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Comparative Techno-Economic and Life Cycle Assessment of Stationary Energy Storage Systems: Lithium-Ion, Lead-Acid, and Hydrogen

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Abstract

This study presents a comparative techno-economic and environmental assessment of three leading stationary energy storage technologies: lithium-ion batteries, lead-acid batteries, and hydrogen systems (electrolyzer–tank–fuel cell). The analysis integrates Life Cycle Assessment (LCA) and Levelized Cost of Storage (LCOS) to provide a holistic evaluation. The LCA covers the full cradle-to-grave stages, while LCOS accounts for capital and operational expenditures, efficiency, and cycling frequency. The results indicate that lithium-ion batteries achieve the lowest LCOS (120–180 EUR/MWh) and high round-trip efficiency (90–95%), making them optimal for short- and medium-duration storage. Lead-acid batteries, though characterized by low capital expenditures (CAPEX) and high recyclability (>95%), show limited cycle life and lower efficiency (75–80%). Hydrogen systems remain costly (>250 EUR/MWh) and less efficient (30–40%), yet they demonstrate clear advantages for long-term and seasonal storage, particularly under scenarios with "green" hydrogen production and reduced CAPEX. These findings provide practical guidance for policymakers, investors, and industry stakeholders in selecting appropriate storage solutions aligned with decarbonization and sustainability goals.

Keywords: fuel cells; life cycle; energy efficiency; battery; sustainable energy

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1. Introduction

The transition to a sustainable energy system based on renewable energy sources (RESs) has been a major strategic goal of global energy policy for the past two decades [1–3]. The rapid growth of photovoltaic and wind power, along with the increased electrification of the transport sector, is causing significant changes in the energy mix and presents new challenges in managing power systems. Because RES production is intermittent and variable, maintaining the balance between supply and demand requires efficient and reliable energy storage solutions [4].

Energy storage plays a crucial role in integrating RESs, enabling excess energy generated during peak times to be stored and used when production drops or consumption rises. The primary technologies used for stationary storage include batteries, primarily lithium-ion (Li-ion) and lead-acid (Pb-acid), as well as hydrogen (H_2)-based systems, which involve electrolyzers, tanks, and fuel cells [1,2,4,5]. Each technology has unique technical features, cost aspects, environmental impacts, and specific applications.

Lithium-ion batteries are characterized by high energy density, relatively long cycle life, and high conversion efficiency (over 90% round-trip efficiency). These advantages make them ideal for applications involving frequent charging and discharging, such as electric vehicles, grid buffers, and microgrids [2,6–11]. However, their production involves extracting critical raw materials, such as lithium, cobalt, and nickel, which pose significant environmental challenges, including water resource depletion, soil pollution, and social issues in the extraction regions [6–8,10–17].

Lead-acid batteries, although an older technology, remain widely used due to their low cost, simple design, and almost complete recyclability. Nevertheless, they have lower energy density, efficiency (around 78%), and cycle life, restricting their use in high-demand applications [5,18–20].

Hydrogen systems have a notable advantage: the ability to store energy over long periods, including seasonally. Through electrolysis, electrical energy is converted into hydrogen, which can be stored for months and later used in fuel cells to generate electricity [4,21–25]. This approach helps address seasonal variations in renewable energy; however, it currently suffers from low overall efficiency (around 30–40%) and high capital costs, particularly for power components such as electrolyzers and fuel cells. The environmental impact of hydrogen systems largely depends on how the hydrogen is produced: "green" hydrogen, generated via electrolysis powered by renewable energy, has a much lower ecological footprint, whereas hydrogen produced using electricity from the conventional grid can generate emissions exceeding those of traditional fossil fuels. In the context of increasing demands for decarbonization and energy security, selecting the right energy storage technology cannot rely solely on technical features or initial investment costs. A comprehensive approach, considering the entire life cycle from raw material extraction and manufacturing to operation, waste management, and recycling, is essential. This holistic assessment, known as LCA, enables an objective comparison of different technologies based on their environmental impact, energy consumption, and greenhouse gas emissions [1–3,23,24].

Alongside LCA, economic analysis using the Levelized Cost of Storage (LCOS) offers a quantitative measure of the total cost of energy provided by the system over its operational lifetime. LCOS accounts for capital investment, operation, and maintenance costs, conversion efficiency, and usage frequency. Comparing LCA and LCOS helps identify technologies that simultaneously reduce environmental impact and deliver competitively priced stored energy.

This study aims to offer a comprehensive and objective basis for choosing the best energy storage technology for stationary applications by combining environmental and economic indicators. By analyzing three technologies, lithium-ion batteries, lead-acid batteries, and hydrogen systems, it presents a comparison that can guide energy firms, policymakers, and investors in planning future energy infrastructure, as shown in Figure 1 [1–5,23,24].

Through a systematic and objective approach, this work aims to support informed decision-making in the scientific, industrial, and political communities related to the future place of fuel cells in the global energy mix [4,20–25].

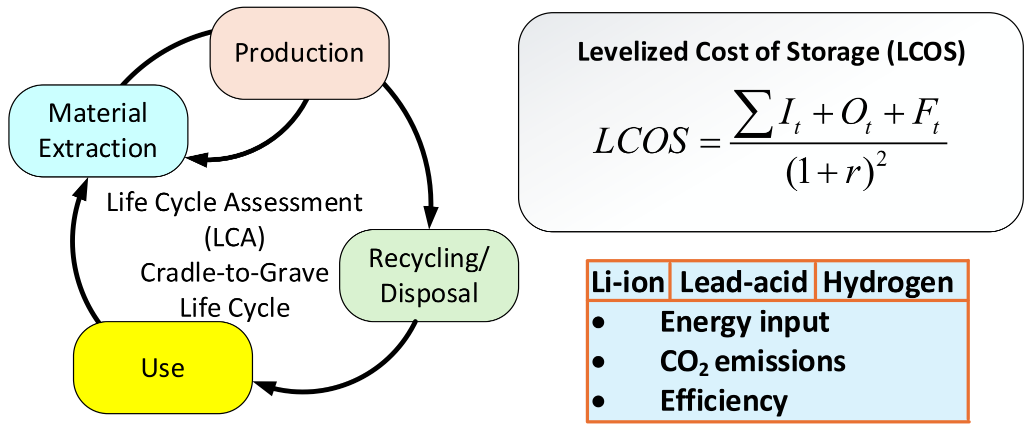

Figure 1. Life Cycle Assessment framework.

2. Literature Review

2.1. Overview of Stationary Energy Storage Technologies

The integration of high shares of renewable RESs into modern power systems necessitates the deployment of stationary energy storage (SES) solutions that can provide both short-term balancing and long-duration energy shifting. Among the most prominent SES technologies are Li-ion, Pb-acid, and hydrogen-based energy storage systems (H_2 systems) [1,2,4,5]. Each technology presents a distinct combination of technical performance parameters, environmental footprint, and economic viability.

Li-ion batteries have emerged as the dominant stationary storage technology due to their high round-trip efficiency (80 ÷ 95%), relatively long cycle life (3000 ÷ 8000 cycles), modularity, and rapid cost decline driven by economies of scale and improvements in manufacturing [2,3,6–9]. Their high energy density and fast response time make them suitable for frequency regulation, smoothing renewable energy, and peak shaving applications [2,3]. In contrast, Pb-acid batteries, despite their significantly lower energy density and shorter lifespan, remain prevalent in specific low-cost or backup applications due to their technological maturity, established recycling infrastructure, and lower upfront capital costs [5,18,19].

Hydrogen-based storage systems are less mature but offer unique advantages in scenarios requiring long-duration or seasonal storage. Their ability to store large amounts of energy for weeks or months is unmatched by any other type of battery. Still, the current technological limitations, such as low round-trip efficiency (typically 30 ÷ 45%) and high capital expenditures (CAPEX), hinder widespread adoption [4,20–24]. Nevertheless, the potential synergies between hydrogen production and decarbonized industrial processes suggest that these systems could become a cornerstone of future low-carbon energy systems as costs decline and efficiencies improve [21,24–26].

Among the alternative technologies for stationary energy storage of increasing importance are redox flow batteries, especially vanadium-redox (VRFB) and zinc-bromine systems. These solutions offer high cyclic stability, modular flexibility, and improved safety, making them promising for long-term storage applications (4–12 h). Despite their scientific and technological potential, they are not included in the present comparison due to limited commercialization by 2025 at the European scale, a lack of consolidated LCOS and LCA data, and high variability in industrial configurations. Future extensions of this study envisage the inclusion of redox flow technologies when more detailed and homogeneous performance and sustainability indicators are available.

2.2. LCOS Analyses

The LCOS metric is widely recognized as a comprehensive indicator of the economic competitiveness of storage technologies, integrating capital expenditures (CAPEX), operational expenditures (OPEX), lifetime energy throughput, and financial discount rates [1,3]. Li-ion consistently exhibits the lowest LCOS in most analyzed scenarios, particularly when operated at high cycle frequencies and under favorable financing conditions [2,3,8]. For instance, Schmidt et al. [2] project LCOS values for utility-scale Li-ion systems falling below 150 USD/MWh by 2030 under optimistic cost decline trajectories.

Pb-acid batteries, while often cheaper to procure initially, show a higher LCOS over their lifetime due to shorter cycle life and lower efficiency (70 ÷ 85%), leading to higher per-unit costs of delivered energy [5,18–20]. The economics of hydrogen systems are markedly different: their high CAPEX (for electrolyzers, storage tanks, and fuel cells/turbines) and low round-trip efficiency result in LCOS values several times higher than those of Li-ion in short-duration storage scenarios. However, the relative cost penalty decreases significantly for storage durations exceeding 12 h, where the marginal cost per unit of stored energy for hydrogen systems approaches that of battery technologies [24–26].

2.3. LCA of Lithium-Ion and Lead-Acid Batteries

LCA studies on Li-ion batteries indicate that their environmental impact is concentrated in the upstream stages, specifically in raw material extraction and cell manufacturing [6–13]. Critical metals such as cobalt, nickel, and lithium contribute disproportionately to greenhouse gas (GHG) emissions, acidification potential, and resource depletion indicators [8,10,11,13,14]. Recycling and second-life applications have been identified as effective strategies for reducing life cycle impacts by up to 40% in GHG emissions and by decreasing the demand for virgin materials [11,13,15–17].

Pb-acid batteries, while less energy-intensive to manufacture, present significant environmental risks due to lead toxicity and the potential for leakage during disposal if not managed within a closed-loop recycling framework. The recycling rates for Pb-acid batteries are generally high (>95%) in developed countries, but poorly regulated recycling in developing regions can cause severe environmental and health hazards [5,18,19]. Comparative LCA studies generally find that Li-ion batteries have a lower overall environmental impact per kWh delivered when operated over equivalent service lifetimes, largely due to their higher efficiency and longer cycle life [5].

2.4. LCA and Techno-Economic Analysis of Hydrogen Storage Systems

Hydrogen energy storage (HES) systems have been analyzed from both an LCA and techno-economic perspective. The environmental performance of HES depends heavily on the hydrogen production pathway: electrolysis powered by renewable electricity yields the lowest GHG emissions (as low as 1 ÷ 4 kg CO_2-eq/kg H_2), whereas hydrogen from fossil-based sources such as steam methane reforming (SMR) can exceed 10 kg CO_2-eq/kg H_2 [21–24]. The storage medium, whether compressed gas, liquid hydrogen, or solid-state hydrides, also influences the life cycle impacts.

From a techno-economic standpoint, the key cost drivers for HES are the CAPEX of the electrolyzers, compression/liquefaction units, and fuel cells or turbines for reconversion into electricity, along with the efficiency losses in each conversion stage. Current round-trip efficiencies of 30–45% contribute to high LCOS values (500 ÷ 1500 USD/MWh), although ongoing R&D efforts aim to improve electrolyzer efficiencies to above an 80% Lower Heating Value (LHV) and reduce costs through economies of scale. Several meta-analyses predict that hydrogen storage could become cost-competitive for seasonal storage applications by the mid-2030s under favorable policy and cost reduction scenarios [23–25].

2.5. Comparative Findings and Research Gaps

Across the reviewed literature, Li-ion emerges as the preferred option for short- to medium-duration storage (2–8 h), offering high efficiency, fast response, and declining costs [2,3,6]. Pb-acid batteries remain competitive in low-demand, stationary backup applications where low upfront cost is prioritized over lifetime cost-effectiveness. Hydrogen systems, while currently expensive and inefficient, are uniquely suited to long-duration and seasonal storage, where batteries would require prohibitively large capacities [4,24–26].

The identified research gaps include

- The absence of standardized LCOS methodologies that integrate LCA outcomes for a holistic sustainability assessment [1–3];
- The need for advanced recycling technologies and closed-loop material supply chains for both Li-ion and Pb-acid systems [11,13,15–20];
- The development of hybrid storage architectures that combine the high efficiency of batteries with the long-duration capacity of hydrogen systems [4,24–26];
- Techno-economic modeling of large-scale hydrogen storage in integrated energy systems, particularly in high-renewable penetration grids [24–29].

3. Materials and Methods

3.1. Selection of LCA Method

Life Cycle Assessment (LCA) was selected as the primary tool for the environmental evaluation of the considered energy storage technologies due to its international recognition and its standardized methodological framework [30,31]. These standards provide the principles, scope, and requirements for conducting a systematic study of environmental impacts across all life cycle stages of a product or system.

In the context of energy storage systems, LCA is particularly valuable because it enables a consistent and quantitative comparison of technologies of different physical natures—electrochemical (batteries) and chemical (hydrogen)—using a common methodological basis. This holistic approach is essential for integrated energy systems, where the technology selection depends not only on economic efficiency but also on environmental performance throughout the entire life cycle.

The methodology consists of four key phases:

- Goal and scope definition: In this study, the objective is to compare lithium-ion batteries, lead-acid batteries, and hydrogen storage systems for stationary applications within cradle-to-grave system boundaries;
- Life Cycle Inventory (LCI): Collection and systematization of input data for resources and emissions, covering raw material extraction, production, operation, maintenance, and end-of-life treatment;
- Life Cycle Impact Assessment (LCIA): Conversion of inventory data into environmental impact indicators such as cumulative energy demand, greenhouse gas emissions, eutrophication, acidification, and recycling potential.

Interpretation of results: Analysis and formulation of conclusions and recommendations to support strategic decisions.

The choice of LCA in this work is motivated by several reasons. First, it ensures systematic coverage of the entire life cycle, avoiding the transfer of environmental burden from one stage to another. Second, it enables comparability across technologies with fundamentally different operating principles. Third, LCA provides policy and market relevance, as institutions and investors often rely on such analyses to align with regulatory and environmental objectives. Finally, in the context of the energy transition, it highlights not only the operational efficiency of storage technologies but also their overall ecological footprint.

By identifying the main environmental "hotspots" across life cycle stages—such as raw material extraction in batteries or hydrogen production in fuel cell systems—LCA provides a basis not only for comparative assessment but also for optimizing future technological development.

3.2. Study Boundaries

The study adopts a cradle-to-grave perspective, covering all stages of the life cycle of the analyzed energy storage technologies—from raw material extraction to end-of-life management. This approach ensures that the full range of environmental and economic impacts is captured and prevents the transfer of burdens from one phase of the life cycle to another.

The system boundaries encompass four main phases:

- Raw material extraction and processing: This stage includes mining, enrichment, and initial processing of critical resources required for system construction. For lithium-ion batteries, these are lithium, cobalt, nickel, and manganese; for lead-acid batteries, this is lead; and for hydrogen systems, these are platinum (used in fuel cell catalysts), steel, and aluminum for high-pressure tanks. Transportation of materials to manufacturing sites is also considered, with emission factors reflecting the mode of transport and fuel efficiency.

Component manufacturing and system integration: All energy and material inputs related to the production of electrochemical cells, electrolyzers, fuel cells, and auxiliary equipment are included. Special attention is given to the energy mix used in manufacturing, as it strongly influences the carbon footprint of cathode/anode production for batteries and the fabrication of electrolyzers.

- Operation phase: This stage accounts for charging and discharging cycles, round-trip efficiency (RTE), frequency of use, scheduled maintenance, and potential replacement of components or modules. Since operational behavior directly affects both LCOS and environmental indicators, this stage is critical for evaluating the long-term sustainability of the technologies.
- End-of-life management: Processes of dismantling, sorting, recycling, and disposal are included. Lead-acid batteries are characterized by high recyclability (>95%), lithium-ion recycling rates are increasing (currently $50 \div 70\%$), and hydrogen system recyclability largely depends on the materials used in membranes and composite storage tanks. Recycling benefits are modeled through system expansion/substitution, where recovered materials offset the need for virgin raw materials.

The analysis is conducted in a European context, using emission factors and energy mixes representative of the projected 2025 EU average. A 20-year operating horizon is applied for both the environmental (LCA) and economic (LCOS) assessments, aligning with the design life of stationary storage installations and investment models in the energy sector.

Several assumptions and limitations apply:

- The effect of extreme operating conditions (e.g., ambient temperature, weather extremes) on system lifetime is not explicitly modeled.
- Technological parameters such as efficiency and cycle life are assumed constant over time, except when replacement is specified.
- Hydrogen electrolysis is considered under a baseline "mixed energy" scenario unless explicitly modeled as renewable-powered (green hydrogen).
- Secondary impacts, such as land use and social sustainability aspects, are not included in the quantitative LCA but are discussed qualitatively in the interpretation section.

By defining these boundaries, the study ensures comparability, transparency, and robustness of the results, while providing a framework suitable for sensitivity analysis and scenario-based extensions.

3.3. Functional Unit

In Life Cycle Assessment (LCA), the functional unit (FU) serves as the reference basis for normalizing all input and output data, ensuring comparability between technologies with different operating principles, capacities, and configurations. The choice of FU is therefore a critical methodological step, as it defines the analytical perspective of the entire study.

For this work, the functional unit is defined as "storage and delivery of 1 MWh of electricity over 20 years of system operation".

This formulation is motivated by several considerations:

- Comparability between heterogeneous technologies: Lithium-ion, lead-acid, and hydrogen storage systems differ substantially in terms of round-trip efficiency, cycle life, and energy density. Expressing the results per 1 MWh of delivered electricity ensures that the analysis is independent of these inherent differences and that environmental and economic metrics can be directly compared.
- Relevance to real-world applications: Energy system operators and investors are primarily concerned with the cost and environmental footprint per unit of useful energy delivered to the grid or end-user. By focusing on delivered energy (rather than installed capacity or storage volume), the FU aligns the assessment with practical decision-making criteria.
- Integration of environmental and economic analyses: In LCOS calculations, costs are naturally normalized to delivered energy. Adopting the same FU in the LCA enables a direct coupling of the environmental and economic results, thereby providing a unified sustainability perspective.
- Avoidance of misleading conclusions: Alternative functional units (e.g., kWh of installed capacity, hydrogen tank volume, or battery mass) could lead to biased outcomes, favoring certain technologies due to their physical characteristics rather than their service provided. The chosen FU eliminates this risk.

Under this FU, all emissions, cumulative energy inputs, and environmental impact indicators (e.g., global warming potential, cumulative energy demand, Abiotic Resource Depletion) are calculated per MWh of delivered energy, considering charging/discharging losses, cycle degradation, and the replacement of components where necessary.

Finally, the 20-year operational horizon reflects the typical design lifetime of stationary energy storage systems in Europe and corresponds to standard investment horizons in techno-economic assessments. This ensures that the FU is both methodologically consistent and practically meaningful for policymakers, system planners, and industry stakeholders.

3.4. Software Used

To ensure methodological rigor and reproducibility, the analysis combines specialized Life Cycle Assessment (LCA) and economic modeling tools. The selection of software was guided by three main criteria: (1) international recognition and validation in academic research, (2) integration with reliable databases for environmental and economic data, and (3) flexibility for scenario and sensitivity analyses.

For the LCA component, three complementary platforms were employed:

- SimaPro—Used for building detailed life cycle models and calculating environmental indicators such as global warming potential (GWP), cumulative energy demand (CED), and Abiotic Resource Depletion (ARD). Its integration with the Ecoinvent database enables access to a wide range of process data. SimaPro was particularly useful for hotspot analysis and visualization of process chains, supporting the identification of the most environmentally critical life cycle stages.
- OpenLCA—Applied as an open-source and highly flexible platform, suitable for integrating alternative databases (e.g., GREET for energy technologies) and automat-

ing comparative assessments. It facilitated the cross-checking of results obtained in SimaPro and enabled the use of multiple impact assessment methodologies (ReCiPe, CML, IPCC), increasing the robustness of the results.

- GaBi—Employed to validate and complement results from SimaPro and OpenLCA, with a particular focus on energy-intensive industrial processes (e.g., electrode manufacturing, hydrogen compression). Its comprehensive industrial databases allowed more precise modeling of complex material and energy flows.

For the economic assessment, the Levelized Cost of Storage (LCOS) was calculated through a two-tiered approach:

- MS Excel/LibreOffice Calc—Used for developing discounted cash flow (DCF) models and performing baseline LCOS calculations. Its transparency and ease of use made it suitable for initial scenario modeling.
- Python 3.10 (NumPy 2.1.4, Pandas 2.3.3, Matplotlib 3.10.7)—Applied to extending the analysis through automated simulations, sensitivity testing, and visualization. Python enabled parametric sweeps of input variables (e.g., number of cycles, electricity price, discount rate) and the generation of comparative figures (LCOS vs. cycles, electricity price, discount rate, storage duration).
- The combined use of spreadsheet-based modeling and Python ensured both interactive parameter exploration and precise numerical processing, balancing accessibility with scientific rigor.

In summary, the methodological framework integrates validated LCA software v.1.02 with global databases and flexible techno-economic modeling tools, ensuring that the results are reliable, transparent, and reproducible. This multi-platform approach also strengthens the credibility of the study by enabling cross-validation of outputs across independent software environments.

3.5. Data Sources

The robustness of both LCA and LCOS analyses depends fundamentally on the quality and consistency of the input data. In this study, multiple complementary data sources were employed to ensure reliability, transparency, and reproducibility. The datasets were systematically cross-validated to minimize uncertainty and potential bias.

3.5.1. LCA Databases

Ecoinvent (v3.9)—The primary source of life cycle inventories, covering extraction, transport, production, and end-of-life treatment of materials relevant to lithium-ion, lead-acid, and hydrogen systems. Its broad coverage (>18,000 processes) ensures representativeness of the modeled systems.

GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies)—Developed by Argonne National Laboratory, GREET was used to cross-check emission factors and cumulative energy demand values, particularly for battery chemistries and hydrogen production pathways.

3.5.2. Scientific and Technical Publications

Peer-reviewed journal articles and systematic reviews were used to validate technological parameters such as round-trip efficiency, cycle life, degradation rates, and recycling potentials. Key sources include *Applied Energy*, *Journal of Power Sources*, *Renewable & Sustainable Energy Reviews*, and MDPI *Energies*. Technical reports from the International Energy Agency (IEA) and the U.S. Department of Energy (DOE) provided reference values for CAPEX, OPEX, and performance projections.

3.5.3. Market and Economic Data

BloombergNEF, IRENA, and IEA market reports—Provided up-to-date cost trends, investment scenarios, and global benchmarks for stationary energy storage systems.

European energy operators—Offered region-specific data on electricity tariffs, grid integration policies, and market structures, ensuring contextual accuracy for LCOS calculations.

3.5.4. Data Validation and Processing

To ensure comparability and methodological transparency, the following procedures were applied:

- Cross-validation: Each key parameter (e.g., efficiency, CAPEX, emission factor) was verified using at least two independent data sources.
- Normalization: All data were harmonized to the functional unit (1 MWh of delivered electricity over 20 years) and to 2025 price levels.
- Geographical adjustment: Emission factors and energy intensities were adapted to the projected 2025 European electricity mix, unless explicitly modeled as renewable-powered (e.g., green hydrogen scenarios).
- Integration into LCA software: The processed datasets were implemented in SimaPro, OpenLCA, and GaBi to calculate environmental indicators, while techno-economic parameters were modeled in Excel and Python.

By combining peer-reviewed literature, validated international databases, and real-world market data, this study ensures a high degree of robustness and transparency. This multi-source, cross-validated approach provides confidence that the reported results are both scientifically sound and relevant for practical applications in energy system planning.

4. Technical Description of the Systems

This section characterizes the three stationary energy storage options using a uniform structure: architecture and components; performance and operating envelope; degradation and operation and maintenance (O&M); safety and compliance; and notes for LCA/LCOS. The goal is to ensure technical comparability and a clear link to the subsequent environmental and techno-economic assessment.

4.1. Lithium-Ion Batteries (Li-Ion)

Architecture and components: Li-ion systems comprise cells (e.g., NMC or LFP chemistries) assembled into modules and racks, managed by a Battery Management System (BMS) that handles cell balancing, protection, and SoC/SoH estimation. Balance-of-plant (BoP) typically includes HVAC/thermal management, fire detection/suppression, power conversion system (PCS), switchgear, and supervisory control.

Performance and operating envelope: The energy density for stationary packs typically falls in the 150–250 Wh/kg range. Round-trip efficiency (RTE) is ~90–95%, with the cycle life commonly 3000–7000 cycles at ~80% depth of discharge (DoD) under controlled thermal conditions. Li-ion offers fast response and high ramp rates; recommended operating temperatures are near 15–35 °C with low self-discharge. LFP tends to trade a slightly lower energy density for improved thermal stability and longevity relative to NMC.

Degradation and O&M: Key drivers are temperature, C-rate, depth of discharge, and calendar time. Preventive O&M mainly concerns firmware updates, periodic inspections, and ensuring proper thermal management; module replacements may be scheduled for long-horizon assets.

Safety & compliance: The primary risk is thermal runaway (cell venting and propagation). Mitigations include cell-to-cell barriers, gas detection, ventilation, and code-compliant fire testing and system certification. Proper enclosure design and spacing are essential.

Notes for LCA/LCOS: LCA hotspots are cathode active materials and upstream mining/refining (Li, Ni, Co). Recycling potential is improving (often ~50–70% material recovery today). LCOS is driven by module/rack CAPEX and BoP (HVAC/PCS); OPEX is typically low due to high efficiency and limited routine maintenance.

4.2. Lead-Acid Batteries (Pb-Acid)

Architecture and components: Lead-acid systems use a Pb/PbO_2 chemistry with a H_2SO_4 electrolyte. Variants include flooded and VRLA (AGM/GEL). Stationary installations add ventilation, spill containment, and standard BoP (PCS, switchgear, monitoring).

Performance and operating envelope: Energy density is ~30–50 Wh/kg; RTE: ~75–80%. Typical cycle life: ~500–1500 cycles at ~50% DoD; deeper cycles accelerate degradation. They tolerate lower C-rates and moderate temperatures; self-discharge is moderate, and ventilation requirements are higher for flooded types.

Degradation and O&M: Sulfation and grid corrosion limit lifetime; equalization charging and electrolyte level checks are required for flooded types (VRLA reduces routine service). More frequent module replacements than those for Li-ion are expected over long horizons.

Safety and compliance: Risks relate to lead toxicity and acid handling; proper PPE, containment, and ventilation are mandatory. The technology benefits from a very mature recycling chain (>95%), but improper recycling can pose environmental/health hazards.

Notes for LCA/LCOS: LCA hotspots are lead smelting/refining and acid handling, partially offset by very high recycling credits. Lower upfront CAPEX supports adoption, but shorter life and lower efficiency increase lifetime energy cost; LCOS is sensitive to replacement intervals and DoD management.

4.3. Hydrogen Storage Systems (Electrolyzer–Tank–Fuel Cell)

Architecture and components: The archetypal configuration couples a PEM electrolyzer (water to H_2), compressed gas storage (typically 350–700 bar), and a PEM fuel cell for reconversion into electricity, plus compressors/dryers, pressure regulation, BoP cooling, PCS, and safety instrumentation. System energy content resides in the stored fuel; the stack sizes set charge/discharge power.

Performance and operating envelope: The mass-specific energy of H_2 is ~33 kWh/kg (fuel basis), but system-level energy density is much lower due to compression and BoP. Round-trip efficiency is ~30–40% (electrolysis $\times$ storage $\times$ fuel cell conversion). Fuel cell stack lifetimes are in the order of 10,000+ operating hours; electrolyzer stacks are comparable or higher under proper duty cycles. Response is fast at the power blocks, while storage duration can extend from days to months, enabling seasonal shifting.

Degradation and O&M: Catalyst/membrane aging (electrolyzer and fuel cell), compressor wear, and filter/dryer maintenance are the main drivers; periodic stack refurbishment/replacement and tank integrity inspections are planned O&M items.

Safety and compliance: Hydrogen's small molecule leads to leak propensity; the design must address ventilation, detection, embrittlement risks, and hazardous-area compliance. Storage systems require pressure-vessel certification and routine inspection.

Notes for LCA/LCOS: LCA is dominated by the electricity source for H_2 production (green vs mixed grid) and compression/liquefaction steps; noble metal catalysts add upstream impacts. LCOS is primarily driven by electrolyzer/fuel cell CAPEX, utilization (cycles and full-power hours), and the price of electricity; competitiveness improves with long durations and low-cost RES power.

Comparative remark: In short-/medium-duration, high-efficiency use cases, Li-ion delivers the best performance–cost balance; Pb-acid remains attractive where very low CAPEX and backup duty dominate; H_2 systems uniquely serve long-duration/seasonal roles, with performance and sustainability hinging on renewable electricity supply and higher utilization—points that are reflected in both the LCA hotspots and the LCOS sensitivities presented later.

To facilitate a direct comparison of the three stationary energy storage technologies, their key technical parameters are summarized in Table 1. The table highlights not only the basic performance indicators—such as energy density, efficiency, and cycle life—but also aspects that are crucial for sustainability and cost assessment, including recyclability, lifetime expectations, and the dominant environmental and economic drivers. This structured overview provides a link between the technical description (Section 3) and the subsequent ecological (Section 4) and financial analysis (Section 5), ensuring continuity in the evaluation framework.

Table 1. Comparative technical parameters of stationary energy storage systems.

Parameter	Lithium-Ion	Lead-Acid	Hydrogen
Energy density (Wh/kg)	150 ÷ 250	30 ÷ 50	System-level much lower (~1 ÷ 2 Wh/g tank basis)
Round-trip efficiency (%)	90 ÷ 95	75 ÷ 80	30 ÷ 40
Cycle life (cycles)	3000 ÷ 7000	500 ÷ 1500	10,000+ operating hours (stacks)
Recyclability (%)	50 ÷ 70	>95	60 ÷ 80
Typical lifetime (years)	15 ÷ 20	5 ÷ 10	15 ÷ 20
Main LCA hotspots	Mining/refining of Li, Ni, Co; cathode production	Lead smelting/refining; acid handling	Electricity source for H_2 production; compression; noble metals
Main LCOS drivers	High CAPEX (modules + BoP), low OPEX	Low CAPEX, frequent replacements, lower efficiency	Electrolyzer/fuel cell CAPEX, electricity price, utilization rate

5. Environmental Indicators

The environmental performance of the three stationary energy storage options is assessed using a set of internationally recognized Life Cycle Impact Assessment (LCIA) indicators. The chosen indicators capture climate impact, energy intensity, local environmental burdens, material criticality, and circularity potential, ensuring that the assessment reflects the most decision-relevant sustainability dimensions.

5.1. Indicator Selection and Methods

Six core indicators were quantified and reported per the functional unit (FU) defined in Section 2.3 (“storage and delivery of 1 MWh of electricity over 20 years of operation”):

- Cumulative Energy Demand (CED)—Total primary energy requirement (MJ/MWh);
- Global Warming Potential (GWP, 100a)—Greenhouse gas emissions over a 100-year horizon (kg CO_2-eq/MWh);
- Eutrophication Potential (EP)—Nutrient-related impacts (g PO_4^{3-}-eq/MWh);
- Acidification Potential (AP)—Acidifying emissions (g SO_2-eq/MWh);
- Abiotic Resource Depletion (ARD)—Non-renewable resource depletion (kg Sb-eq/MWh);
- Circularity Potential (CP)—Share of materials recoverable via recycling (%).

The indicators were calculated using the ReCiPe 2016 midpoint (the hierarchist perspective) for CED, EP, AP, and ARD, and IPCC GWP 100a for climate impact. Datasets were drawn from Ecoinvent v3.9 and complemented and cross-checked with GREET values where relevant. Normalization and weighting were not applied; the results are presented directly per FU.

5.2. End-of-Life and Circularity Modeling

End-of-life processes were modeled using system expansion/substitution, where recovered secondary materials offset the production of virgin raw materials.

- Lead-acid batteries achieve >95% closed-loop recycling, providing significant substitution credits;
- Lithium-ion recycling rates were modeled at 50–70%, reflecting the current EU practice, with credits for recovered Ni, Co, and Li;
- Hydrogen systems provide recycling potential mainly through Pt catalysts, steel/aluminum vessels, and limited credit for composite tanks.

The reported circularity potential (CP) corresponds to practically achievable recycling rates under current industrial processes, not theoretical maxima. CP is therefore interpreted together with ARD and GWP to provide a realistic measure of circularity.

5.3. Hotspots, Uncertainty, and Scope Limitations

The selected indicators highlight the dominant hotspots for each technology:

- Li-ion: GWP, CED, and ARD are driven by cathode material extraction and energy-intensive cell production; EP and AP reflect mining and chemical processes.
- Lead-acid: AP and EP stem from sulfuric acid and lead refining; high CP reduces the overall footprint.
- Hydrogen: GWP and CED are dominated by electricity use for electrolysis; ARD reflects platinum use; AP and EP are tied to the electricity mix and compression processes.

Other impact categories (e.g., human toxicity, photochemical smog, land use) were considered but excluded from the core set as less critical for the comparative scope of stationary storage. The results inherit uncertainty from both background datasets (regional electricity mix and mining processes) and foreground assumptions (efficiency, cycle life, and replacements). Uncertainty is addressed through cross-validation of the data sources, scenario analysis, and sensitivity studies presented in Section 6.

6. Economic Indicators

The economic assessment of the energy storage technologies under consideration is based on the Levelized Cost of Storage (LCOS) approach, which provides a comparable measure of the storage costs per unit of energy delivered. LCOS is complemented by several secondary indicators that provide a deeper understanding of the capital and operating cost structure.

6.1. Definition and Methodology

The primary economic metric is the LCOS, which represents the discounted lifetime cost of storing and delivering electricity, expressed in EUR/MWh of delivered energy. It is calculated as

$$\mathrm{LCOS} = \frac{\sum_{t=1}^{n} \frac{\mathrm{CAPEX}_t + \mathrm{OPEX}_t + E_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{delivered,t}}{(1+r)^t}} \quad (1)$$

where

CAPEX—capital costs for purchasing and installing the system; OPEX—operating and maintenance costs; E_t—energy costs for charging (depending on the price of electricity and the efficiency of the system); $E_{delivered,t}$—energy delivered in the t-th year; r—discount rate; n—analyzed period (years).

Key financial assumptions include the following: Time horizon: 20 years (aligned with LCA FU); discount rates: 5%, 8%, and 12% (to reflect conservative, baseline, and high-risk financing conditions); electricity input prices: 30 ÷ 70 EUR/MWh (reflecting EU market projections for 2025); cycle frequency: 100 ÷ 600 cycles/year (low to high utilization). This formulation ensures comparability across technologies with different lifetimes, efficiencies, and utilization patterns.

LCOS allows a direct comparison of the cost-effectiveness of different technologies, considering the entire life cycle and the relationship between capital investments, operating costs, and operating parameters.

6.2. Cost Components and Drivers

The LCOS captures both capital intensity and operational behavior, which differ strongly among the technologies:

- Lithium-ion batteries: High initial CAPEX driven by cells, racks, and balance-of-plant (thermal management, PCS). Low OPEX and replacement needs (only partial module replacements). High round-trip efficiency (90 ÷ 95%) reduces electricity input costs.
- Lead-acid batteries: Low initial CAPEX, but frequent replacements (shorter cycle life) increase long-term costs. Lower efficiency (75 ÷ 80%) increases electricity input requirements. Maintenance costs (ventilation, electrolyte checks for flooded types) also add to OPEX.
- Hydrogen systems (electrolyzer–tank–fuel cell): Very high CAPEX due to electrolyzer, compression, and fuel cell stacks. OPEX is dominated by electricity input, reflecting low round-trip efficiency (30 ÷ 40%). Replacement of stacks and compressors is required within the 20-year horizon. LCOS is highly sensitive to electricity price and utilization rate.

Thus, while batteries are CAPEX-driven and efficient, hydrogen is OPEX-driven but capable of long-duration operations.

6.3. Complementary Economic Metrics

In addition to LCOS, two complementary indicators are considered:

- Payback period (PBP): The time required for cumulative cash inflows (savings from avoided grid costs) to equal the initial investment. For batteries, the PBP can be achieved within 6–10 years under favorable conditions; hydrogen systems generally exceed the 20-year horizon without subsidies.
- Net present value (NPV): The discounted value of the total lifetime benefits minus costs. A positive NPV indicates an economically viable project; the results strongly depend on the discount rate and utilization.
- Scenario analyses (Section 6) evaluate the sensitivity of LCOS, the PBP, and the NPV to changes in discount rate, cycle frequency, storage duration, and electricity price. These indicators provide a more comprehensive picture of investment feasibility than LCOS alone.

The current economic analysis uses average EU electricity prices and discount rates valid for 2025 in order to ensure comparability and consistency with the LCA parameters. However, we acknowledge that in real scenarios, there are significant variations between Member States, driven by different energy policies, subsidies, tax regimes, and market dynamics. To partially address this heterogeneity, the sensitivity of LCOS to electricity prices and discount rates is included in Section 6, but future research could focus on regionally specific scenarios and the inclusion of tariff incentives and support policies.

Also, the methodology in the current version does not include cascading use, for example, the reuse of batteries from electric vehicles, despite its potential to lower LCOS and improve environmental performance. The main reason is the lack of standardized data on residual capacity, market prices, and the reliability of reused components, which would introduce a large uncertainty. However, the topic has been identified as an important direction for expansion and will be included in future assessments through scenario modeling and sensitivity analysis.

7. Results and Comparison

This section presents the summarized results of the analysis of the three energy storage technologies considered: lithium-ion batteries, lead-acid batteries, and hydrogen systems. The comparison encompasses both environmental and economic indicators, with the data normalized to the functional unit, 1 MWh of energy delivered over 20 years of operation. The summarized results for the different technologies, presented by key indicators, are shown in Table 2.

Table 2. Comparison of key environmental and economic indicators of lithium-ion, lead-acid, and hydrogen systems.

Indicator	Li-ion Batteries	Pb-Acid Batteries	Hydrogen Systems
CED (MJ/MWh)	5500 ÷ 7200	3000 ÷ 4500	8500 ÷ 10,000
GWP (kg CO_2e/MWh)	350 ÷ 500	250 ÷ 400	800 ÷ 1100
EP (g ${PO_4}^{3-}$ eq/MWh)	60 ÷ 90	80 ÷ 120	70 ÷ 100
AP (g SO_2 eq/MWh)	150 ÷ 200	200 ÷ 300	100 ÷ 150
ARD (kg Sb eq/MWh)	0.15 ÷ 0.25	0.10 ÷ 0.15	0.20 ÷ 0.30
CP (% recyclability)	50 ÷ 70	>95	60 ÷ 80
LCOS (EUR/MWh)	120 ÷ 180	90 ÷ 140	250 ÷ 400
Payback period (yrs)	8 ÷ 12	5 ÷ 8	>15
Efficiency (RTE, %)	90 ÷ 95	75 ÷ 80	30 ÷ 40

Figure 2 shows the dependence of the Levelized Cost of Storage (LCOS) on the number of annual charge/discharge cycles for three stationary energy storage technologies: lithium-ion batteries (Li-ion), lead-acid batteries (Pb-acid), and hydrogen systems (H_2 systems). The analysis assumes a 4 h storage configuration, where the system is sized to fully discharge at nominal power over 4 continuous hours per cycle. A 20-year operational life and 300 cycles per year are used as the baseline.

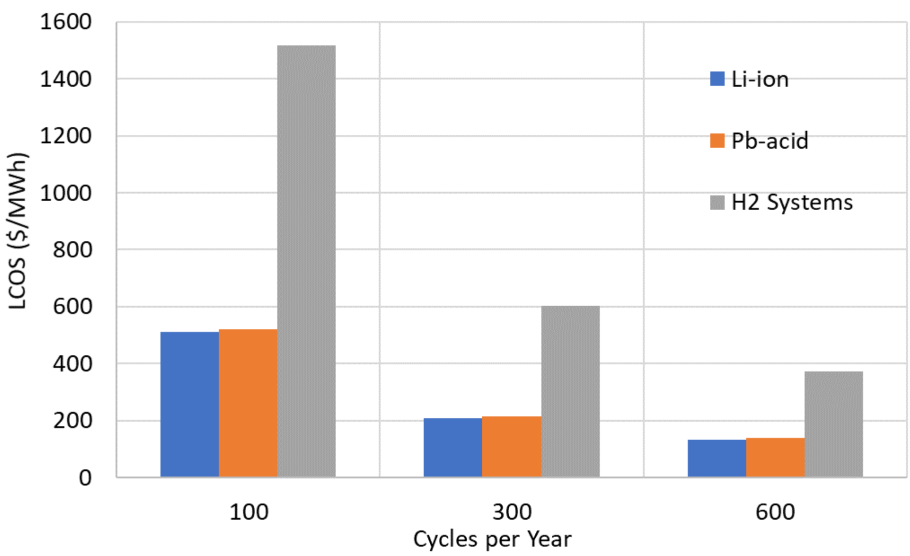

Figure 2. LCOS vs. annual cycles for 4 h storage duration (full discharge at nominal power).

A clear trend of a decreasing LCOS with an increasing number of annual cycles is observed for all technologies. Lithium-ion and lead-acid batteries exhibit similar LCOS values in all considered scenarios, with the cost decreasing to approximately USD 120–USD 130/MWh at 600 cycles/year. However, hydrogen systems remain significantly higher, despite a similar downward trend from around USD 1500/MWh at 100 cycles/year to below USD 400/MWh at 600 cycles/year.

This result highlights the importance of optimal loading of storage systems, as a higher number of cycles leads to a lower value of the stored energy. This effect is significant for technologies with high capital costs, such as those related to hydrogen.

Figure 3 shows the impact of electricity prices on the Levelized Cost of Storage (LCOS) for the three stationary storage technologies: lithium-ion batteries (Li-ion), lead-acid batteries (Pb-acid), and hydrogen systems (H_2 systems), for a 4 h configuration, a 20-year service life, and 300 cycles/year.

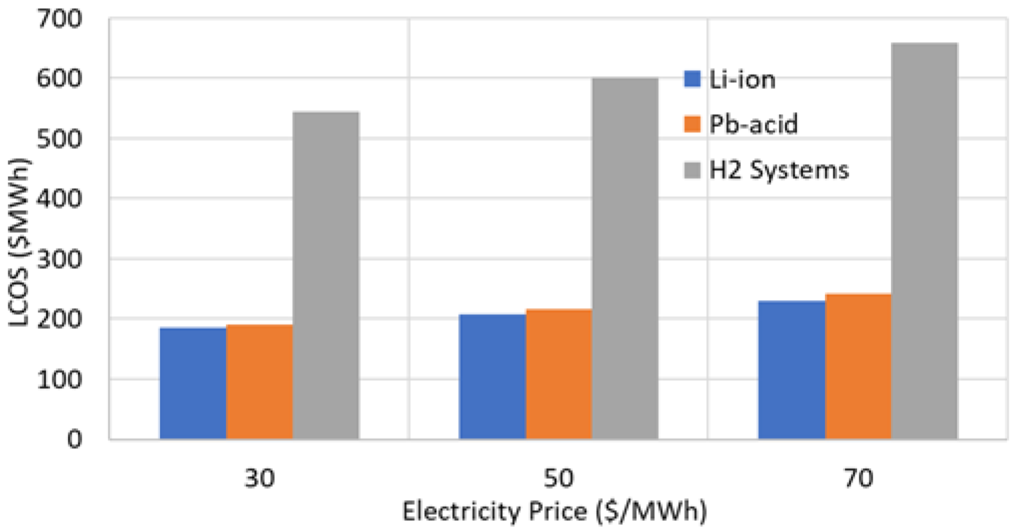

Figure 3. LCOS sensitivity to electricity price (4 h, 20-year life, 300 cycles/year).

An almost linear relationship is observed with increasing electricity prices, with the LCOS increasing for all three technologies. Lithium-ion and lead-acid batteries maintain similar values in all scenarios considered, with the LCOS increasing from approximately USD 185 to USD 190/MWh at an electricity price of USD 30/MWh to USD 230 to USD 240/MWh at USD 70/MWh.

Hydrogen systems, due to their lower energy efficiency, show significantly higher sensitivity to electricity prices. For USD 30/MWh, the LCOS is around USD 550/MWh, and at USD 70/MWh, it reaches approximately USD 660/MWh. This highlights the key role of electricity price in the economic feasibility of hydrogen technologies compared to battery solutions.

Figure 4 presents the impact of the discount rate on the Levelized Cost of Storage (LCOS) for the three technologies, lithium-ion batteries (Li-ion), lead-acid batteries (Pb-acid), and hydrogen systems (H_2 systems), for a 4 h configuration, 20-year service life, and 300 cycles/year.

It is observed that with increasing discount rate, LCOS increases for all technologies, which is due to the higher capital costs reflected in higher levels of required return. For lithium-ion and lead-acid batteries, the change is moderate, from ~185 ÷ 200 USD/MWh at 5% to ~230 ÷ 245 USD/MWh at 12%.

However, for hydrogen systems, the effect is significantly more pronounced due to the high initial capital and longer payback period. The LCOS increases from around

USD 520/MWh at 5% to over USD 720/MWh at 12%. This shows that the economic competitiveness of hydrogen technologies is highly sensitive to the financial parameters of the project.

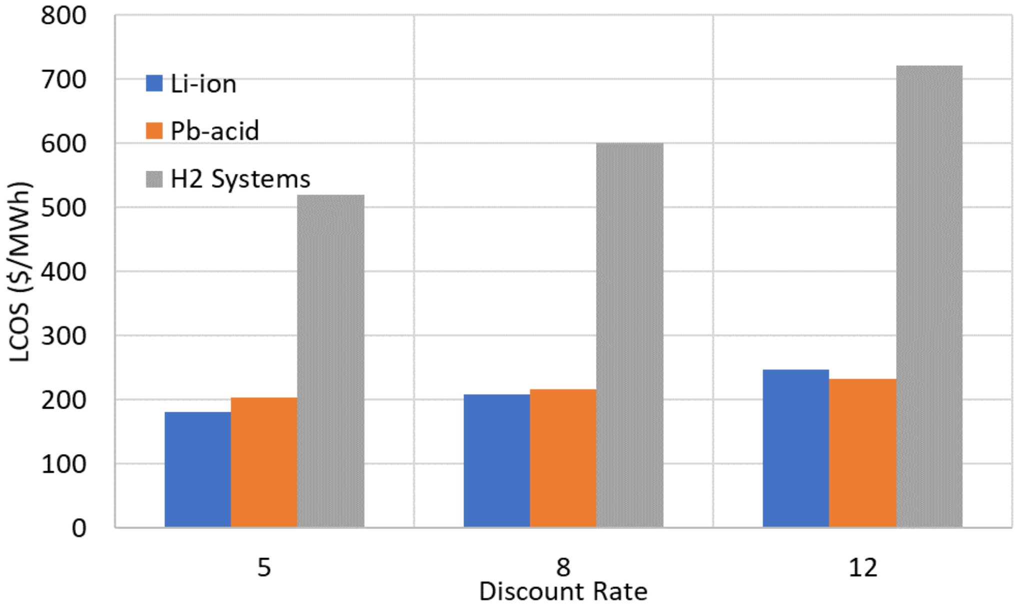

Figure 4. LCOS sensitivity to discount rate (4 h, 20-year life, 300 cycles/year).

Figure 5 presents the impact of storage duration on the Levelized Cost of Storage (LCOS) for lithium-ion batteries (Li-ion), lead-acid batteries (Pb-acid), and hydrogen systems (H_2 systems) at a 20-year service life and 300 cycles/year.

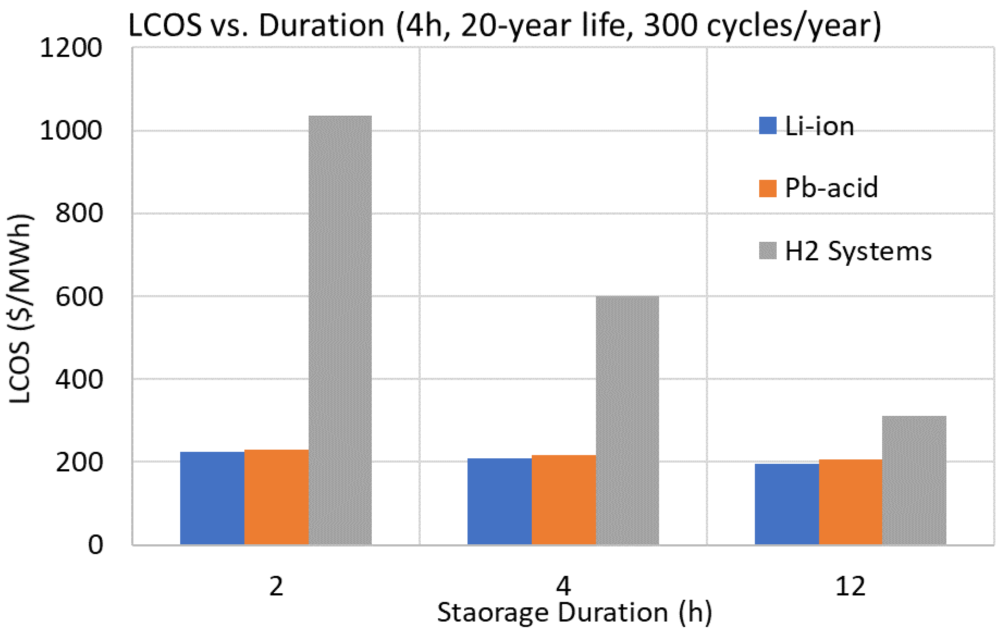

Figure 5. LCOS sensitivity to storage duration (4 h, 20-year life, 300 cycles/year).

The results show that for battery technologies (Li-ion and Pb-acid), the LCOS remains relatively stable over different storage durations, around USD 190 ÷ 220/MWh, decreasing slightly for longer periods (12 h). This is due to the better utilization of capital costs with higher system capacity.

However, hydrogen systems show much greater variation. At a 2 h duration, LCOS reaches over USD 1000/MWh, which is a result of high fixed costs spread over a small amount of stored energy. At 12 h, the LCOS drops significantly, to around USD 310/MWh, indicating that hydrogen technologies are more competitive in applications requiring long-term storage of large volumes of energy.

Figure 6 shows the origin of the energy that covers the load for the three technologies. The green segments (energy from storage, battery/fuel cell, load) dominate for all three options. For Li-ion, almost all of the load is powered indirectly through the battery, as the optimization directs the available PV energy first to charging and not directly to the load. For Pb-acid, the largest share is observed; part of the PV cannot be absorbed by the battery due to lower power and efficiency and is consumed directly. The grid/load share remains low and similar across the technologies, indicating a high degree of self-sufficiency of the system from PV and storage at the same total load (~8 MWh for the considered period).

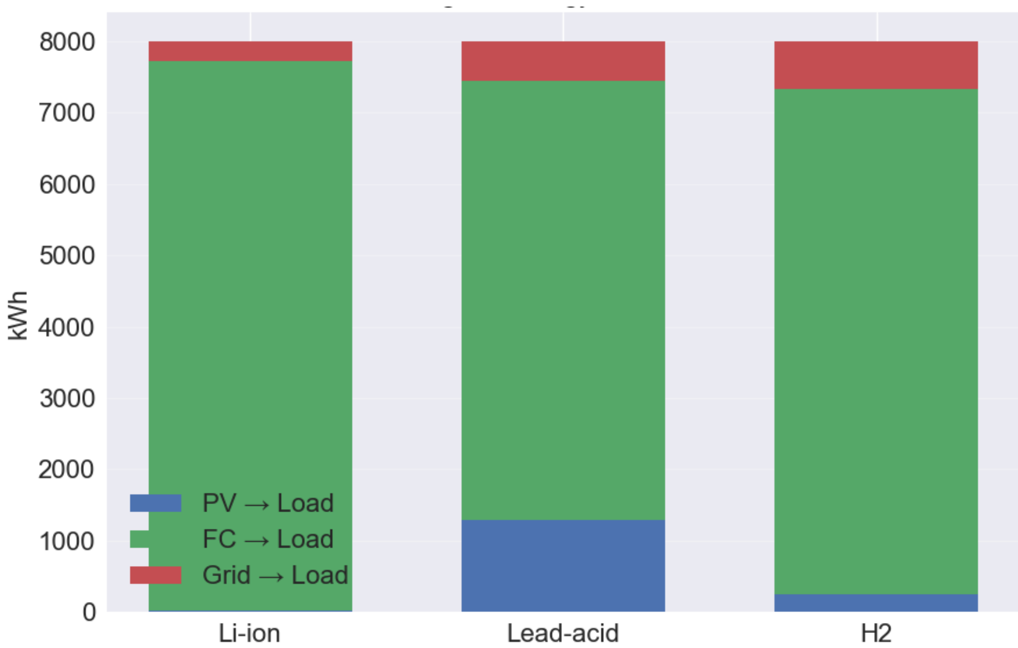

Figure 6. Energy origin for lithium-ion, lead-acid, and hydrogen systems.

Figure 7 shows the hourly and daily dynamics of the state of charge (SoC) of the Li-ion battery. A typical daily pattern is observed: in the early hours, the SoC is low, then between noon and late afternoon, it rises quickly due to PV production, often reaching high levels. During the evening and night, the battery supplies the load, and the SoC slowly decreases. Sunny days exhibit lower charging and a higher load, while days with significant afternoon shading show nearly full charging and extended night discharge. Overall, the battery operates within a broad but manageable SoC range, demonstrating good coordination between the PV system, load, and management strategy.

Figure 8 shows the diurnal and hourly charge dynamics of a lead-acid battery. The general pattern is shallower cycling compared to Li-ion: in the morning, the SoC is lower, and in the afternoon, it rises and often remains for a long time in the 80 ÷ 100% range, which is typical with a limited depth of discharge to preserve cycle life. The charge is more gradual, and the nighttime decline is smoother. Days with brighter areas around noon suggest a weaker PV or a higher load, while sunny days lead to distinct "plateaus" at a high SoC. Overall, the system operates in a narrower window and avoids deep discharges.

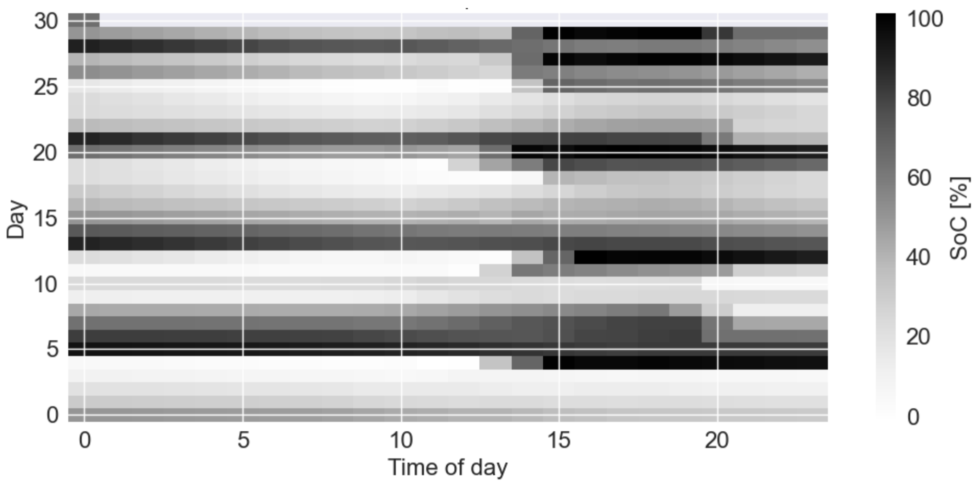

Figure 7. State of charge dynamics for a lithium-ion system.

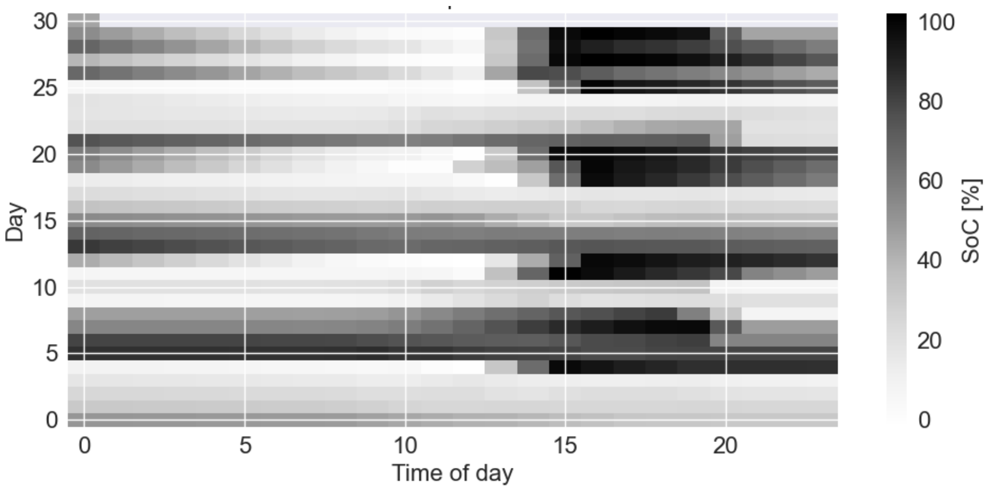

Figure 8. State of charge dynamics for a lead-acid system.

Figure 9 decomposes the greenhouse gas footprint (GWP) of the lithium-ion system by life cycle stages. The core of the emissions comes from the "Operation" phase (≈21 kg CO_2e/MWh), i.e., from the electricity supplied from the grid during operation. The contributions from "Production" and "Transport" are negligible compared to operation, and "O&M" and "EoL" hardly change the amount. The recycling credit is weak (a slightly negative value), as it is spread over the significant energy supplied over the entire life. The total GWP is around 21 kg CO_2e/MWh, indicating that the strongest lever for reduction is the decarbonization of the supply of electricity and increasing self-consumption from PV. The blue bar highlights the operational emissions, while the gray dashed line shows the cumulative GWP across all life cycle stages.

Figure 10 shows the decomposition of the greenhouse gas footprint of the lead-acid system. Almost all of the GWP (≈81 kg CO_2e/MWh) comes from the "Operation" phase, i.e., from the electricity imported from the grid due to lower efficiency and more losses compared to Li-ion. The contributions from "Production" and "Transport" are small, and "O&M" and "EoL" are negligible. Despite the high recyclability of Pb-acid (>95%), the recycling credit is weak on a MWh basis and does not compensate for operational emissions. Therefore, the strongest levers for reducing the footprint are increasing self-consumption from PV and/or decarbonizing the grid mix. The blue bar represents emissions during the operation phase, while the gray dashed line indicates the cumulative GWP across all life cycle stages.

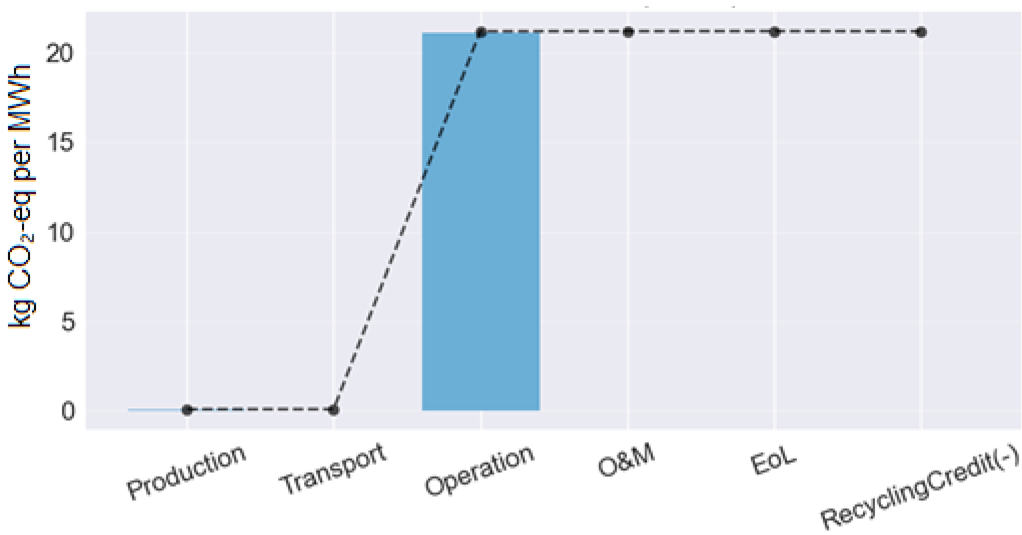

Figure 9. GWP breakdown of the lithium-ion system by life cycle stage.

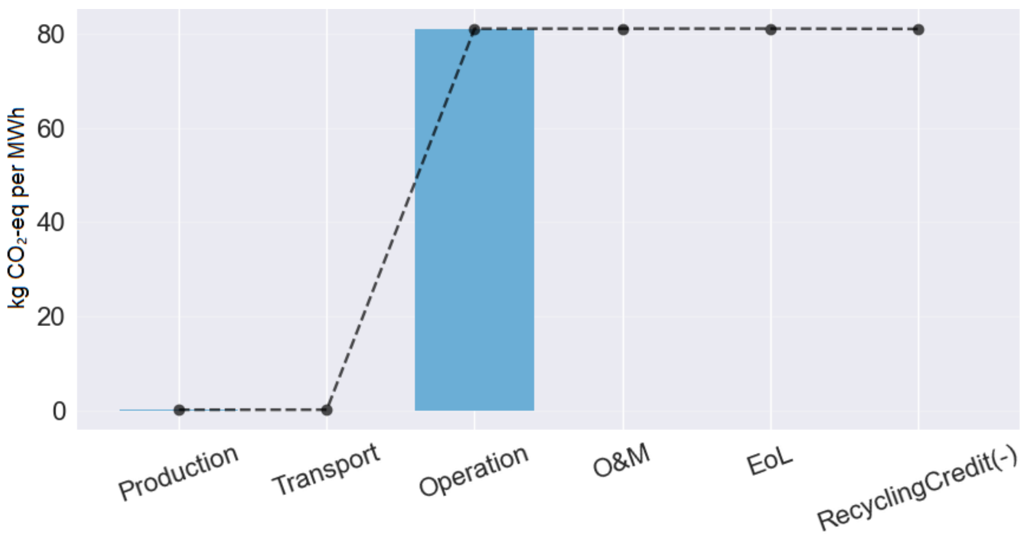

Figure 10. GWP breakdown of the lead-acid system by life cycle stage.

Figure 11 shows that almost the entire greenhouse gas footprint of the hydrogen system (≈187 kg CO_2e/MWh) comes from the "Operation" stage. This is due to the low total efficiency (electrolyzer + fuel cell) and the additional auxiliary/standby consumption, which leads to a significant import of electricity from the grid. The contributions from "Production", "Transport", "O&M", and "EoL" are minimal per unit of delivered energy, and the credit from recycling is negligible. As a result, H_2 has the highest GWP among the technologies considered. The main levers for improvement are a higher share of PV to the electrolyzer and FC, increasing η_EL/η_FC, reducing auxiliary loads, and optimizing the dimensions to limit grid import. The blue bar indicates operational emissions, and the gray dashed line shows the cumulative GWP across all life cycle stages.

Figure 12 shows the distribution of PV energy between self-consumption, grid export, and curtailment. For all three technologies, the share is practically the same: ~60% self-consumption, ~30% export, and ~10% curtailment. This equalization is not accidental; it reflects the constraints imposed in the model (a minimum of 60% self-consumption and a maximum 30% export); therefore, the choice of technology hardly changes the way PV is utilized. However, small differences may appear due to different internal losses and load/charging profiles. Reducing curtailment could be achieved by better matching of the capacities, increasing the export limit, or shifting consumption to hours with PV surplus.

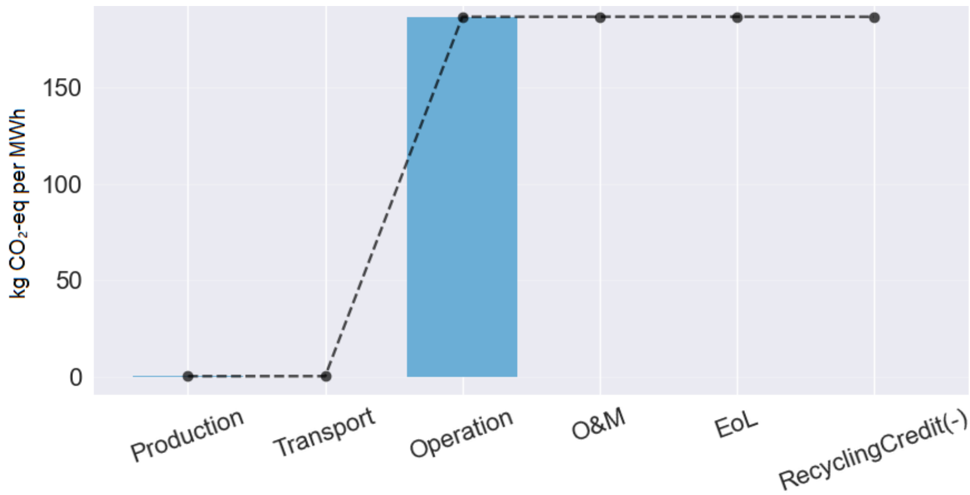

Figure 11. GWP breakdown of the hydrogen system by life cycle stage.

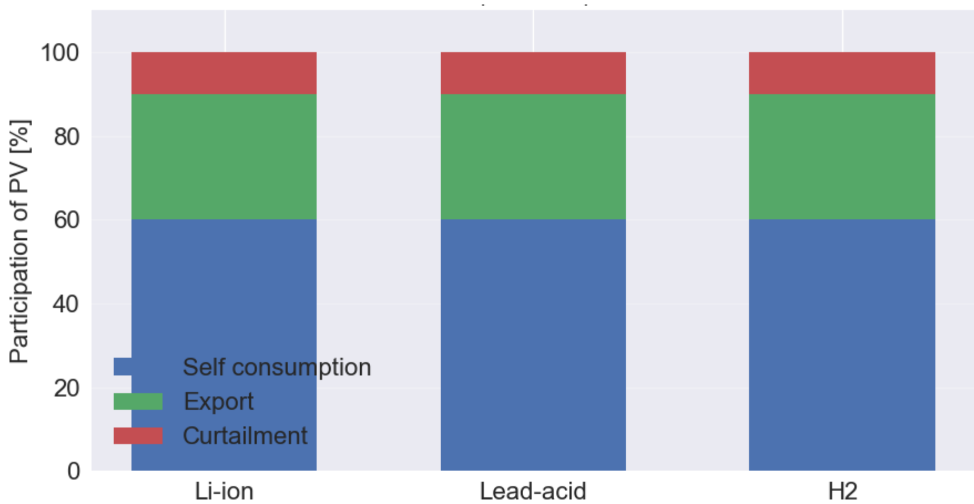

Figure 12. PV energy distribution between self-consumption, grid export, and curtailment.

Figure 13 compares the environmental impact (GWP on the y-axis) and the Levelized Cost of Storage (LCOS on the x-axis), with bubble size representing round-trip efficiency (RTE). Li-ion appears in the lower-right corner, combining the lowest emissions (~20–25 kg CO_2e/MWh) and the highest efficiency, but with an LCOS of around −7 to −8 BGN/MWh. Pb-acid has higher GWP and a slightly more negative LCOS (about −18 BGN/MWh). H_2 shows the highest GWP and the lowest efficiency, with an LCOS around −21 BGN/MWh. Note: Negative LCOS values indicate that, under current tariffs and export revenues, the net cash flow is positive. However, this outcome is highly sensitive to energy prices and regulatory constraints. From an "ecology + efficiency" standpoint, Li-ion is the most favorable option, although the economic preference may shift under different market or policy conditions.

Figure 14 shows a breakdown of the present value of the net present value (NPV) by component for the three storage technologies. In all cases, the dominant component is Energy_NPV (in red), which reflects the net cost of importing/exporting electricity over the entire life cycle. This cost is highest for H_2, lower for lead-acid technology and lowest for lithium-ion. For Pb-acid, there is also a visible Replacements_NPV component (in purple), related to the need for replacement due to a limited cycle life. The components CAPEX (blue), OPEX_NPV (green) and Salvage_NPV (brown) are not visualized due to their very small values compared to the others, but are included in the analysis. The economic results are mainly determined by energy efficiency and the net energy balance.

Increasing self-consumption or optimizing import/export prices have the strongest effect on costs, and for Pb-acid systems, replacements also have an additional burden.

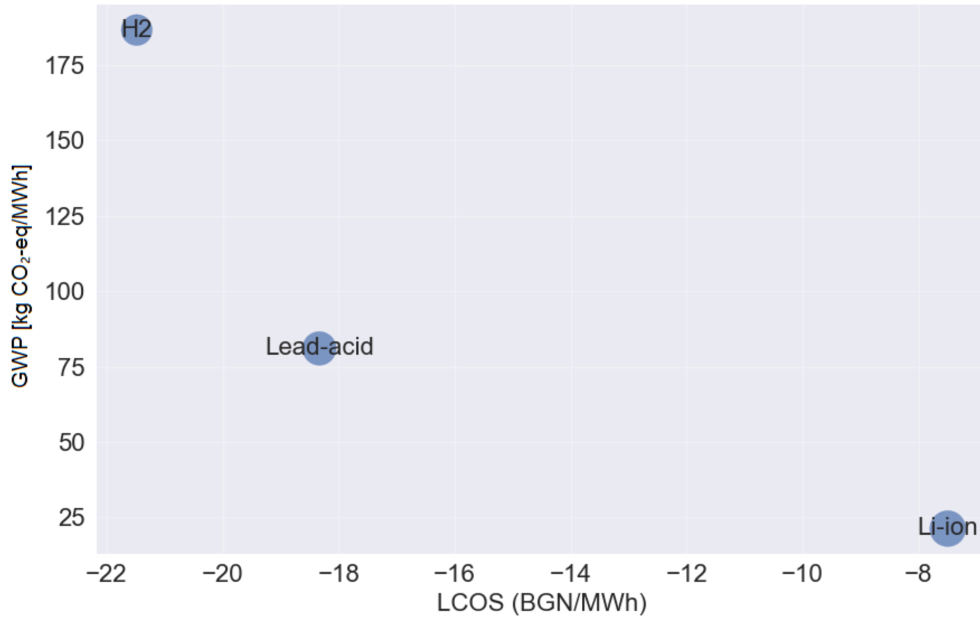

Figure 13. Eco-economic trade-off between LCOS and GWP.

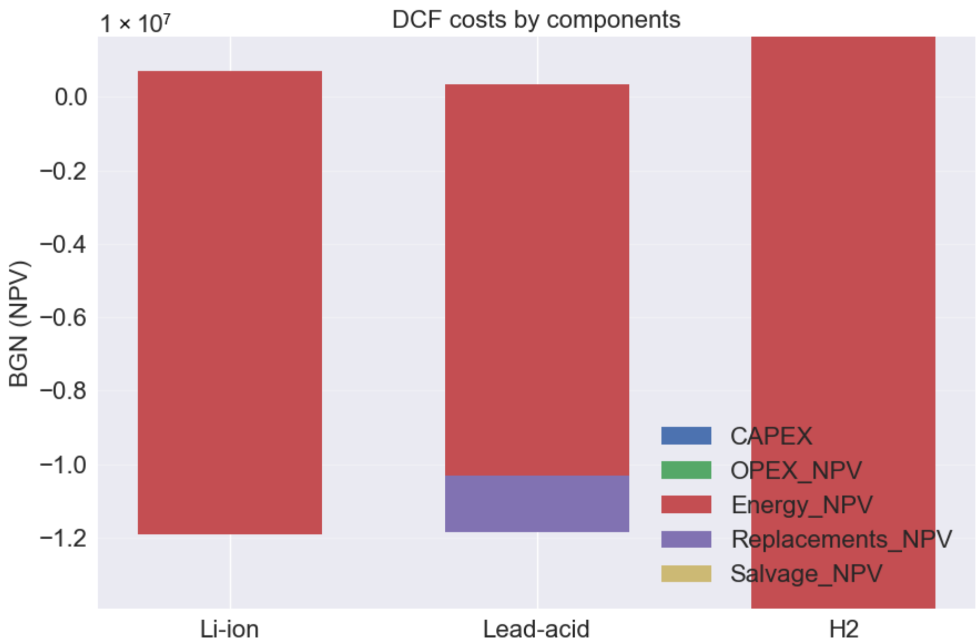

Figure 14. Discounted cost structure by component.

Figure 15 shows the hourly interaction between the load, PV generation, battery (charge/discharge), exchange with the grid (import/export), possible PV limitation, and the state of charge (SoC).

During the daytime hours, the battery is mainly charged by PV, and during the evening peaks (~100–120 h), strong discharges are observed, which limit the load peaks and limit the import from the grid. When PV and the battery are not sufficient, there are short pulses of grid import to cover the shortage and partially restore the SoC. The export and limitations of PV are minimal; the available energy is directed to self-consumption. The SoC profile clearly illustrates the strategy: accumulation during the day and targeted discharge around the peaks, the main mechanism through which the Li-ion system synchronizes PV with demand.

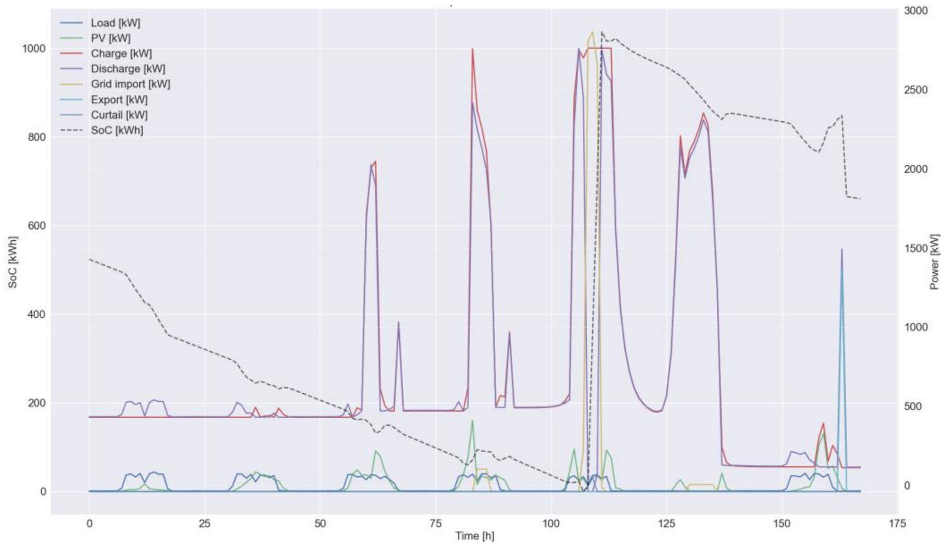

Figure 15. Dispatch profile with lithium-ion storage.

Figure 16 shows the lead-acid battery profile showing lower charge/discharge rates compared to Li-ion and more frequent grid import pulses to cover load peaks (around 100 ÷ 115 h and ~135 ÷ 155 h). Due to the lower efficiency and limited allowable depth of discharge (typically ~60% DoD), the SoC drops faster and recovers more slowly, often requiring partial grid recharging. Short export peaks are also visible during periods of stronger PV production, the battery reaches a power/capacity limit, and part of the energy is exported to the grid. Overall, the system still limits evening peaks but does so less aggressively and with greater grid dependence compared to Li-ion, which is a consequence of the lower power and lower RTE of Pb-acid.

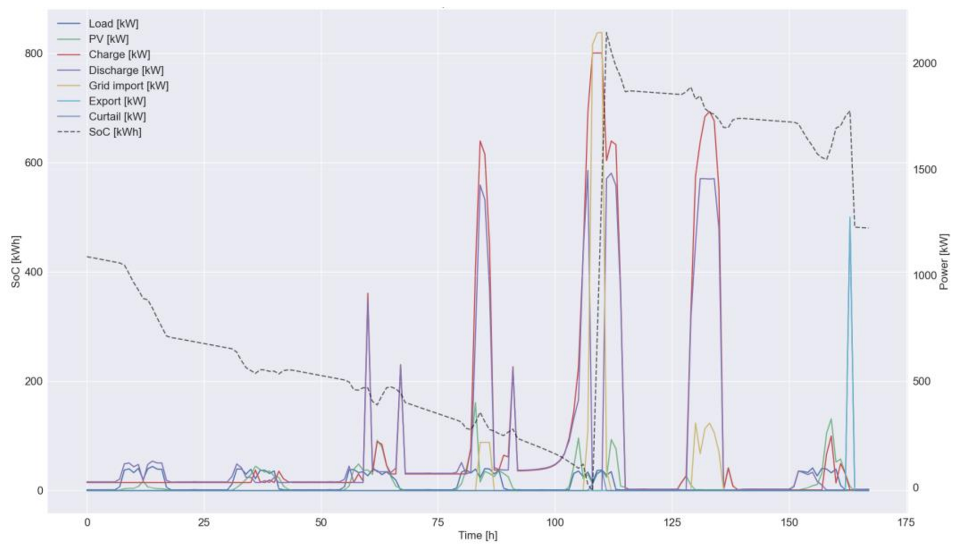

Figure 16. Dispatch profile with lead-acid storage.

Figure 17 shows a typical power-to-gas-to-power mode. The electrolyzer is activated mainly for hours with PV and/or low system costs to produce hydrogen. The fuel cell then feeds energy back to the load, mostly in the evening and during shortages. Due to the low effective RTE and the constant auxiliary consumers, there are distinct peaks of grid import ~105 ÷ 110 h and ~128 ÷ 132 h covering both the shortage and the additional power for the electrolyzer. Export is episodic (around 160 h), and PV curtailment is minimal, with the electrolyzer absorbing the surplus. Overall, the system provides the supply during the hours without sun but with higher dependence on the grid and higher losses compared to the batteries.

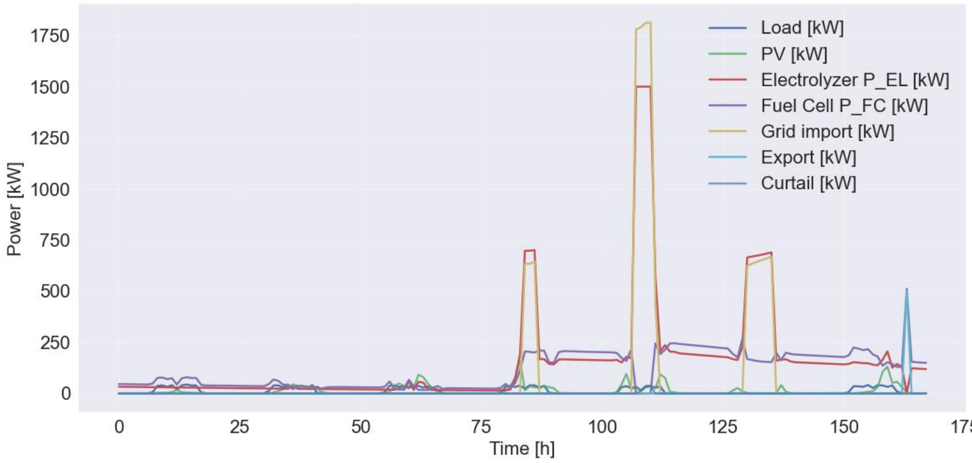

Figure 17. Dispatch profile with hydrogen storage.

Figure 18 compares the three technologies on a set of indicators normalized to the interval 0–1; for the "cost/impact" axes (LCOS, GWP, AP, EP), the values are inverted, i.e., a lower actual level gives a higher score. Li-ion shows the largest area in RTE and autonomy, as well as high scores in AP and EP, i.e., good efficiency and a relatively lower environmental impact per MWh. Lead-acid dominates in CP (recyclability) and is balanced but without strong advantages in efficiency. H_2 only stands out in LCOS in this scenario (freed/net cost after revenue) but remains with the lowest scores in RTE, autonomy, and environmental indicators, indicating a trade-off between economy and impact/efficiency. The general conclusion from the radar is that Li-ion offers the best profile, Pb-acid high circularity with moderate results, and H_2 a specific economic advantage in the considered configuration but with a significantly weaker resource–environmental and efficiency profile.

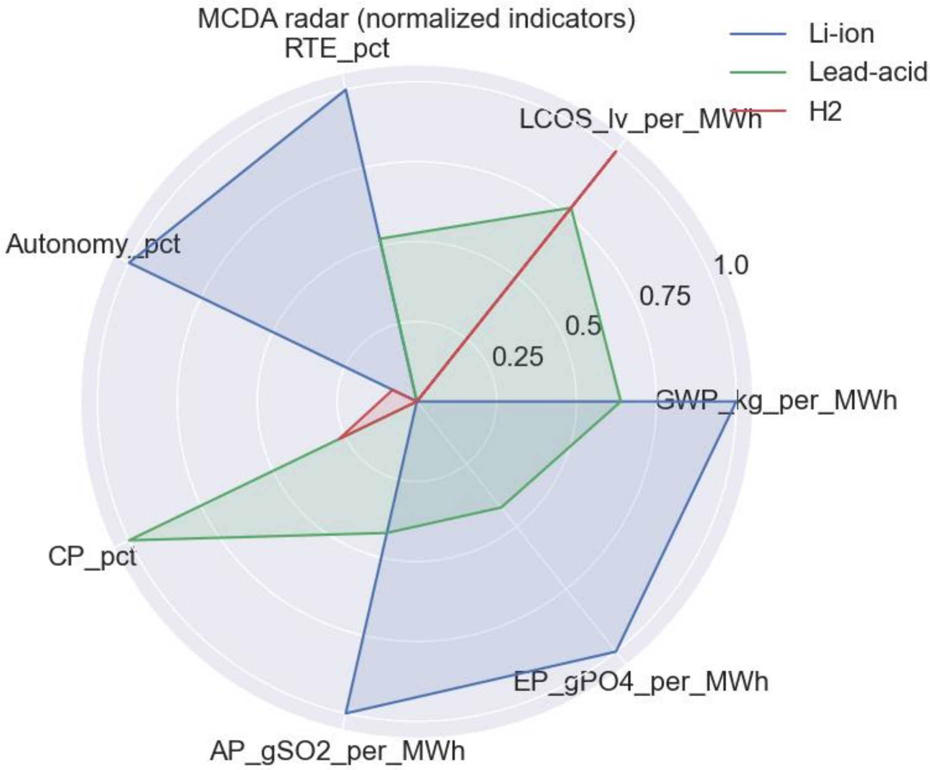

Figure 18. Multi-criteria comparison of the three storage technologies.

In hydrogen systems, there is a clear trend of a decreasing LCOS with an increasing storage duration beyond 12 h (Figure 5). The main reason for this "convergence" is in the capital cost structure, where a significant part of the CAPEX (electrolyzer, fuel cell, control systems) remains constant regardless of the storage volume. With longer storage periods, the main increase is in the costs of tanks (EUR/kWh), which are less intensive. This leads to a more efficient distribution of fixed investments over more delivered energy, which lowers the LCOS. This behavior is particularly pronounced in seasonal storage scenarios, where lithium-ion batteries require a disproportionately large capacity.

8. Discussion

This section synthesizes the techno-economic and environmental findings for lithium-ion batteries, lead-acid batteries, and hydrogen systems. The discussion follows the structure of the sensitivity analysis (cycles, electricity price, discount rate, and storage performance) and then interprets the operational and LCA evidence extracted from Figures 6–18.

The LCOS–cycling relationship confirms the canonical inverse relationship between PC and unit cost. At low cycles (≈100 technology cycles/year), all show an increased LCOS, with hydrogen being the most unfavorable due to cumulative conversion losses and a higher specific capital expenditure (CAPEX). Increasing the number of cycles to 600/year significantly reduces the LCOS in all areas, with the steepest gradient observed for hydrogen, indicating that high performance is a prerequisite for its economic viability (Figure 2).

The LCOS increases quasi-linearly with the price of the input electricity for all technologies (Figure 3). The slope is significantly larger for hydrogen, reflecting its lower efficiency in two-way conversion (electrolysis plus reconversion). Batteries show a more muted response, making them economically more predictable under tariff volatility.

Increasing the discount rate increases the LCOS for all cases (Figure 4), as expected for capital-intensive assets. The effect is most pronounced for hydrogen due to its higher target investment and longer effective payback period, while batteries are relatively less sensitive.

The duration of the technology is distinguished the most clearly (Figure 5). The LCOS of batteries is relatively flat from the short to medium term and is easily used over longer periods due to better capital utilization. Hydrogen shows a sharp decrease in the LCOS when moving from short-term to long-term use, which is consistent with its structural advantage in long-term and seasonal applications.

The decomposition of the supplied energy shows that the product is mainly served by stored energy, with direct photovoltaic batteries used as a secondary channel and the remainder covered by grid imports (Figure 6). Lead-acid batteries show the largest share of direct photovoltaic batteries in the product, while the hydrogen case shows a slightly higher dependence on grid energy, which helps to express its higher operational global warming potential.

The SoC heat maps show stable diurnal cycles for both batteries (Figures 7 and 8). Lithium-ion batteries charge faster at noon and discharge better in the evening peaks, consistent with a tighter RTE and power capacity, while lead-acid batteries show deeper fluctuations and a tendency to remain at high heat levels later in the day, reflecting tighter power/efficiency constraints.

Dispatcher capacity traces confirm these patterns (Figures 15–17). Lithium-ion batteries cover sharp demand ramps with limited grid imports; moderate curtailments and volume occur around PV peaks. Lead-acid batteries follow a similar quality profile but with more frequent imports during ramps. The hydrogen system alternates between electrolyzer operation (charging the H_2 supply when PV or cheap power is available) and fuel cell discharge during peaks; short import peaks coincide with the electrolyzer operating near its nominal capacity, illustrating the energy-intensive hydrogen charging.

The DCF breakdown highlights Energy_NPV (net life cycle energy purchases minus sum revenue) as the dominant cost component in this scenario for all technologies (Figure 14). Only lead-acid batteries show a visible net present value of replacement (Replaces_NPV), consistent with their shorter life cycle. This highlights that the tariff design and operating profile can exceed the capital cost of equipment in the life cycle economy.

The split between self-consumption, sum, and curtailment (Figure 12) clusters around ~60/30/10% for all three technologies, mainly because the minimum self-consumption and size constraints are binding. Loosening these boundaries would likely widen the technological gap (e.g., higher sum utilization with a larger electrolyzer capacity).

The LCOS–GWP bubble plot positions lithium-ion batteries as the most favorable option in this case, with lead-acid intermediates and hydrogen as the least favorable (Figure 13). The apparent near-zero or negative LCOS values reflect the interaction of purchase and sale prices and come from the sum; they are tariff-specific and should not be generalized without caution. The waterfall plots for each technology (Figures 8, 10 and 11) and the accumulated contributions (Figure 14) demonstrate that the cost and environmental impact distribution strongly depend on the intended use case and market context.

- For short- to medium-term applications with frequent cycling and tariff volatility, batteries, especially lithium-ion, offer higher efficiency, lower operational global warming potential (GWP), and better cost-effectiveness
- For long-term or seasonal balancing with high usage, the cost-effectiveness of hydrogen improves significantly, provided that electricity prices and capital costs are favorable.
- Policy instruments (self-consumption obligations, export restrictions, bid-ask spreads) strongly shape both the LCOS and GWP; careful tariff design is as important as hardware selection.

Overall, the evidence highlights a complementary portfolio: batteries as the workhorse for intraday flexibility and hydrogen as a candidate for long-term storage, depending on the usage and pricing conditions.

Beyond the direct comparison of battery and hydrogen storage technologies, broader system-level analyses highlight the role of thermodynamic optimization of the hydrogen production pathways [28] and strategies for reducing the reliance on conventional fossil resources such as coal during the energy transition [29]. These complementary studies emphasize that storage solutions cannot be assessed in isolation but must be aligned with ongoing decarbonization efforts across the entire energy sector.

This study uses a limited set of LCIA indicators, focusing on climate impact, energy intensity, and resource efficiency, due to their high relevance in strategic planning and policy analysis. However, we recognize the importance of additional indicators such as human toxicity (HTP) and land use, especially for technologies involving heavy metals or large infrastructures. Also, the H_2 system considered is based on compressed storage, but future versions of the analysis will include alternatives such as liquefied and solid hydrogen, in order to reflect the environmental and engineering differences between them.

The economic assessment in this study is based on EU-averaged input parameters, including electricity prices and discount rates, valid for 2025 and consistent with the assumptions in the LCA analysis. The aim of this approach is to provide a unified framework for comparison between different technologies. However, we recognize that variations between EU Member States in terms of market prices, energy policies, tariffs, and subsidies can significantly affect the real value of the LCOS. Therefore, future studies envisage scenario analysis with regionally specific parameters (e.g., for Germany, Spain, and Bulgaria) and the inclusion of subsidy mechanisms and regulatory incentives into the assessment framework.

Additionally, the current methodology does not include the secondary value of components, such as the cascading use of lithium-ion batteries after their use in electric vehicles. While such applications have the potential to significantly reduce the LCOS and GWP, they require detailed input data on the residual capacity, reintegration costs, and operational reliability in a stationary environment. Due to this uncertainty, they are not included at this stage but are identified as a priority direction for future expansion, especially in the context of a circular economy and sustainable business models.

Additionally, future extensions of the analysis may include redox flow batteries, such as vanadium-redox and zinc-bromine systems, which are showing increasing interest as long-term stationary storage solutions. As empirical data on their efficiency, environmental profile, and market applicability accumulate, they will represent a valuable addition to multi-criteria comparative assessments.

9. Conclusions

This study delivered a structured techno-economic and environmental comparison of three stationary energy storage technologies—lithium-ion batteries, lead-acid batteries, and hydrogen systems—over a 20-year horizon, normalized to a functional unit of 1 MWh of delivered electricity. By integrating LCA with LCOS, the analysis connects sustainability outcomes with cost performance under EU-2025 conditions.

Key findings: Lithium-ion shows the most favorable profile for short- to medium-duration storage: high round-trip efficiency (≈90–95%), the lowest LCOS (≈120–180 €/MWh), and the lowest GWP per delivered MWh. Lead-acid remains competitive in cases where very low upfront cost and high recyclability (>95%) are valued, though its lower efficiency (≈75–80%) and shorter cycle life increase lifetime costs. Hydrogen systems are currently more expensive (≈250–400 EUR/MWh) and carbon-intensive due to conversion losses, but they provide unique value for long-duration and seasonal storage—especially when powered by low-carbon electricity and under scenarios with declining electrolyzer and fuel cell CAPEX.

Sensitivity insights: LCOS decreases with more cycles for all technologies but rises with electricity price—hydrogen being the most sensitive because of its lower efficiency. Higher discount rates affect capital-intensive technologies most, again impacting hydrogen. Longer storage durations leave the battery LCOS nearly unchanged, while they improve hydrogen economics considerably.

Implications for practice:

- Intraday balancing (≈2–8 h, frequent cycling): Lithium-ion offers the best mix of efficiency, speed, and cost predictability;
- Backup or low-cycle duty: Lead-acid remains suitable where CAPEX and recyclability are the main drivers;
- Long-duration/seasonal shifting: Hydrogen gains relevance under renewable-powered operation, higher utilization, and declining component costs;
- Hybrid solutions: Combining batteries (short-term) with hydrogen (seasonal) can reduce both the LCOS and GWP at system level.

Policy and design levers: Tariff design (self-consumption mandates, export limits, price spreads) and the carbon intensity of charging electricity strongly shape both the LCOS and GWP. Decarbonizing charging supply, improving utilization, and minimizing grid imports are the most powerful levers to reduce cost and climate impact simultaneously.

Limitations and future work: This study applied fixed efficiency, simplified degradation models, and representative tariff assumptions. Future research should include dynamic tariffs and emission factors, stochastic PV/load variability, chemistry-specific degradation and replacement, standardized LCOS–LCA frameworks, and explicit second-life and recycling modeling. These enhancements will refine the boundary between battery and hydrogen advantages and guide robust, low-carbon storage deployment.

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Abbreviations

The following abbreviations are used in this manuscript:

CAPEX	Capital Expenditures
CED	Cumulative Energy Demand
DoD	Depth of Discharge
FC	Fuel Cell
GWP	Global Warming Potential
GHG	Greenhouse Gas
HES	Hydrogen Energy Storage
H_2 systems	Hydrogen-Based Energy Storage Systems
LCOS	Levelized Cost of Storage
LCA	Life Cycle Assessment
Li-ion	Lithium-Ion Battery
LHV	Lower Heating Value
O&M	Operation and Maintenance
Pb-acid	Lead-Acid Battery
RES	Renewable Energy Source
RTE	Round-Trip Efficiency
SoC	State of Charge
SES	Stationary Energy Storage
SMR	Steam Methane Reforming

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