management (recycling or disposal). Below is an expanded analysis based on recent studies and technological developments.

1. Raw Material Extraction

Extraction of lithium, cobalt, nickel, and other metals is resource-intensive, leading to soil degradation, water shortages, and biodiversity loss, particularly in regions like the Democratic Republic of Congo (for cobalt) and South America (for lithium) (Domingues, De Souza, and Luiz 2024).

Mining and processing require significant water, often straining local supplies and contributing to pollution if not properly managed (Domingues, De Souza, and Luiz 2024; Vinayak et al. 2024). Mining operations can release heavy metals and toxic chemicals into the environment, affecting local communities and ecosystems (Kang, Chen, and Ogunseitan 2013; Domingues, De Souza, and Luiz 2024).

2. Battery Production

Manufacturing is energy-intensive, with electricity use accounting for about 40% of the total life cycle GHG emissions of Li-ion batteries. Emissions vary by region: for example, 124.5 kg CO₂eq/kWh in China versus 72.9 kg CO₂eq/kWh in the US, reflecting the carbon intensity of the local electricity grid (Llamas-Orozco et al. 2023).

Production processes can contaminate water supplies and release air pollutants, including soot and sulfur, especially if powered by fossil fuels (Kang, Chen, and Ogunseitan 2013).

3. Use Phase

While the use phase of Li-ion batteries in electric vehicles and stationary storage is relatively clean, the environmental benefits depend on the source of electricity used for charging. Renewable energy use maximizes benefits; fossil-fuel-based grids diminish them (Llamas-Orozco et al. 2023). Differences in GHG emissions between chemistries has to be considered. LFP (Lithium Iron Phosphate) batteries generally have lower GHG emissions than nickel-based chemistries (NMC, NCA), with LFP at 55 kg CO₂eq/kWh (Llamas-Orozco et al. 2023).

4. End-of-Life Management

A. Recycling

Recycling Li-ion batteries dramatically reduces environmental impacts compared to mining new materials (Machala et al. 2025): GHG emissions are 58% to 81% less than mining and processing virgin materials. The water use is 72% to 88% less. Energy use can be 77% to 89% less.

Recycling reduces the risk of toxic metals (cobalt, nickel, lead) entering the environment and lessens landfill fires caused by discarded batteries (Kang, Chen, and Ogunseitan

2013). New recycling methods, such as reductive calcination and electrochemical recycling, are making recycling more efficient and less polluting. Mechanical separation and closed-loop systems are also being developed to further lower impacts and recover more materials.

B. Disposal Risks

Improper disposal leads to the leaching of heavy metals and organic solvents, contaminating soil and groundwater, and increasing the risk of long-lasting landfill fires. Combustion or decomposition of batteries can release toxic gases, including lithium and cobalt oxides, affecting air quality (Xiaodong and Ishchenko 2024).

Table 2. Comparative and Chemistry-Specific Insights

Impact Category	Conventional (Mining)	Recycling (Circular)	Key Notes
GHG Emissions	High	58–81% lower	Even lower for scrap-based recycling
Water Use	High	72–88% lower	
Energy Use	High	77–89% lower	
Toxicity (Heavy Metals)	High	Significantly reduced	Recycling prevents environmental release
Landfill/Fire Risk	High	Lower	Recycling reduces landfill fires and contamination
Resource Depletion	High	Lower	Recycling recovers critical metals
Chemistry (LFP vs. NMC/NCA)	NMC/NCA: higher GHG	LFP: lower GHG	LFP best for mineral resource use

The environmental impacts of Li-ion batteries are significant across their life cycle, with the largest burdens arising from raw material extraction and battery production. However, recycling offers a clear path to dramatically reduce greenhouse gas emissions, energy and water use, and pollution. The transition to advanced recycling technologies, sustainable sourcing, and a circular economy is essential for minimizing the environmental footprint of Li-ion batteries as demand continues to grow.

7.8.1 Life Cycle Assessment of NMC-811 batteries

A comprehensive analysis and evaluation of the life cycle of lithium-ion batteries requires a detailed knowledge of the technology, with particular reference to each battery type, the type and quantity of the raw materials used, the energy requirement of the manufacturing process, and the amount of waste generated.

The purpose of this study is to prepare the life cycle analysis of a lithium-ion battery for electric vehicles in Hungary. To this end, various manufacturers documentation were found, and the analysis was used by sources of information that provided the necessary data on the technology used in the fullest way, the production processes, the raw materials used and the extent of environmental impact. As part of the dissertation, the life cycle of the test battery was analyzed from the production of raw materials to the treatment of waste from the resulting waste.

Among the lithium-ion batteries presented in the literature review, we chose the type of active material for the NMC811 for the analysis. The election was justified by the fact that, according to current industry trends, manufacturers are increasingly turning to the use of this type of cells, primarily because of their favorable energy density, lower cobalt and cost-effectiveness. Increasing the proportion of nickel allows batteries to store more energy with the same weight or size, which is key to increasing the range of electric cars. In addition, production costs and environmental loads also reduce, as it requires less cobalt, which is expensive, rare, and raises environmental and ethical problems.

7.8.1.1 Production of batteries

The analysis is based on a battery factory operating in Hungary, which is available enough to determine the entire life cycle of the battery manufactured there. Since the work of the NMC811 active material is the subject of analysis, it was obviously one of the tasks to detect such a battery manufacturing plant used in an electric car or the use of data.

There are many battery factories in Hungary, and I found satisfactory information from the SK on battery factory in Ivánca, while this plant specifically produces only NMC811 batteries, resulting in more precise results for a manufactured battery.

7.8.1.2 Description of manufacturing technology

Below the technology is a uniform environmental permit for the plant

Cells for lithium vehicle cumulators are produced at the plant, which is then made into modules according to the needs of the customers.

The manufacturing technology consists of four stairs:

- Production of electrodes,
- To assemble cells,
- Formatting,
- Module assembly.

(1) Production of electrodes

The production of electrodes begins with the preparation of suspensions. The anode is used for graphite and black coal, which is dissolved in ion-exchange water, while in the cathode, the NMC811 active substance (lithium nickel-cobalt mangan oxide) is dispersed in NMP (N-Methyl 2-pyrrolidone) solvent. The anode is added to the anode CMC (carboxymethyl cellulose) and the cathode is added to the cathode PVDF (polyvinylidene difluoride). The suspensions thus produced are then applied as a solvent mixture to the appropriate conductive metal carrier - at the anode to copper foil and aluminum foil at the cathode.

The coated foils are then dried, squeezed and then cut in the longitudinal direction as a closing step of the electrode production, forming smaller electrode coils.

(2) Cells assembly

The next technological process is the assembly, which will take place in the first step, which results in electrode sheets with a welding ear from electrode coils. After the cutting operation, the moisture and solvent content of the plates is removed. To this end, they are placed in a vacuum dryer with nitrogen gas.

The dried electrode plates are then packed with separators (stacking, stacking) together with separator plates, and then the disks tab are blended. As a closing step, the cells thus produced are filled with electrolytes, primarily LIPF₆ (lithium hexafluorophosphate).

(3) Formatting

As a first step in the formatting process, the cells are rotated to make the electrolyte evenly moisten the electrodes. This is followed by the prefilling, during which the cells are activated and then the aging, which is the procedure for stabilizing cells. At the end of the process, charging and discharge cycles are checked for cells, thus exploring defective pieces.

(4) Module assembly

The cells are placed in a modules where their clips are connected using a collection rail. The collection rail is then connected to the protective circuit unit and the module house is closed. The finished module then goes through various tests for control and quality assurance.

7.8.1.3 Material flows

There was no detailed information on material and energy currents in the process of manufacturing, so I treated the life cycle as a black box model, so I only took into account materials and energy flows that flow into and out of the manufacturing process. Table 3 illustrates the starting data for production.

Table 3: Battery Factory Material

Type	Unit	Value
Production capacity	GWh/y	30
Energy consumption	GWh/y	1 471
Water consumption	m ³ /y	1 898 000
Wastewater emissions	m ³ /y	1 262 900
NMP consumption	t/y	13 500
Non-hazardous waste	t/y	14 175
Hazardous waste	t/y	35 520

The above data were collected mainly from a uniform environmental permit for the plant, except for information on waste. These were taken from the environmental impact assessment document because it contains much more detail the types, places and quantities of waste.

The plant has an annual production capacity of 30 GWh. Manufacturing capacity shows the overall energy storage capacity of batteries produced by the plant during one year. For example, if you produce 100 kWh batteries in the plant one year, with 30 GWh/year capacity, it means that a total of 300,000 such batteries can be made a year.

The energy consumption is 1,471.3 GWh per year. The amount of water consumption is 1,898,000 cubic meters per year, of which 1,262,900 cubic meters are issued as sewage. The plant uses 13,500 tons of NMP (N-Methyl-2-Pyrrolidone) each year, which is used to relieve active material used in the cathode. The amount of waste generated during the operation is also significant: 14,175 tons of non-threats per year and 35,520 tons of hazardous waste are produced.

The energy consumption of the site is unclear, I did not find information on the network energy use of the site. The uniform environmental permit also contains only the amount of natural gas used. In this case, I appreciated the annual energy consumption. As a comparison, I took the energy use of the Samsung battery factory in Göd's uniform environmental permit. With 26 GWh/year capacity, 497 GWh/year is network energy consumption.

This only covers network consumption. However, the Ivánca plant also uses 93,590 640 m³ of natural gas annually during production. If the heating value of the gas is 34.54 MJ per cubic meter, it will be about 897.83 GWh per year. I detail the calculation below.

$$1 \text{ kWh} = 3,6 \text{ MJ}$$

$$34,54 \text{ MJ} = 9,59 \text{ kWh}$$

$$\text{Natural gas (m}^3/\text{y)} \times \text{Calorific value (Wh/m}^3\text{)} = \text{energy (Wh/y)}$$

$$93\,590\,640 \text{ m}^3/\text{y} \times 9,59 \text{ kWh/m}^3 = 897\,833\,952 \text{ kWh} = 897,83 \text{ GWh/y}$$

Subsequently, adding the value of energy (897.83 GWh/year) from the gas (897.83 GWh/year) and the value of network energy use (573.46 GWh/year) will be added to one year, which is approx. 1471.30 gwh. This value is representative and is likely to be significantly higher than the real value, since the power consumption of the site is unknown and I could only estimate it.

Based on Table 1 data, the specific values of production can be calculated. By sharing annual data, the annual manufacturing capacity is obtained how much energy, water,

solvent use the battery, water, solvent, and how much wastewater and waste. These results are shown in Table 4.

Table 4: The specific material currents of the battery manufactured

Type	Unit	Value
Energy use	kWh/kWh _{capacity}	48,57
Water use	l/kWh _{capacity}	63,27
Wastewater discharge	l/kWh _{capacity}	42,10
NMP use	kg/kWh _{capacity}	0,45
Non-hazardous waste	kg/kWh _{capacity}	0,47
Hazardous waste	kg/kWh _{capacity}	1,18

Based on the specific values, it can be determined by the amount of material and energy that is used to produce a battery with a particular energy storage capacity.

7.8.1.4 Battery composition

The batteries consist of different materials that can be used to meet the needs of different areas of use by taking advantage of its favorable properties. The quantitative and qualitative knowledge of these materials used is key to life cycle analysis.

The batteries used in electric vehicles can be divided into three main functional units: cells, modules and battery pack. Electrochemical energy conversion is done in cells, which are the smallest functional units of the battery. These cells are arranged into modules, which, thanks to their modular structure, can be easily combined to achieve the desired power and capacity. Each module is composed of the battery pack, which ensures the connection between the electric vehicle and the energy storage system, taking into account the specific energy supply and control requirements of the vehicle.

During the work, I used the Greet Model database to determine the amount of materials of the NMC811 batteries. The data used can be detailed in Table 5.

The specified source was used by masses, which were converted to bulk rates, so the list of materials became applicable to any mass battery.

Table 5 shows 71.26% of batteries weight, followed by the package, which accounts for 23.03% of the weight, while the module materials represent only 5.71%.

Looking at the cell, it is clear that a significant part of its weight comes from the materials of the cathode and anode (graphite), which together account for 31.08% and 20.60% of the weight, as shown in Figure 7. These are followed in mass of copper and aluminum by 11.19% and 5.87%. The remaining 46.11% is made up of other components of the cell.

The battery factory manufactures the batteries solely to the module, so only the masses of cells and modules in Table 5 should be taken into account. So, when it comes to a battery weighs x , 76.97% of it will be manufactured in the battery factory.

The specific energy density of lithium ion batteries used in electric cars is approx. 80 - 150 WH/kg.

If the specific energy density of the battery is 150 WH/kg at 82 kWh, the total weight of the battery is approx. 546.67 kg. For simplification, I calculated 547 kg. Cells and modules account for 76.97% of this mass, ie approx. 421 kg. By pushing the mass ratio in Table 5, we get the mass of each material on the battery of a given mass. The results are shown in Table 6.

Table 5: Material list of NMC811 battery cells, modules and packages used in electric vehicles

	NMC811	Mass ratio [kg anyag / kg battery]	Tömeg %
Cell	Active cathode mixture	0,222	22,15
	Graphite	0,147	14,68
	Carbon black	0,012	1,23
	Binder (PVDF ⁽¹⁾)	0,025	2,54
	Copper	0,112	11,19
	Aluminum	0,059	5,87
	Electrolyte: LiPF ₆	0,018	1,83
	Electrolyte: EC ⁽²⁾	0,051	5,12
	Electrolyte: DMC ⁽³⁾	0,051	5,12
	Plastic: PP ⁽⁴⁾	0,011	1,07
	Plastic: PE ⁽⁵⁾	0,002	0,25
	Plastic: PET ⁽⁶⁾	0,002	0,22
	Σ Cell	0,713	71,26
Modul	Copper	0,003	0,28
	Aluminum	0,045	4,53
	Plastic: PE	0,001	0,11
	Insulation	0,001	0,07

	Electronics	0,007	0,71
	Σ Modul	0,057	5,71
Package	Copper	0,001	0,06
	Aluminum	0,141	14,14
	Steel	0,006	0,64
	Insulation	0,004	0,44
	Coolant	0,046	4,63
	Electronics	0,031	3,13
	Σ Package	0,230	23,03

1 polyvinylidene difluoride, 2 ethylene carbonate, 3 dimethyl carbonate, 4 polypropylene, 5 polyethylene, 6 polyethylene terephthalate

Table 6: A mass of materials that make up a given mass battery

Unit	Structure	Materials	Mass [kg]	Modul m/m %
Cell	Active Cathode Mix	NMC811	121,174	28,78
	Cathode carrier layer	Aluminum	32,089	7,62
	Cathode binder	PVDF (Polyvinylidene Difluoride)	6,955	1,65
	Active anode mixture	Graphite	80,309	19,07
		Carbon Black	6,730	1,60
	Anode support layer	Copper	61,229	14,54
	Anode binder	SBR (Styrene Butadiene Rubber)	6,955	1,65
	Electrolyte	Lithium hexafluorophosphate (LiPF6)	10,026	2,38
		Ethylene carbonate (EC)	27,995	6,65
		Dimethyl carbonate (DMC)	27,995	6,65
	Separator	Plastic: PP	5,828	1,38
Plastic: PE		1,353	0,32	
Plastic: PET		1,179	0,28	
Modul		Copper	1,526	0,36
		Aluminum	24,804	5,89
		Plastic: PE	0,624	0,15
		Insulation	0,382	0,09
		Electronic components	3,885	0,92

[Materials highlighted with red were not included in the GaBi's calculation - and then write about it at databases]

Active cathode mixture is a complex material produced by the use of various compounds and through various chemical procedures. As I have been detailed in the literature review, the name NMC811 indicates the proportion of nickel, manganese and cobalt in the mixture. However, these are not in elementary form, but in the form of various compounds, transformed into the desired structure of the desired structure for several steps, which is eventually used during the production of cathode. These materials and specific amounts are shown in Table 7.

Table 7: The ingredients of the NMC811 active material

NMC811	kg/kg NMC811
Precursor	0,949
LiOH	0,246

In the table, the precursor is the result of a precipitation procedure, the flow of material below is shown in Table 8.

Table 8: Material flow of the NMC811 precursor production.

Reagent	kg/kg Precursor
NiSO ₄	1,340
MnSO ₄	0,168
CoSO ₄	0,163
NaOH (100%)	0,890
NH ₄ OH (100%)	0,124

In order for these values to be used to calculate the battery input material, it must first be determined the proportion of each material to be used in relation to the entire weight of the battery.

According to Table 5, 0.222 kg NMC811 is present in 1 kg battery. Thus, knowing the compounds needed to produce active material (Table 7), they can be calculated to produce 1 kg of battery. An example of counting is shown below:

$$0,222 \text{ kg} \times 0,949 \text{ kg} = 0,210 \frac{\text{kg precursor}}{\text{kg battery}}$$

The results based on these calculations are shown in Table 9.

9. Table NMC811 Active Material Components and Weight M/M-A

NMC811	kg / kg NMC811	kg / kg battery
Prekurzor	0,949	0,210
LiOH	0,246	0,055

This calculation can be used similarly to the materials needed to produce a precursor, as it is known how many kg of precursor per kg battery is required for production. An example of this is calculated below:

$$\frac{\text{kg precursor}}{\text{kg akumulátor}} \times \text{NiSO}_4 \text{ (m/m)} = \frac{\text{kg NiSO}_4}{\text{kg battery}}$$

$$0,210 \frac{\text{kg precursor}}{\text{kg battery}} \times 1,340 \text{ kg} = 0,28 \frac{\text{kg NiSO}_4}{\text{kg battery pack}}$$

The results based on these calculations are shown in Table 10. Here, the precursor was replaced by the materials to see more visible what materials and the amount needed to produce NMC811 cathode for 1 kg of battery.

Table 10: NMC811 active ingredients and weight per kg battery

NMC811	kg/kg battery
NiSO ₄	0,282
MnSO ₄	0,035
CoSO ₄	0,034
NaOH (100%)	0,187
NH ₄ OH (100%)	0,026
LiOH	0,055

Knowing the specific mass of the ingredients of the active substance, they will receive the weight needed to produce a 547 kg battery by weight of the battery. Complemented with these masses, Table 10 is obtained, the starting mass currents shown in Table 11 below are obtained.

Table 11: A mass of materials required to produce a given mass battery

Unit	Structure	Materials	Input mixture [kg]	Mass [kg]
Cella	Active cathode mix [NMC811]	NiSO ₄	84,511	66,457
		MnSO ₄	10,595	
		CoSO ₄	10,280	
		NaOH (100%)	56,131	
		NH ₄ OH (100%)	7,820	
		LiOH	16,349	
	Cathode support layer	Aluminum		17,599
	Cathode binder	PVDF (Polyvinylidene Difluoride)		3,815
	Active anode mixture	Graphite		44,045
		Carbon Black		3,691
	Anode support layer	Copper		33,581
	Anode binder	SBR (Styrene Butadiene Rubber)		3,815
	Electrolyte	Lithium Hexafluorophosphate (LiPF6)		5,498
		Ethylene Carbonate (EC)		15,354
		Dimethyl Carbonate (DMC)		15,354
Separator	Plastic: PP		3,196	
	Plastic: PE		0,742	
	Plastic: PET		0,647	
Modul	Copper		0,837	
	Aluminum		13,604	
	Plastic: PE		0,342	
	Insulation		0,209	
	Electronics		2,131	

7.9 Practical Case Studies

7.9.1 Large-Scale Grid Deployments

Hornsedale Power Reserve, South Australia This 150 MW / 194 MWh lithium-ion battery (NMC) installation is operated by Neoen and Tesla. Since commissioning in 2017, it has delivered frequency control, grid balancing, and backup power services, reducing reliance on gas peaker plants. The system helped avoid blackouts during extreme weather and

demonstrated significant emission reductions, with an estimated 50,000 tonnes of CO₂ saved annually by displacing fossil generation.

Dalian VRFB and Li-ion Hybrid – China This pioneering hybrid battery project combines 100 MW / 400 MWh of VRFB and 100 MW / 100 MWh of lithium-ion in a grid-connected configuration. The lithium system offers fast response, while VRFBs provide deep-discharge load balancing. The combination improves lifetime environmental efficiency by distributing duty cycles according to chemistry-specific strengths. It represents a model for future hybrid architectures.

7.8.2 Second-Life Battery Projects

Nissan LEAF 4R Energy Project – Japan Used Nissan LEAF EV batteries are repurposed into stationary storage for schools, municipal buildings, and sports arenas. These second-life packs are typically 20–30 kWh each and extend usable life by 5–10 years. LCA analysis shows a reduction in material-related emissions of up to 35% compared to new batteries.

BOS AG Microgrid Projects – Sub-Saharan Africa German company BOS AG deploys second-life Li-ion battery modules into solar microgrids across remote communities. These systems reduce diesel consumption by over 90%, support cold-chain logistics for vaccines, and enable stable lighting and communication. Environmental performance is improved by extending battery utility and reducing electronic waste exports.

7.9.2 Lessons Learned

- Second-life applications significantly reduce embodied carbon
- Hybrid energy storage configurations improve environmental efficiency
- Geographic proximity of recycling and manufacturing infrastructure matters for net lifecycle impacts

These real-world cases show that battery systems, particularly lithium-ion, are environmentally competitive when coupled with renewables and circular design strategies. Future expansion must prioritize sustainable sourcing, localized recycling, and long-term ecosystem planning.

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8 Conclusions and Economic Analysis

8.8 Cross-Comparative Qualitative Analysis of Selected Technologies

Technical Performance

- **Response time & power quality.** *Flywheels* and *ultracapacitors* deliver sub-second response, making them ideal for frequency regulation and power quality services. *Gravity* and *VRFB* systems respond in seconds, while *hydrogen* systems, limited by electro-chemical conversion, require minutes.
- **Round-trip efficiency & cycle life.** Ultracapacitors ($\approx 95\%$) and flywheels (85–95 %) provide the highest efficiencies and virtually unlimited cycles ($>10^6$). Gravity storage achieves 80–90 % with $>50\,000$ cycles. VRFBs operate at 70–80 % with 15 000–20 000 cycles. Hydrogen lags at 20–30 % efficiency but offers effectively unlimited seasonal duration.

Costs

- **Up-front CAPEX.** Gravity systems currently lead long-duration cost metrics at 130–220 USD kWh⁻¹ of storage capacity. VRFBs follow at 400–600 USD kWh⁻¹. Electrolyser-based hydrogen systems exceed 1 000 USD kWh⁻¹ when reconversion is included, while flywheels and ultracapacitors show the highest per-kWh figures (1 000–3 000 USD kWh⁻¹) but low cost per kW.
- **Levelised Cost of Storage (LCOS).** High utilisation and long lifetimes drive LCOS for gravity (≈ 50 –100 USD MWh⁻¹) and VRFBs (≈ 100 –150 USD MWh⁻¹). Flywheels can reach 40–60 USD MWh⁻¹ in high-cycle ancillary markets. Hydrogen LCOS remains >150 USD MWh⁻¹ today but is projected to fall below 80 USD MWh⁻¹ by 2035 with falling electrolyser and renewable electricity costs, there is however a high risk in this prediction.
- **Investment cost scaling** is evident across storage technologies. Small-scale lithium-ion installations face up to 20% higher costs compared to utility-scale systems with equivalent duration. This principle extends to other technologies, emphasizing the role of economies of scale in storage deployment.

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Scalability & Siting

- *Gravity* and *hydrogen* offer multi-GWh potential but are site-dependent (topography, geological formations, large balance-of-plant). *VRFB* stacks are modular and can be sized independently in power and energy, beneficial for commercial & industrial (C&I) sites up to hundreds of MWh. *Flywheels* and *ultracapacitors* scale in power rather than energy, and are most competitive below 30 minutes of discharge.

A **hybrid portfolio** unlocks the highest system value: ultracapacitors/flywheels for milliseconds-to-minutes grid support, VRFBs for daily shifting, and gravity or hydrogen for multi-hour to seasonal balancing. Integrating complementary technologies smooths renewable variability while optimising overall LCOS and environmental impact.

Overall, the comparative matrix confirms that technology choice should be driven by application-specific duty cycles, site constraints, and policy incentives rather than a single “best” option.

Lithium-ion batteries dominate current and near-future stationary storage markets, particularly for applications requiring under 8 hours of discharge and fewer than 500 cycles per year. Their high round-trip efficiency and falling costs reinforce their competitiveness, mirroring trends seen in crystalline silicon solar cells. However, specialized needs—long-duration discharge, high cycle frequency, or continuous cycling—may require alternative technologies with superior cycle life or lower energy-specific costs.

Speaking of long duration discharge, **discharge duration** is not a fixed attribute but rather a design-dependent parameter. Technologies such as flywheels demonstrate this flexibility: design trade-offs between turbine sizing and reservoir capacity allow for tuning

discharge durations. Similarly, flywheel systems can be engineered for short or long durations based on materials and structure.

Developers optimize systems by balancing energy-specific and power-specific costs. When turbine costs are high but reservoir costs are low, longer durations become economically preferable. For lithium-ion projects, real-world data illustrates that median discharge duration is around 1.3 hours, with most applications ranging from 40 minutes to 4 hours. Some projects exceed 8 hours, reflecting shifting trends based on evolving market and technological conditions.

This adaptability underscores the importance of contextual system design and highlights the financial and operational trade-offs in aligning technology selection with discharge requirements.

Table 8.1: Cross comparative analysis of selected technologies

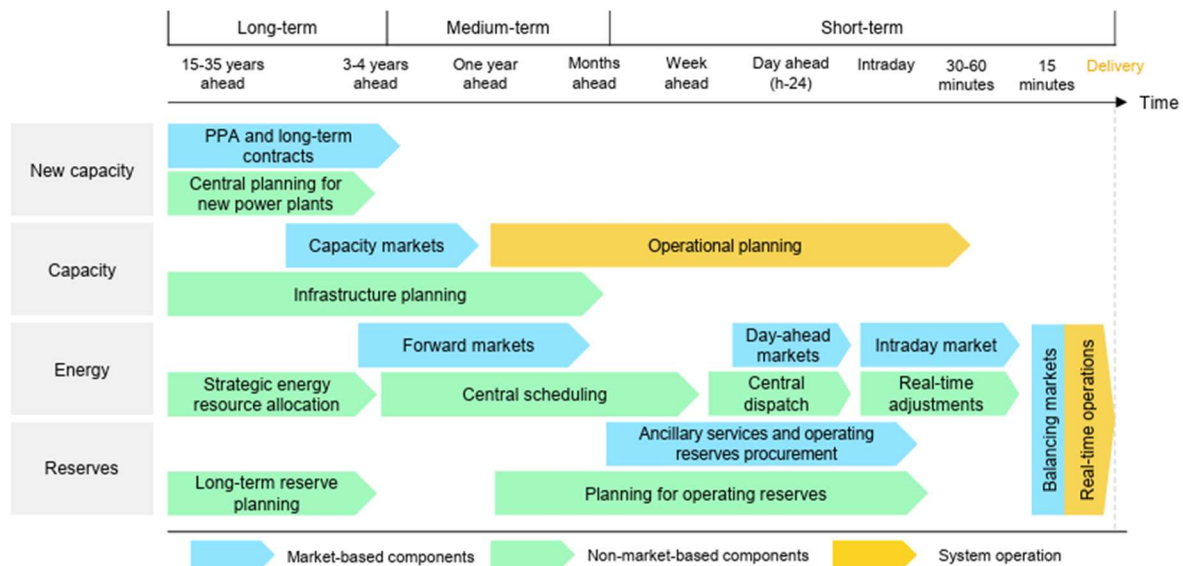
			Fly wheel	Lithium ion	Sodium sulphur	Lead acid	Vanadium redox flow	Hydrogen	Super capacitor	Gravitational storage
Round-trip efficiency	%	η_{RT}	86%	86%	75%	72%	68%	35%	92%	85%
Depth-of-discharge	% cap	DoD	100%	80%	80%	80%	100%	100%	100%	100%
Cycle lifetime	cycles	Lifetime cyc	200,000	3,500	4,000	900	20,000	10,000	300,000	50,000
Temporal degradation	%/year	Deg _t	0%	1%	1%	1%	0,1%	0%	0%	1%
Self-discharge	% cap	η_{self}	10%	1%	5%	1%	0%	5%	15%	0%
Response time	seconds	T_{res}	<10	< 10	< 10	< 10	< 10	< 10	< 10	<30
Construction time	years	T_{con}	1	1	1	1	1	1	1	2
Power density	kW/m ³	-	3,000	6,000	160	200	5	5	100,000	<10
Energy density	kWh/m ³	-	50	450	200	70	30	600 (at 200)	20	<1

								bar)		

8.9 Market potential

In this section, the market potential of storage technologies is evaluated in the context of current electricity market conditions. Specifically, the analysis focuses on opportunities in day-ahead markets, ancillary services, and capacity mechanisms (future-oriented markets) across EU countries, serving as a benchmark to assess the applicability of various storage technologies.

The figure illustrates the timeline and interaction of the different mechanisms involved in electricity delivery, highlighting business opportunities for storage technologies throughout the electricity value chain. Storage systems can participate across multiple time horizons—from long-term capacity planning and short-term market trading to balancing and ancillary service markets that support real-time system operations



IEA. CC BY 4.0.

Figure 8.2 Market potential of energy storage technologies

The blue segments represent market-based components, which offer direct revenue opportunities for storage operators. These include participation in day-ahead and intraday energy markets, capacity auctions, and ancillary services procurement—all of which are analysed in more detail in this chapter. In contrast, the green segments denote

non-market-based mechanisms, such as infrastructure planning and central scheduling, while the yellow bars correspond to system operation activities.

Although non-market mechanisms do not offer direct market access, they can still present business opportunities for storage technology providers, particularly through government or utility-led procurement tenders. However, such bilateral contracts are often confidential and case-specific, making systematic assessment more difficult. Consequently, this chapter concentrates on the market-based potential only of storage technologies, evaluating their economic viability within current and emerging electricity markets.

8.9.1 Day-ahead market potential

The day-ahead market is the primary platform where the majority of electricity is traded across the EU. In this market, balancing responsible parties—such as producers, traders, and retailers—submit their sell and buy bids, which are then matched by designated market operators.

To assess the market potential of storage technologies in this segment, historical pricing data from the ENTSO-E Transparency Platform [ref] was analysed. The focus was on daily

and seasonal price variations, which provide insight into opportunities for energy shifting and arbitrage.

Figure 8.3 illustrates price fluctuations over a typical winter and summer week in 2024, shown at 15-minute resolution. The data highlights pronounced intra-day variability across EU bidding zones, pointing to short-term storage potential.

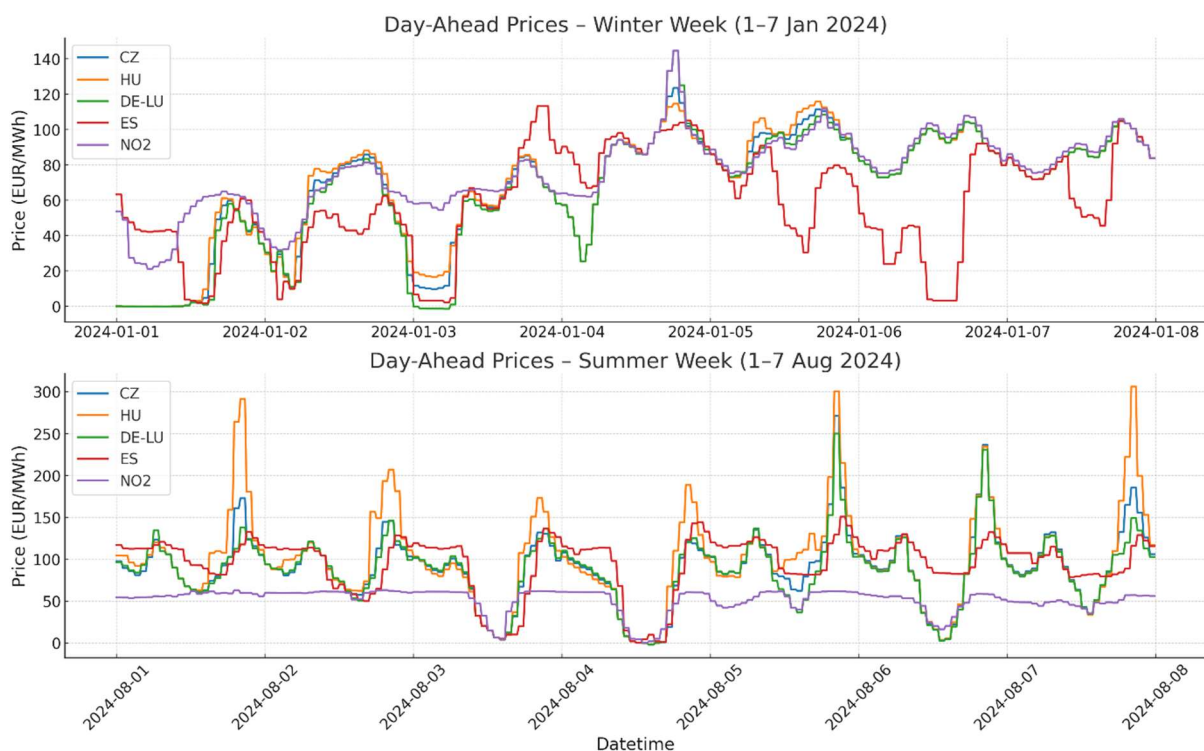


Figure 8.3 Day-ahead prices winter and summer week in 2024 - 15 minute resolution

In winter, prices tend to be lower at night and peak during high-demand hours, creating clear windows for storage-based arbitrage. In contrast, the summer price pattern often reflects a “duck curve” effect: midday solar generation causes price dips, followed by sharp increases during evening demand peaks. These dynamics reinforce the value of storage

technologies that can absorb surplus energy during low-price periods and discharge when prices spike.

Figure 8.4 presents the weekly median day-ahead electricity prices for selected EU bidding zones in 2024, highlighting seasonal price trends relevant to long-duration energy storage. In theory, pronounced seasonal price differences—typically with lower prices in summer (due to abundant solar generation) and higher prices in winter (due to heating demand)—could signal opportunities for seasonal storage.

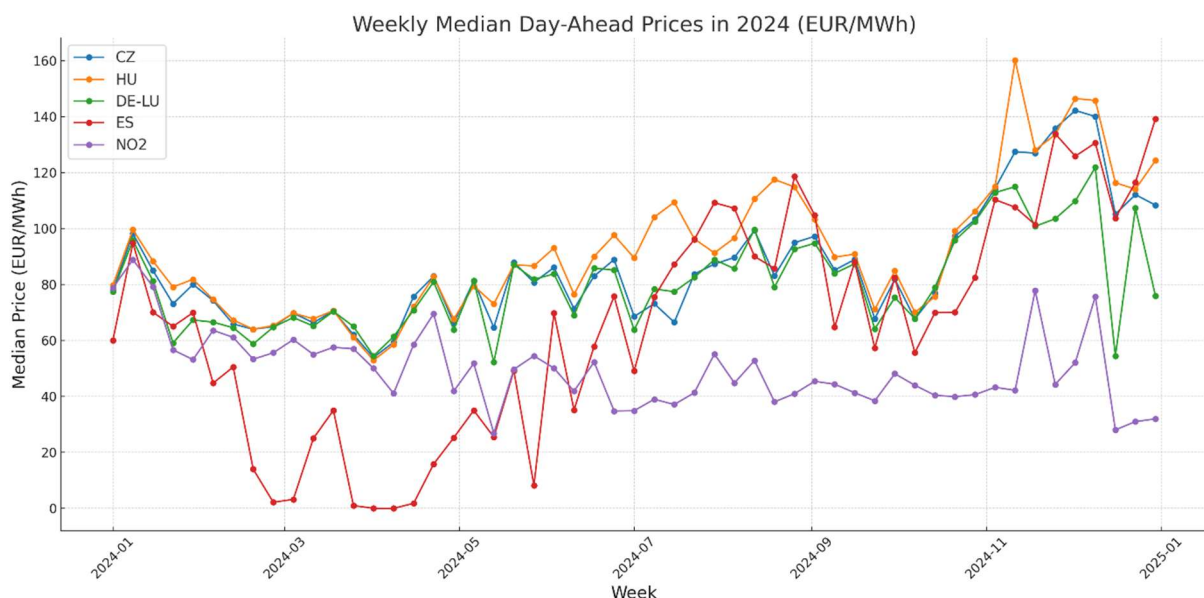


Figure 8.2 Day-ahead prices in year 2024 – weekly median

However, the data suggests that such patterns are not consistently observed across most regions. A notable exception is Spain (ES), where a clear summer price depression reflects high photovoltaic (PV) penetration and midday oversupply. This condition points to some theoretical potential for seasonal energy shifting in high-solar regions.

In contrast, other countries such as Germany, Czechia, and Hungary exhibit more muted or irregular seasonal variation, influenced by a diverse generation mix and, in the case of Hungary, a strong linkage to gas market prices. These dynamics limit the profitability of storing energy over long durations purely for arbitrage.

As a result, while the day-ahead market supports short-term storage applications, it does not offer a robust market signal for seasonal storage, except in regions with very high solar penetration and sustained summer price suppression.

Figure 8.5 presents the monthly distribution of daily price spreads—calculated as the difference between the daily maximum and minimum prices—for selected EU bidding zones in 2024. This analysis provides a direct indicator of price volatility and, by extension, the short-term market potential for energy storage systems.

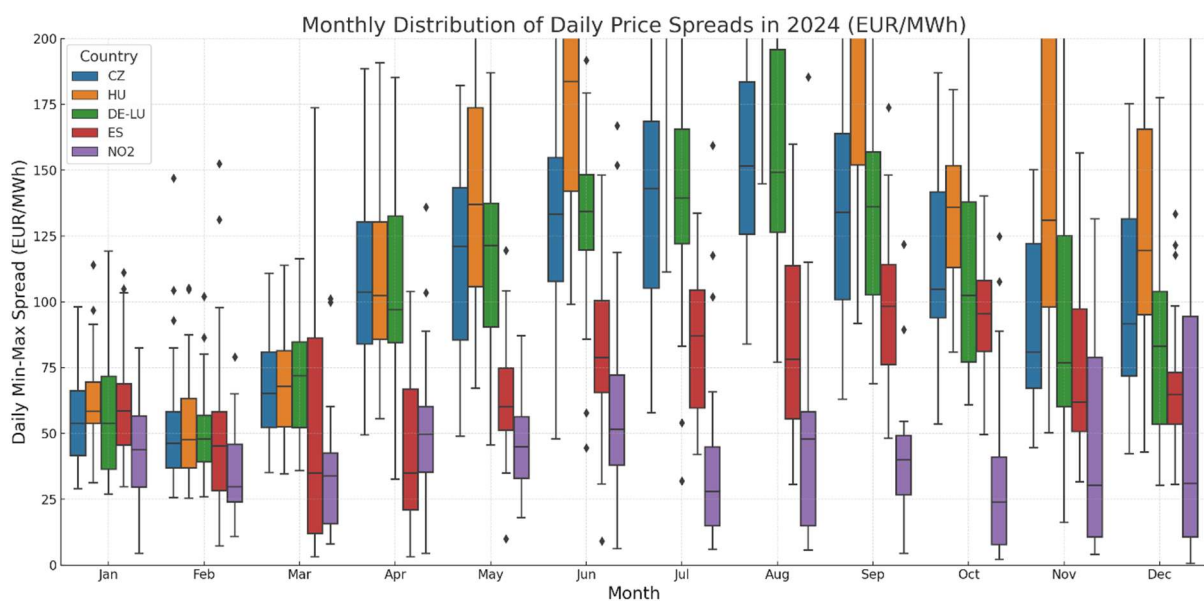


Figure 8.3 Daily price spreads (volatility) - monthly distribution

The boxplot visualization reveals that the median daily spread typically ranged between €50–150/MWh, with extreme values reaching up to €800/MWh during periods of significant market stress. Such price spreads define the upper boundary of achievable revenue for storage operators using day-ahead arbitrage strategies. For these strategies to be economically viable, the total cost of supplying electricity from storage—including round-trip efficiency losses, grid fees, taxes, and margins—must be well below the average spread.

While short-term volatility presents a clear opportunity for intraday and daily storage technologies, the day-ahead market does not support seasonal storage business models. Except for Spain, where high PV penetration leads to consistent summer price depressions, seasonal patterns are weak or absent. Broader price dynamics are often influenced by external factors such as gas prices, geopolitical conditions, and national policy shifts, which obscure any pure supply-demand seasonality.

Moreover, the interconnected nature of EU bidding zones—enabled by cross-border trade and a shared marketplace—introduces additional complexity. Local volatility may be dampened or amplified depending on regional flows, further underscoring the need to evaluate storage potential in a cross-zonal context.

The tabular overview of the daily-price spread for each bidding zone is shown here under:

Table 8.2 Monthly Distribution of Daily Price spreads 2024 - Czech Republic bidding

Month_Name	Country	median	mean	min	max
Jan	CZ	53.7	55.1	29.0	98.1
Feb	CZ	46.2	53.4	25.6	146.9
Mar	CZ	65.1	67.4	35.1	110.9
Apr	CZ	103.6	107.8	49.4	188.6
May	CZ	121.1	117.5	49.0	251.7
Jun	CZ	133.2	136.9	48.0	224.5
Jul	CZ	143.1	138.2	57.8	209.7
Aug	CZ	151.5	157.8	83.9	287.9
Sep	CZ	134.0	144.2	63.0	498.0
Oct	CZ	104.8	123.4	53.6	237.4
Nov	CZ	80.9	125.5	44.6	684.9
Dec	CZ	91.6	126.1	42.3	737.3

Table 8.3 Monthly Distribution of Daily Price spreads 2024 – German bidding zone

Month_Name	Country	median	mean	min	max
Jan	DE-LU	53.7	55.8	26.8	119.2
Feb	DE-LU	47.8	50.9	25.9	102.1
Mar	DE-LU	71.9	70.8	35.9	116.3
Apr	DE-LU	96.9	107.1	32.7	185.2
May	DE-LU	121.4	116.3	45.7	211.2
Jun	DE-LU	134.2	131.7	44.6	191.7

Jul	DE-LU	139.4	139.3	31.9	227.9
Aug	DE-LU	149.1	156.4	77.0	244.0
Sep	DE-LU	136.1	149.4	68.9	573.7
Oct	DE-LU	102.4	114.4	60.8	235.4
Nov	DE-LU	76.9	126.2	16.2	724.6
Dec	DE-LU	83.2	114.5	30.4	828.9

Table 8.4 Monthly Distribution of Daily Price spreads 2024 – Spain bidding zone

Month_Name	Country	median	mean	min	max
Jan	ES	58.5	60.9	29.7	111.1
Feb	ES	45.3	49.5	7.2	152.4
Mar	ES	35.0	55.0	3.2	173.7
Apr	ES	35.0	40.8	3.3	103.9
May	ES	60.1	64.8	10.0	119.5
Jun	ES	78.8	83.0	9.1	148.1
Jul	ES	86.9	83.9	42.0	133.6
Aug	ES	78.2	83.4	30.6	159.8
Sep	ES	98.3	98.5	48.1	173.8
Oct	ES	95.5	93.5	49.6	140.2
Nov	ES	61.8	72.9	31.7	156.5
Dec	ES	64.8	68.0	30.6	133.4

Table 8.5 Monthly Distribution of Daily Price spreads 2024 - Hungary bidding zone

Month_Name	Country	median	mean	min	max
Jan	HU	58.4	62.1	31.3	114.0
Feb	HU	47.6	53.6	25.4	105.2
Mar	HU	67.9	68.0	34.7	113.8
Apr	HU	102.2	108.9	55.7	190.7
May	HU	137.0	143.0	67.3	304.6
Jun	HU	183.6	187.4	99.0	423.5
Jul	HU	317.0	415.1	111.3	920.2
Aug	HU	228.5	279.2	144.7	649.9
Sep	HU	201.4	303.7	91.7	911.9
Oct	HU	135.8	140.6	81.0	243.8
Nov	HU	131.0	262.9	50.3	792.0
Dec	HU	119.5	163.5	43.0	742.7

Table 8.6 Monthly Distribution of Daily Price spreads 2024 - Norway bidding zone

Month_Name	Country	median	mean	min	max
Jan	NO2	43.8	42.6	4.5	82.6
Feb	NO2	29.8	34.5	10.9	79.0

Mar	NO2	33.8	34.5	8.0	101.2
Apr	NO2	49.7	50.7	4.5	136.0
May	NO2	44.9	45.2	18.1	87.1
Jun	NO2	51.5	58.3	6.2	166.9
Jul	NO2	27.9	38.7	5.9	159.4
Aug	NO2	47.9	46.1	5.7	185.4
Sep	NO2	40.1	39.7	4.6	121.8
Oct	NO2	23.8	32.3	2.3	124.9
Nov	NO2	30.3	46.0	4.0	131.5
Dec	NO2	31.1	86.2	0.6	794.8

8.9.2 Balancing and ancillary market potential

The balancing and ancillary service markets operate in parallel to energy markets and are typically managed by transmission system operators (TSOs). These markets are designed to procure balancing capacity that can be activated on command to ensure real-time

stability of the transmission and distribution systems. Their role is crucial for maintaining frequency, voltage, and system integrity across interconnected grids.

As part of the EU's internal market harmonization, these services are increasingly standardized and liberalized, allowing the participation of independent aggregators and third-party flexibility providers. The main standardized balancing products include:

- Frequency Containment Reserve (FCR): Provides fast, automatic correction of frequency deviations within seconds; helps maintain synchronisation across the grid.
- Automatic Frequency Restoration Reserve (aFRR): Activated automatically via dispatch systems with a maximum ramp time of 7.5 minutes; enables continuous rebalancing of the system.
- Manual Frequency Restoration Reserve (mFRR): Activated manually by TSOs with a maximum ramp time of 12.5 minutes; used for system adjustments beyond aFRR scope.

Balancing services are typically procured through two stages:

- Capacity reservation: Bidders offer reserve capacity that can be activated if needed. TSOs must always maintain backup capacity (N+1 criterion), ensuring they can withstand the loss of the largest generation unit in their control area.
- Energy activation: Reserved capacities are called upon based on real-time system needs, and are activated in merit order, from the lowest to highest price offers.

Market procurement can be long-term (often filled by dispatchable fossil or hydro assets) or day-ahead, where flexible and fast-response technologies such as batteries, pumped hydro, cogeneration units, and demand-side response are especially competitive.

The balancing and ancillary markets offer strong revenue potential for a wide range of storage technologies—including batteries, pumped hydro, flywheels, and even flexible industrial loads—thanks to their fast response and short cycle durations.

Figure 8.6 presents an overview of aFRR and mFRR capacity reservation prices in 2024 for selected EU countries. As illustrated, day-ahead procured aFRR capacity prices typically ranged from €5 to €60/MW/day, while mFRR prices ranged from €0 to €42/MW/day. These prices are subject to significant variation across countries and over time, influenced by system demand, capacity scarcity, and technology mix.

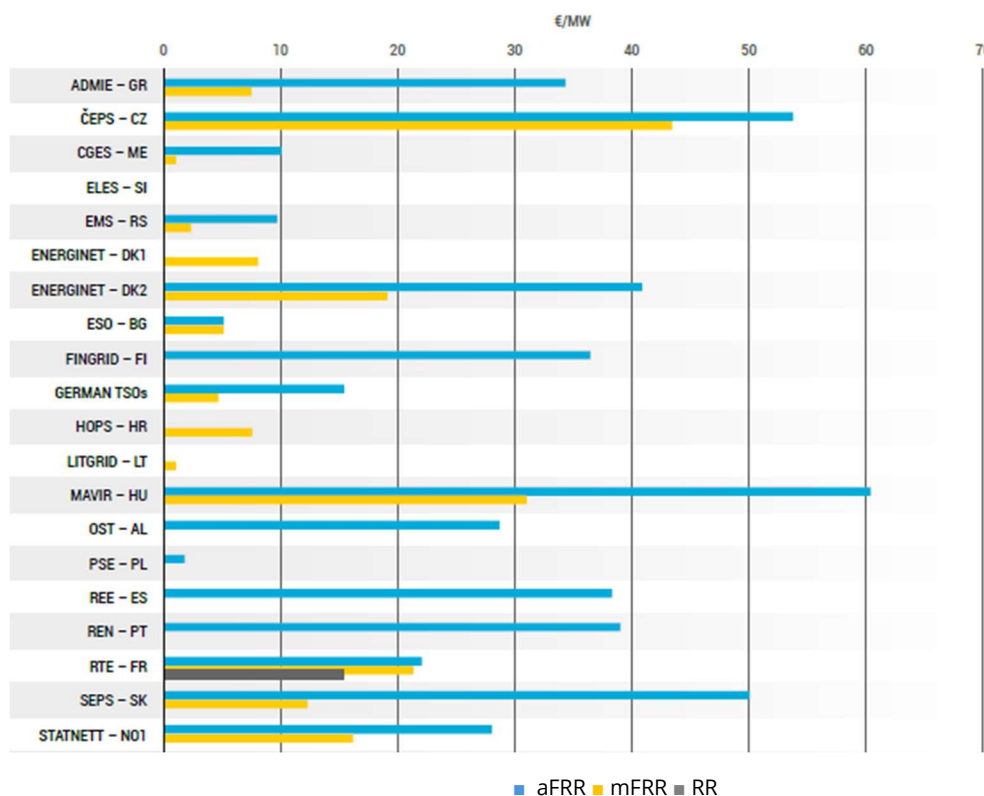


Figure 8.6 Volume-weighted average price for the procured capacities per product type

Figure 8.6 presents the average activation prices for aFRR balancing energy in 2024, distinguishing between upward services (activated in response to supply deficits) and downward services (activated to absorb surplus generation) across selected EU countries.

The average price for upward flexibility generally ranges between €90–300/MWh, reflecting the cost of dispatching additional generation or reducing consumption during imbalances. A notable outlier is Hungary (MAVIR), where the average price exceeds €600/MWh, indicating extreme stress or limited competitive supply in specific periods.

For downward flexibility, prices range from €0 to €120/MWh in most regions, with Hungary again standing out for recording negative average prices, suggesting situations where participants paid to reduce generation or increase demand.

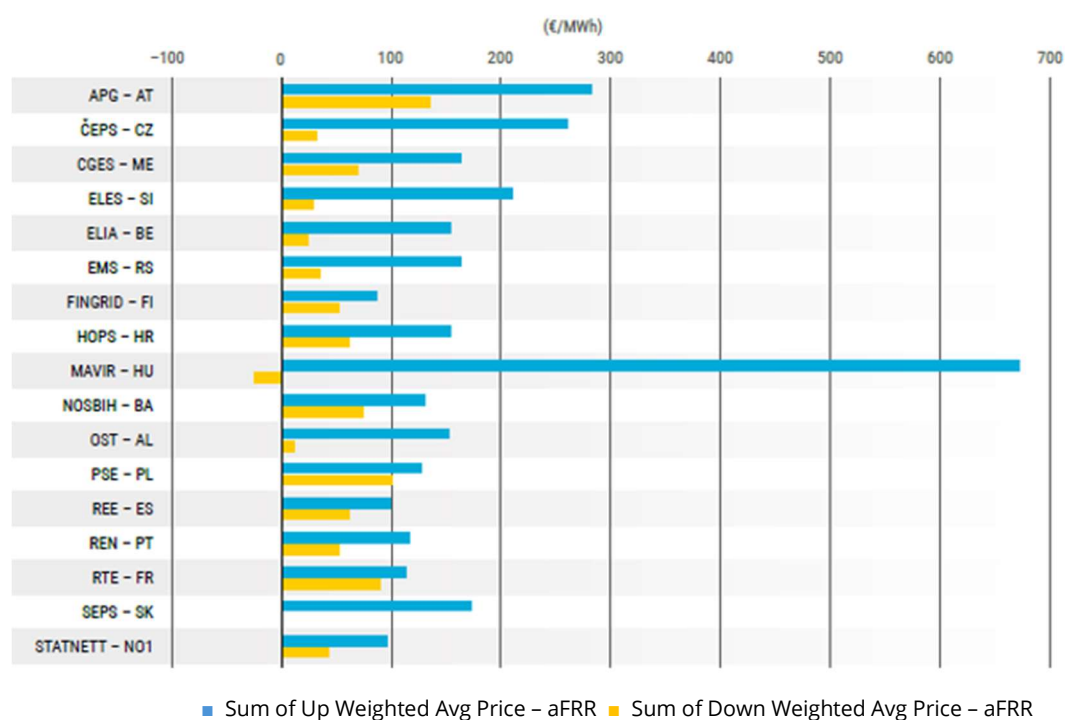


Figure 8.7 Volume-weighted average price of balancing energy activation (upward/downward) for aFRR

Figure 8.7 illustrates the average activation prices for mFRR (manual Frequency Restoration Reserve) services in 2024, broken down into upward and downward categories across selected European countries.

The average price for upward mFRR activation spans a wide range—from approximately €50/MWh up to €1,200/MWh—highlighting substantial variation in flexibility needs, system conditions, and market needs across regions. The downward activation prices are generally lower, falling between €0 and €250/MWh.

This broad spread reflects both market volatility and scarcity pricing in certain contexts, particularly where balancing resources are limited or bidding competition is low. For storage operators and aggregators, such high and dynamic price signals represent significant opportunities to generate revenue through fast-response services—especially when deploying assets capable to satisfy the obligatory and relatively strict requirements of both upward and downward flexibility services.

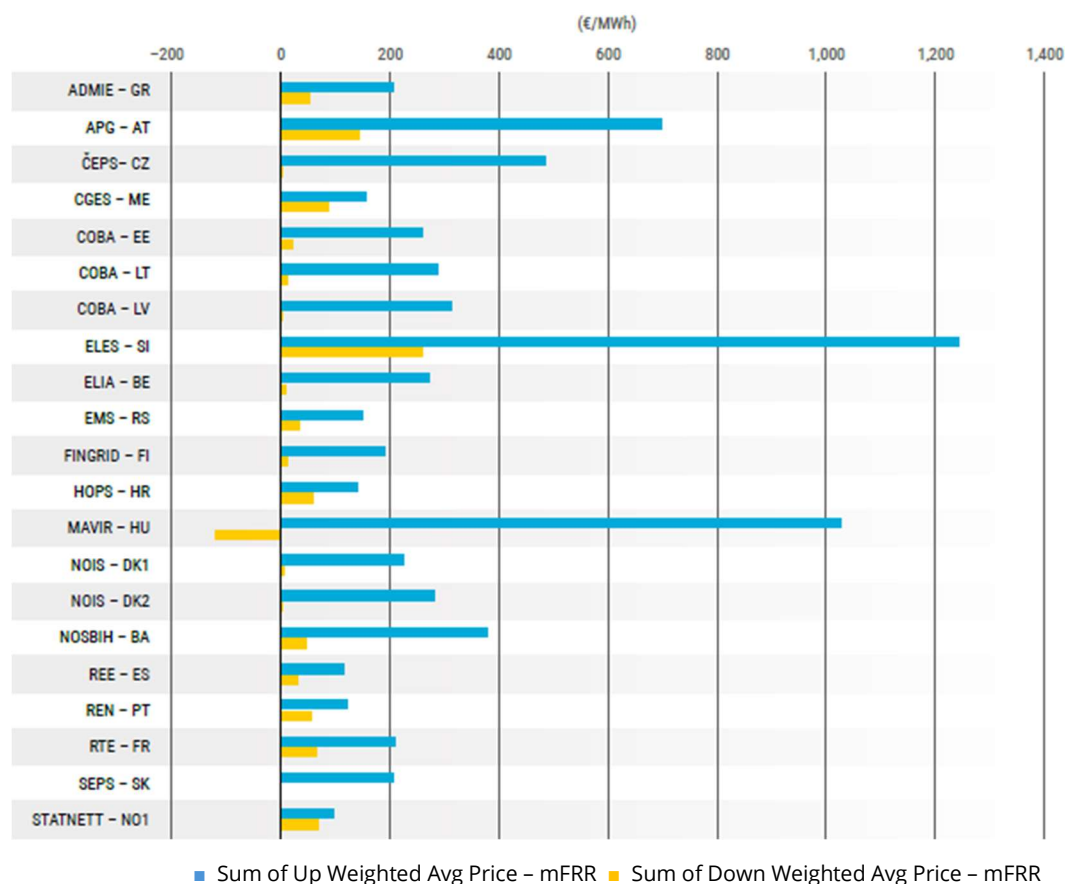


Figure 4.8 Volume-weighted average price of balancing energy activation (upward/downward) for mFRR

The balancing and ancillary service markets are characterised by high price volatility and unpredictable activation patterns, making it challenging to establish long-term, stable business models. Successful participation in these markets demands technical excellence, operational agility, and deep market expertise, particularly regarding asset responsiveness and aggregation strategies.

Although the total traded volumes in balancing markets are relatively small compared to the wholesale day-ahead market, they remain highly significant from a revenue perspective. This is especially true today, as the traditional providers of flexibility—such as fossil-fuel power plants—are being phased out, while the need for fast, flexible balancing capacity grows alongside the increasing share of variable renewable energy.

Given this backdrop, ancillary services present a highly attractive opportunity for storage technologies. Revenues are typically earned through a combination of capacity reservation payments and activation-based compensation, allowing well-positioned storage assets to capitalise on both availability and responsiveness.

8.9.3 Capacity (Futures) market potential

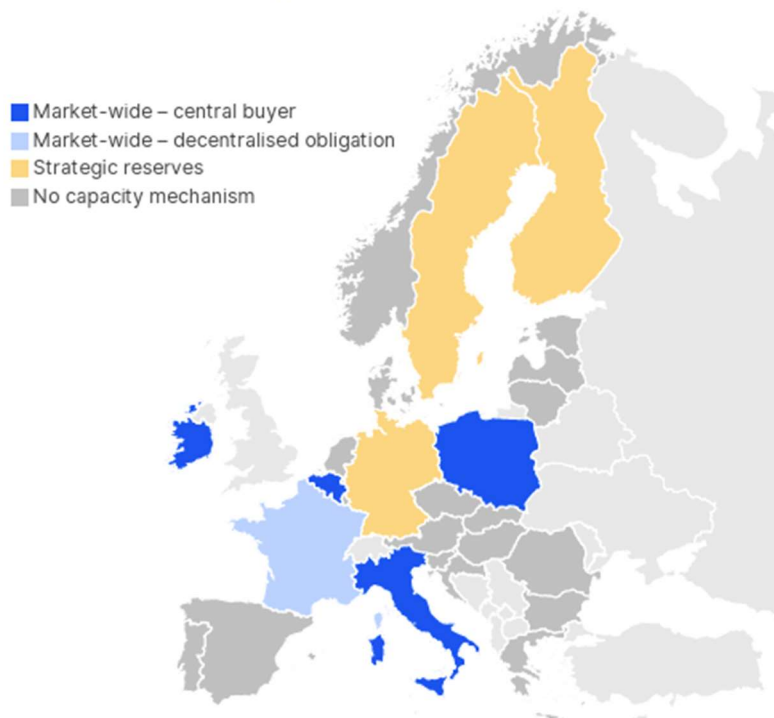
Capacity market mechanisms are designed to provide long-term hedge fund for power plants or other devices securing the peak events or left standby for emergency situations. In exchange, TSO or government implementing these mechanisms provide payments to these power plants serving strategic reserves. These capacity payments are in addition to the earnings power plants gain by selling electricity on the energy market. The support measures, in form of capacity payments, are designed to minimise the impact on existing energy market functioning and are added to the earnings power plants gain by selling electricity. This capacity market is meant especially for those critical plants or devices, where the financial viability is problematic due to specific irregular operation regime. This may also apply to several new storage technologies, especially seasonal one, where the established energy markets does not offer sufficient business opportunities.

To note, the capacity trading mechanisms emerging and this type of auctions is not available across the whole EU. Some countries secure the critical capacity in the form of strategic reserves on a bilateral basis and there are still many countries, they do not have established any capacity mechanisms, securing the capacity e.g. by the governmental share of in the ownerships of the critical power plants (often fossil-based) as seen in the

Figure 8.9 adopted from Acer report
(https://acer.europa.eu/sites/default/files/documents/Publications/Security_of_EU_electricity_supply_2024.pdf)

Source adequacy is ensured via traded capacity mechanisms across Europe with marked differences, such as decentralised capacity markets (France), centralised capacity markets (Belgium or Poland, with a zonal design in Italy, or accounting for local congestions in Ireland) and strategic reserves (Germany, Scandinavia), etc.

Figure 7: Status of capacity mechanisms in the EU – 2023



Source: Created by ACER based on NRA data.

Figure 8.9 Acer report figure

While capacity mechanisms open to all new and existing capable technologies are now an integral part of the European electricity market, as confirmed by the Commission in the last market design revision, there is not yet a common vision at the EU level on their design. Several design shortcomings remain in the capacity mechanisms implemented so far in Europe. Especially an uneven trading field for the full participation of all types of capacities, not clear rules for cross-border participation and it may send the undesired signal as payment are generally fixed and do not reflect periods of peak demand/scarcity

(which correspond to the periods for which assets have been contracted as part of the capacity mechanism).

Nevertheless, yet the capacity market can support specific storage systems and demand side response ensuring the critical adequacy of supply. It can be demonstrated by the latest action break down from UK, where approximately 25% of the awarded capacities for following are represented by batteries and demand side response.

The current market-based capacity mechanism runs two auctions to procure capacity for each "Delivery Year". The first auction is held four years ahead of the delivery year (T-4 auction), to allow enough time to build any new capacity needed. As much as 95% of the expected capacity is procured at this stage. To make sure the auction doesn't procure too much, the Electricity System Operator provides estimates of peak demand, and the amount of extra capacity needed.

The second auction is run (T-1 auction). This allows any last-minute adjustments to be made, as it is impossible to accurately predict peak demand four years in advance. It also recognises that some of the new Capacity Providers which signed up in the first auction might be unable to deliver and need to be replaced at this stage.

Staging the auction in two phases helps to ensure the Capacity Market doesn't build more new capacity than needed. Allowing existing and new power stations to bid also makes it clear how much existing capacity is available. (ref <https://www.lowcarboncontracts.uk/our-schemes/capacity-market/>)

The clearing capacity prices is given in EUR/MW/Year or EUR/kW/day and the prices vary greatly across the recent capacity auctions depending on system conditions and CM design Prices in recent CM auctions. The example results for auctions held in past year are shown in Figure 8.10

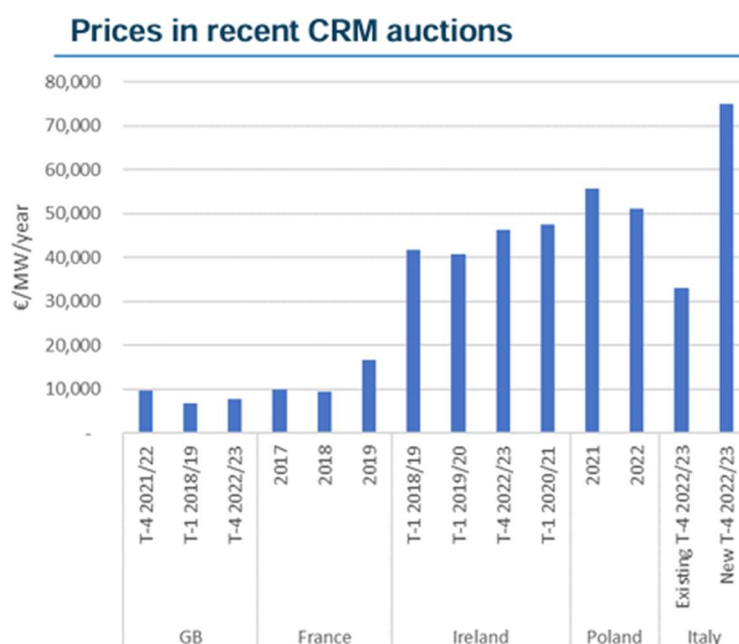


Figure 8.10 Prices in recent CRM auctions (<https://usea.org/sites/default/files/event-FABIEN%20ROQUES%20PRZ%20-%20USEA%20WEBINAR%20-%20Capacity%20Markets%20-%2017%20June%202020.pdf>)

The prices in recent Capacity market auctions ranges from **10 000 EUR/MW/Year to 70 000 EUR/MW/Year** across the EU countries supporting the investment to capacities for year 2022/2023.

8.10 Return on Investment per Technology

For each of the abovementioned technologies a simple return period based on comparable parameters and most common use cases was calculated in order to provide a comparable overview of the technologies seen as an investment opportunity.

Table 8.8 Overview of the input parameters (based on previous chapters)

Technology		Gravity-Based Energy Storage	Flywheel Energy Storage	Hydrogen Energy Storage	Vanadium Redox Flow Batteries (VRFBs)	Ultracapacitors (Supercapacitors)	Li-ion batteries
C	Day-to-Night Energy Shifting	✓ Common (hours to day)	✗ Not suitable (seconds-minutes only)	✓ Possible but less efficient for daily (better seasonal)	✓ Very common (hours)	✗ Not suitable (seconds-minutes only)	✓ Very common (hours)

Seasonal Storage	Seasonal Storage	✗ Not practical	✗ Not suitable	✓ Main use case (weeks to months)	✗ Not practical	✗ Not practical	✗ Not practical
	Grid Support	✓ Possible (slow response)	✓ Excellent (fast frequency response)	✓ Possible (slow ramp)	✓ Good (minutes scale)	✓ Excellent (ultra-fast)	✓ Excellent (fast response)
	Market Arbitrage	✓ Feasible (energy shifting)	✗ Not suitable (no bulk storage)	✓ Feasible (seasonal or bulk shifting)	✓ Feasible (daily shifting)	✗ Not suitable	✓ Common (daily or hourly trading)
CAPEX		130–220 USD/kWh (shaft: ~130–180, tower: ~150–200, rail incline: ~160–220)	1,000–3,000 EUR/kWh; 200–700 EUR/kW (power capacity)	~500–1,500 EUR/kWh for electrolysis, storage tanks, fuel cell; varies by system size	~€300–€600 per kWh of energy capacity for multi-hour systems, 100 MW, 10-hour VRFB system put costs around €350 per kWh	Very high per kWh ~€4,600 - 9,200; low per kW cost due to high power density	Battery pack: 100–150 USD/kWh; Installed system: 300–500 USD/kWh
OPEX [yearly]		1.5–4% of CAPEX (~45–65 USD/kW-yr shaft/tower; ~35 USD/kW-yr rail)	~0.7 EUR per kW per year; minimal maintenance	~2–5% of CAPEX yearly for maintenance (electrolyser, compressor, fuel cells)	1–2% of CAPEX per year; minimal maintenance due to stable electrolytes	0.1–0.5% of CAPEX yearly; negligible operational costs	1.5–4% of CAPEX per year
ADDITIONAL REVENUE		Revenue from grid services (e.g., up to 90 k€/MW-year for FCR-N)	Revenue from frequency regulation, UPS, power quality services	Revenue streams: grid services, selling green hydrogen to industry, mobility sector	Revenue: energy arbitrage, peak shaving, ancillary grid services (FCR, aFRR), backup power	Revenue from fast frequency response, power smoothing, regenerative braking, UPS support	Energy arbitrage €40k–100k; Peak shaving €20k–60k; FCR/aFRR €70k–130k

CAPACITY_INPUT	Tower: 4 MW / 35 MWh; Shaft: 2–4 MW / 2–4 MWh; Rail: 50 MW / 12 GWh	5–50 kWh per unit; scalable to multi-MWh; 1–250 kW per unit; plants up to multi-MW	Highly flexible: from small kW-scale to MW-scale systems; storage as compressed /liquid hydrogen (100s of MWh possible)	Energy capacity defined by electrolyte tank size; power by cell stack size; flexible MW-scale deployments	Low energy (Wh range); designed for short-term bursts (seconds–minutes)	Flexible: defined by system design; typical C-rate ~1C; scales MW–MWh
CAPACITY_OUTPUT	Same as input (depends on mass and lift height)	Same as input; very fast discharge (milliseconds); high power density	Electric output via fuel cells or turbines; lower conversion efficiency (overall 40–60%)	Independent power scaling; typical stacks rated from 100 kW to multi-MW	Extremely high power output; discharge in milliseconds to seconds	For a real, grid-connected battery including inverter and HVAC losses: ~85–90% is typical.
#_CYCLES [yearly]	330 full cycles/year; mechanical life >50,000 cycles (~30 years at ~4 cycles/day)	10,000–100,000 cycles; daily cycling possible; negligible degradation	Electrolyser/fuel cell lifespan ~60,000–80,000 hours; cycle count varies but supports frequent cycling	Can cycle 15,000–20,000 times with negligible capacity fade	Supports millions of cycles (>1,000,000) without degradation	Up to ~365 full cycles/year; total cycle life 1,000–3,500+ cycles
LIFE_CYCLE [years]	30–50 years (major overhaul every 15–20 years)	20–30 years (with maintenance; some warranties for 10+ years)	15–30 years; tanks can last 20–30 years; electrolyser stack replacement required every 8–15 years	20–30 years; electrolyte reusable indefinitely; stacks and pumps replaceable	20–40 years lifespan; depends on environmental conditions more than cycling	10–15 years typical calendar life

Legend:

ADDITIONAL_REVENUE - all revenue coming from other sources than selling energy to the grid, e.g. balancing services, market speculation etc.

1-(CAPACITY_OUTPUT/CAPACITY_INPUT) - storage technical efficiency

#_CYCLES [yearly] - full cycle equivalent, i.e. charging and discharging of 100 % capacity

Still, the differences between the common uses describes for each technology entails a necessity to adjust the calculation, because the structure of main revenue steams vary according to this.

For each technology, a simple return period was calculated. It means that the calculation abstracts from the market realia and do not include influence of inflation and discount rate on the value of the foreseen future cash flows. This is due to low level of predictability of the future price relations in area of described technologies. In case of each technology, it was assessed whether the simple return period – taking into account the actual market prices – might be shorter than its technical lifespan. Here again the assumed lifespan abstracts for any reinvestment needed which should already be included in the estimated operational costs (OPEX). The calculations rely on conservative scenarios, i.e. employs the upper bounds of the estimated cost ranges to provide a secure foundation for future decisions. Nevertheless, the expected technological advancements and bigger scale of the deployment of these technologies is about to bring visible cost reductions.

Finally, the estimation of number of round trips (cycles equivalent to full charging and full discharging of the storage) relies here also on the technical parameters of the technology and abstains from smart management based on price signals to optimise the hardware depreciation in relation to revenues to be gained while interacting offensively with the market. This justify using average market price differences to simulate the long-term stable revenues (in form of savings or true cash flows).

8.10.1 Gravity-based Energy Storage

Basing on the reviewed data the most common use case of this technology is day-to-night energy shifting, extended by possible revenues to be gained from the grid operators as a reward for stability supporting services.

Taking into account the average input and output price difference of almost 259 EUR/MWh the simple return period of this technology (its sub-variations) ranges from 3 to 4 years, assuming it runs for its full technical capacity of 330 round-trips a year.

Table 7 Gravity-based storage – Return Period

	Gravity (Shaft)	Gravity (Tower)	Gravity (Rail Incline)
CAPACITY_INPUT [MWh]	35	35	12000
CAPACITY_OUTPUT [MWh]	29,75	29,75	10200
#_CYCLES [yearly]	330	330	330
LIFE_CYCLE [years]	40	40	40
CAPEX [EUR]	5 481 000	6 090 000	2 296 800 000
OPEX [yearly]	219 240	243 600	91 872 000
ADDITIONAL_REVENUE	3 150	3 150	4 500
NET CASHFLOW [EUR yearly]	2 231 754	2 207 394	747 393 450
Δp [EUR]	257,88	257,88	257,88
Δp^* [EUR]	76,52	79,95	83,65
SIMPLE_RETURN_PERIOD	3	3	4

Legend:

Δp - average yearly difference of per MWh charging and discharging price

Δp^* - average yearly difference of per MWh charging and discharging price ensuring return period - life cycle

SIMPLE_RETURN_PERIOD - return period not including discount, inflation and alternative cost

Investing in this technology is to be thus a domain of a big public players aiming at other strategic goals in the energy sector than generating an attractive ROI.

8.10.2 Flywheels

In case of flywheels intra-day and seasonal price fluctuations are not a significant source of revenues which are dominated by the cashflows generated by delivering grid supporting services. A typical installation between 10-20 MW can usually reach the revenue aiming for 1 M EUR which differs from auction to auction and is defined by the contracts with the grid operator. Conservative estimates (relying on EUR 800 K yearly

revenue) imply a return period much longer than the technical lifespan of the technology. As a result it is not recommendable to invest in such technologies, while motivated by return. On the other hand, the yearly revenue guaranteeing the payback of the investment within the technical life cycle of the hardware is EUR 1.28 EUR which could be reached by topping the TSO/DSO contracts by contracts to industrial players who might be interested in employment of the flywheels as the backup energy source for their local networks. From this point of view, it could be a strategic public investment, motivated by the need to secure a stable power supply for a locally based industrial cluster etc.

Table 8 Flywheel storage – Return Period

	Flywheel
CAPACITY_INPUT [MW]	20
CAPACITY_OUTPUT [MW]	19
#_CYCLES [yearly]	10,000–100,000
LIFE_CYCLE [years]	30
CAPEX [EUR]	60 000 000
OPEX [yearly]	14 000
ADDITIONAL_REVENUE	800 000
Δp [EUR]	N/A
Δp^* [EUR]	N/A
SIMPLE_RETURN_PERIOD	76

8.10.3 Hydrogen Energy Storage

Hydrogen, being an energy carrier used in versatile ways as an energy storage medium, may be applied in various use cases. For the purposes of this document, the analysis of the day-to-night energy shifting (H2 to Power), seasonal storage (H2 to power) and selling hydrogen was conducted, including also some estimations of additional revenues to be reached by providing grid services. Of course, the most probable scenario is the mixed usage of H2 manufacturing installation.

In any of these applications does the hydrogen installation ensure a return period shorter than the technical lifespan of the installation even though we, as in the previous cases, assume the full exploitation of the installation (360 cycles a year). In Day-to-Night shifting mode it generates even a negative yearly cashflow, since the average prices differences

are by far too low (258 EUR, when at least 591 EUR prices spread needed) to cover a relatively high OPEX and dissolve CAPEX in the generated surplus. Seasonal application will be paid back in 47 years, indicating the price spread need for 777 EUR/MWh, while the actual amounts for 695 EUR/MWh. The same applies for installation aimed at low-carbon H2 selling (2 EUR / H2 kg). Due to this price the return period exceeds 53 years. Even if the prices raised to 5 EUR, which is typical for fully green hydrogen, the return period remain still over the installation's technical lifespan and exceeds 31 years. Nonetheless, the production cost was calculated *ex works*, it means the expenditures for transporting the product from the factory gate to place of application were not included.

Table 8.9 Hydrogen exploiting storage setups – Return Period

	H2 (Day-to-Night)	H2 (Seasonal)	H2 selling (low carbon)	H2 selling (green h2)
CAPACITY_INPUT [MWh]	20	20	20	20
CAPACITY_OUTPUT [MWh]	7	7	N/A	N/A
#_CYCLES [yearly]	360	360	360	360
LIFE_CYCLE [years]	30	30	30	30
CAPEX [EUR]	50 000 000	50 000 000	30 000 000	30 000 000
OPEX [yearly]	2 500 000	2 500 000	1 200 000	1 200 000
ADDITIONAL_REVENUE	1 350 000	2 025 000	1 500 000	1 500 000
CASHFLOW [EUR yearly]	726 841,00	1 078 436,00	561 818,18	954 545,45
Δp [EUR]	257,88	695,00	N/A	N/A
Δp* [EUR]	590,31	776,70	N/A	N/A
SIMPLE_RETURN_PERIOD	N/A	47	54	32

8.10.4 Vanadium Redox Flow Batteries (VRFBs)

Similarly to flywheels, the common use case of the vanadium redox flow batteries (VRFBs) is providing balancing services to the grid. For smaller installations, as described in Typical

Use Cases of VRFB Energy storage, the return period is about 12 years, basing just on the estimated revenues from TSO/DSO's capacity payments and energy activation. This performance may be still improved by combining with other source of revenues, e.g. peak shaving or a short-term arbitrage. Due to a high number of cycles during the lifespan and a low grade of the hardware degradation the impact of including other use cases in the business model might be significant.

Table 8.10 Vanadium Redox Flow Batteries (VRFBs) – Return Period

	Vanadium Redox Flow Batteries (VRFBs)
CAPACITY_INPUT [MWh]	5,5
CAPACITY_OUTPUT [MWh]	4,4
#_CYCLES [yearly]	360
LIFE_CYCLE [years]	40
CAPEX [EUR]	3 300 000
OPEX [yearly]	66 000
ADDITIONAL_REVENUE	350 000
Δp [EUR]	N/A
Δp^* [EUR]	N/A
SIMPLE_RETURN_PERIOD	12

8.10.5 Supercapacitors/Ultracapacitors

As described before the main rationale behind the installation of supercapacitors/ultracapacitors is providing the balancing services to the grid. This activity is the main source of revenue in the presented calculation. Despite extremely high per KWh capital expenditures and thanks to low maintenance and operations costs, high power density and generous ancillary service market in Czechia an example installation allows paying back just a year before its typical lifespan ends. Baring in mind that it is a simple return period it means that the investment might be still quite risky and should be taken into consideration rather from strategic perspective as a grid strengthening element enabling more RES integration.

Table 8.11 Supercapacitors/Ultracapacitors – Return Period

	Ultracapacitors (Supercapacitors)
CAPACITY_INPUT [MW]	5 (~ 0.02 MWh , 5 sec)
CAPACITY_OUTPUT [MW]	4,75
#_CYCLES [yearly]	500,000-1,000,000
LIFE_CYCLE [years]	15
CAPEX [EUR]	5 000 000
OPEX [yearly]	25 000
ADDITIONAL_REVENUE	400 000
Δp [EUR]	N/A
Δp^* [EUR]	N/A
SIMPLE_RETURN_PERIOD	14

8.10.6 Ion-lithium batteries

Ion-lithium batteries (reference technology) is the most settled technology out the described here. Their use cases varies from peak shaving in the household scale to grid supporting services and market arbitrage, especially if combined with smart management systems. Their role in seasonal energy storing is also growing. Due to difficulties in estimating ‘cannibalisation effect’ between these three use cases, all of them was presented ceteris paribus even though the most realistic operation nowadays relies in the smart combination of them, enabled by advanced management systems.

Table 8.12 Ion-lithium batteries – Return Period

	Io-Li Batteries (Day-to-Night)	Io-Li (Seasonal)	Io-Li (grid support)
CAPACITY_INPUT [MWh]	5	5	5
CAPACITY_OUTPUT [MWh]	4,35	4,35	N/A
#_CYCLES [yearly]	360	360	360
LIFE_CYCLE [years]	30	30	30
CAPEX [EUR]	2 500 000	2 500 000	2 500 000
OPEX [yearly]			

	100 000	100 000	100 000
ADDITIONAL_REVENUE			375 000
CASHFLOW [EUR yearly]	292 509,95	978 471,80	050 000,00 ¹
Δp [EUR]	257,88	695,00	N/A
Δp^* [EUR]	N/A	N/A	N/A
SIMPLE_RETURN_PERIOD	9	3	3

In case of seasonal usage and providing ancillary services, this technology offers a very short, 3-year simple return period of installation with capacity about 5 MWh. In case of peak shaving (typical household use case) the return period is longer (8 years) but still significantly shorter than the lifespan of the hardware. To keep the technology comparable to others, there were used the same assumptions as for the other technologies, i.e. maximal exploitation of technical potential, i.e. 360 cycles with an yearly average price spread a year), which is rather unrealistic. Thus, the presented result may be more optimistic than on real. Still, the investment into this technology seem to be a very secure choice.

ANNEXES of Environmental impact analyses:

This chapter includes 6 additional annexes to the main CSESS document to provide more comprehensive information. That is the **Environmental Impact Analysis** of the technologies that each partner was asked to provide. These documents thus form a coherent body of information that will serve as a basis for providing data and inputs for the development of the online modelling tool in the SO2 Activities.

1. Gravity Based Storage, Flywheel energy storage systems (GESS, FESS):

- LCA_StoreMore-FES-GES-Final-2025-05-30_visibility elements added

2. Hydrogen energy Storage systems (HESS):

- 1.5_Catalogue_v5_with_capacitors_FTN_V01 (HESS)

3. Ultracapacitors:

- Environmental Impact of Ultracapacitors_SC_09062025

4. Vanadium Redox Flow Batteries

- Environmental Impact Evaluation of Vanadium redox flow Energy Storage

5. Battery energy storage systems (BESS):

- LCA_Li-Ion_StoreMore
- STP StoreMore_Inception report - Material Recyclability and Environmental Impact Ratings for Energy Storage Technologies