Journal of Trends in Computer Science and Smart Technology (ISSN: 2582-4104)
www.irojournals.com/tcsst/

UPS-Tailored Next-Generation Battery Technologies: Variability, Sustainability, Comparative Analysis and a Technology Roadmap

Manoharan S.[1], Mahalakshmi B.[2], Sindhu M P.[3], Vidyalakshmi R[4], Anandhi K.[5], Gaayathry K.[6]

[1]Department of Electrical and Electronics Engineering, JCT College of Engineering and Technology, Coimbatore, India.
[2]Department of Physics, Hindusthan College of Engineering and Technology, Coimbatore, India.
[3]Department of Mathematics, Sri Eshwar College of Engineering, Coimbatore, India.
[4]Department of Electrical and Electronics Engineering, Karpagam College of Engineering, Coimbatore, India.
[5]Department of Mechatronics, Sri Krishna College of Engineering and Technology, Coimbatore, India
[6]Department of Instrumentation and Control Engineering, Saranathan College of Engineering, Trichy, India

Email: [1] manoish07@gmail.com, [2]bmahalakshmimanohar@gmail.com, [3]mayasindhumpk@gmail.com, [4]vidyalakshmi.r@kce.ac.in, [5]anandhipilai@gmail.com, [6]gaaykrish@gmail.com

Abstract

The global uninterruptible power supply forecast market is estimated at nearly USD 4.04 billion in 2024 owing to the growth in demand at data centers and other crucial sectors. Despite the great deal of information available in battery research, most of the literature on uninterruptible power supply does not consider the variability (temperature, depth of discharge, duty cycle) and mode of operation (grid-interactive vs. Standalone) performance during other operational modes. This review overcomes these deficiencies by providing three contributions: (1) variability in uninterruptible power supply specific quantitative performance metrics; (2) a growth map predicting the adoption of various battery chemistries in UPS on a short, medium, and long-term basis; (3) a sustainability assessment through the lens of primary materials, recyclability, and costs from the life cycle. Representative outcomes include: low-cost standby solutions from VRLA batteries, but limited cycle life (500–1,500 cycles); continuous UPS applications are dominated by LFP and LTO chemistries, which have a high tolerance to deep cycles; Li–S batteries have a high energy density (350–600 Wh/kg), but poor cycle life (<1,000); flow batteries have limited energy power density, but excel in longevity (>10,000 cycles) and are still too bulky for compact uninterruptible power supply systems. These conclusions provide a reasonable assessment of the cross technology trade-offs and the underlying research gaps to derive a pathway towards next generation reliable UPS batteries.

Keywords: UPS, Battery Technologies, Lithium-Ion, Sodium-Ion, Solid-State Batteries, BMS, Sustainability, Hybrid Systems, Thermal Management.

DOI: https://doi.org/10.36548/jtcsst.2025.3.016
Received: 29.08.2025, received in revised form: 02.09.2025, accepted: 17.09.2025, published: 30.09.2025

1. Introduction

Uninterruptible Power Supply (UPS) systems are critical components for providing lasting and reliable power to crucial industries, such as hospitals, data centers, manufacturing, and communications. Increased reliance on digital services, cloud computing and artificial intelligence has caused a greater demand for continuous power during times when grid instabilities, renewable energy intermittency, and cyber-security threats are also on the rise [1].

A UPS can keep sensitive equipment and systems operating normally and without interruption during a power disruption by supply uninterrupted power, even with varying loads of HVAC cooling. Therefore, when utilizing UPS battery systems that can operate 24/7 and are modular, distributed and scalable, systems are highly reliable, and maintenance is reduced. While sealed lead-acid and nickel-based batteries were once more reliable and affordable than alternative technologies, their inherent limitations in energy density, efficiency and environmental impact accelerated the shift toward newer chemistries. By 2020-2025, transformative materials such as silicon-doped graphite anode, solid-state electrolyte, lithium sulfur cathode, lithium-ion/super capacitor hybrid, etc. have changed UPS technology for batteries by deeply enhancing energy densities, cycle-life, charge rates, temperature mismatches, and environmental issues. The lithium-ions available (Lithium Nickel Manganese Cobalt Oxide -NCM, Lithium Iron Phosphate -LFP, Lithium Titanate -LTO and Lithium Manganese Oxide- LMO) are currently significant players in all UPS markets. At the same time, exploring the risks associated with critical raw materials, like cobalt and nickel-based chemistries has increased demand for more environmentally friendly alternatives - think sodium-ion, magnesium-ion and even zinc-air batteries. Even though sodium-ion, zinc-air, and magnesium-ion batteries are still in development and are not yet ready for use in today's UPS systems, they are clearly promising candidates for future UPS systems.

Different from electric vehicle and grid/battery storage batteries, UPS batteries require ultra-fast response implementation, exceptional reliability, minimal maintenance and modularity which are generally undocumented user needs in the battery field. To the best of our knowledge, most reviews overlook reporting how battery performance is relative to the mode by which UPS systems operate (standby, continuous, or grid-tied). Furthermore, we are not aware of any reviews that report the availability of the raw materials used in these batteries, or the life-cycle environmental impacts that are critically important for the deployment of UPS systems [2]. In this review we address all of these issues and specifically (i) identifying UPS-related sources of variability of operation; (ii) comparing legacy, commercial and emergent chemistries in a stringent UPS context (iii) quantifying sustainability and supply-chain related vulnerability (iv) aggregating a techno economic roadmap for a prioritized UPS implementation.

This paper is organized as follows. Section 2 gives the problem statement and research gap, section 3 addresses the methodology, section 4 provides a classification of UPS battery technologies. Section 5 looks at the impact of variability-temperature, depth of discharge (DOD), and duty modes. Section 6 provides a comparison of grid-interactive and standalone UPS arrangements. Section 7 checks availability of resources, ethical issues, and recyclability of UPS battery technologies. Section 8 covers updates to battery management systems and section 9 will tackle challenges on deploying in real-world scenarios. Section 10 gives a UPS battery roadmap, while section 11 provides suggested future directions.

2. Problem Statement and Research Gap

Even though significant strides have been made in improving cycle life and energy density, there have been great advances in cycle life, energy density, and costs; there are still significant gaps in UPS specific research:

Variability in Reality: Comparative studies do exist, but do not cover much of the variability in ambient temperature or the scope that cycling duties may impose on battery life and capacity.

Grid-interactive vs Emergency Only Backup: Different cycling profiles, different expectations of reliability, and size differences between grid-interactive UPS and emergency only backup UPS are often missing system-wide assessments.

Sustainability and Recyclability of Raw Materials: Discussions on recyclability, criticality of raw materials, and the environmental impact of UPS batteries have been infrequently addressed.

Long-term Maintenance Schedules and Advanced BMS Implications: Very few take into consideration the long-term maintenance schedules or investigate reliability, and the effect on potential costs of advanced battery management systems (BMS).

This review intends to help resolve these gaps by providing a comparative assessment based on application, alongside a detailed technology roadmap for UPS batteries, which brings together these important considerations and costs: notable gaps remain in UPS-specific studies

3. Methodology

Using the Scopus, Web of Science, and IEEE Xplore databases, a systematic review was carried out over 2020-2025 with relevant search tags "UPS battery," "cycle life," "thermal management," "raw material sustainability" "recyclability" and "battery management system." The initial search provided 550 (Scopus), 420 (Web of Science), and 315 (IEEE Xplore) records. The records were filtered based on inclusion criteria that emphasized peer-reviewed studies with primary data or meta-analysis data that are most pertinent to stand-alone or high-reliability stationary applications similar to UPS. Based on this, non-stationary applications, such as EV fast-charging, were disqualified. If deemed applicable the analysis included parameters such as energy/power density, cycle life based on real-duty cycle, response time, thermal stability, cost, safety, maintenance, environmental footprint, and supply chain risk frameworks.

4. Classification of UPS Battery Technologies

There are four main types of battery systems for UPS: obsolete, commercial, prototype and research phase. Older zinc carbon and nickel based batteries are considered obsolete due to compatibility performance issues or environmental concerns. In the commercial category, about 99% of batteries used in UPS systems are various forms of Valve-Regulated Lead Acid (VRLA) batteries or lithium-ion based batteries which provide an excellent cost, safety and performance ratio. As lithium-ion batteries overtake older technologies, new prototypes using solid-state, lithium-sulfur, and sodium-ion are under development as viable responses to a few major challenges related to safety, stability, and energy density. One of these new prototypes is expected to achieve commercialization. For example, other research-phase chemistries like zinc–bromine and vanadium redox flow batteries being developed have potential applications for long-duration storage but do not fit well in small-footprint UPS systems.

4.1 Legacy and Commercial Chemistries

Table 1 provides an overview of the general characteristics of widely adopted legacy and commercial UPS battery chemistries, highlighting key performance metrics such as energy density, cycle life, modularity, efficiency, cost, and safety. This information emphasizes critical trade-offs among sustainability factors that are important for evaluating UPS battery performance, reliability, and suitability across different UPS applications.

Table 1. UPS-Relevant Comparison: Key Characteristics of Legacy and Commercial UPS Battery Chemistries

Parameter	VRLA	NMC Li-ion	LFP Li-ion	LTO Li-ion	Relevance to UPS Operational Features
Energy Density (Wh/kg)	30-50	~150-220 [3]	90-160 [3]	80-120	Impacts modularity and footprint: - critical for any UPS deployment constrained for space.
Cycle Life (cycles)	500-1500	1000-2000 [3]	2000-5000 [3]	10,000-20,000 [4]	Directly affects maintenance cycles, assurance/reliability of system, and total cost of ownership.
Efficiency (%)	70-80	90-95	90-95	>95	Affects energy waste and operating costs – important consideration for UPS loads with continuous operation.
Operating Temp (°C)	-40 to 71	–20 to 55	–20 to 60	–40 to 55	Impacts the environmental ability to set operating parameters and address cooling/heating issues.
Cost	Low[5]	Medium [6]	Low[6]	Low [7]	Important for footprint during scaling of deployment and ROI targeting for different UPS market segments.
Safety	Medium	Medium	High	High	Critical for mission-critical UPS system where operational survivability during a failure is mandatory.
Toxicity	Moderate to High	Higher (Co/Ni)	Low	Very Low	Relevant for environmental criteria, compliance, and recycling plan.
Response Time	Moderate [8]	Fast [9]	Fast [10]	Fast [11]	Allows recovery and conditioning of UPS, as

					well as stabilization during grid disturbances quickly.
Modularity	Limited	Good	Excellent	Excellent	Allows UPS configurations to expand and can be easily serviced and upgraded.

The key takeaways from Table 1 are summarized below:

- **NMC Lithium-Ion:** They have an energy density of 150 - 220 Wh/kg providing UPS compactness, however, cobalt-based supply and cost issues, toxicity concerns, and some thermal stability issues hinder their overall adoption.

- **LFP Lithium-Ion:** They are stable in thermal degradation, have no cobalt components, possess a long cycle life, with a less than 5% failure rate, and overall safety in general. Their reliability has started to make them more favorable than NMC systems in critical UPS applications where performance is more desirable than system size.

- **LTO Lithium-Ion:** They provide utmost safety with an ultra-long cycle life and additional advantages; however, the energy density is low at recycle time's property, following 80 - 120 Wh/kg. This also means they are larger, very expensive, and thus appropriate for high-reliability unique UPS systems.

In terms of cost, VRLA technology is still the cheapest for use in standby systems, even with the short operational life and toxicity issues. In continuous and grid interactive UPS, the wide temperature and deep discharge tolerance of the LFP and LTO chemistries make them stand out. The NMC offers high energy density, but the associated cobalt supply risks and thermal safety issues make it less appealing for mission-critical UPS systems.

4.2 Prototype, Emerging and R&D Chemistries

A summary of various definitions of prototype, emerging, and R&D UPS battery chemistries is provided in Table 2, outlining their design principles, performance potential, technical challenges, and expected benefits over conventional chemistries in the critical areas of energy density, cycle life, safety, and cost. The numbers included in the table reflect both quantitative and qualitative differences that are significant for modular UPS scaling and maintenance as well as for gathering information for future technology development pathways.

Table 2. Performance and Application Context: Prototype, Emerging and R&D UPS Battery Chemistries

Parameter	Sodium-ion	Solid-State Li-ion	Li-Sulfur	Flow (Zn-Br, VRFB)	Relevance to UPS Operational Features
Energy Density (Wh/kg)	100-160[12]	~300–400[13]	350–600[14]	15–40 [15]	Higher energy density allows UPS modules to be made small, which is necessary for some space constrained applications. Lower

					density limits modularity in a small footprint.
Cycle Life (cycles)	>3,000	~1,000	<1,000	>10,000	Longer cycle life reduces maintenance, and downstream impacts to service delivery, and reliable operation - and maintenance is required for economic efficiencies.
Efficiency (%)	~92	90–95	~76–80	70–80	Higher efficiency provides a maximum saving on energy and, more importantly - reduces the degradation in continuous operation of UPS systems.
Operating Temp (°C)	–20 to 65	–20 to 60	–10 to 40	Ambient	Wide temperature range means that UPS has flexibility in deployment without costly thermal infrastructure for maintaining temperature regimes.
Cost	Low	Higher	Low	Medium to High	Cost controls whether a system can be modular, and whether it is feasible for a large roll-out of UPS. Cost is also related to whether the technologies will be used in premium applications only.
Toxicity	Low	Very Low	Low	Low	Low toxicity means environmentally-compliant disposal and less risk in handling for critical infrastructure.
Safety	High	Higher	High	High	High safety standards, in the case of mission-critical UPS insurance against any failure, and hazard not just for

					the UPS but also wider community.
Response Time	Fast [16]	Fast [17]	Moderate [18]	Fast [19]	Fast response means instantaneous power delivery during outages; slower response limits use of technology for any critical function in a UPS type application.
Modularity	Good	Excellent	Moderate	Limited	A highly modular system allows for easy UPS system scaling and maintenance/upgrading flexibility; a lower modularity system is inherently less flexible.

UPS battery technologies continue to evolve into a variety of areas as a result of many driving forces such as safety, sustainability, and energy density. As outlined in Table 2, the above renders the following conclusions.

- **Sodium-ion:** Sustainability potential, moderate cycle life (>3000 cycles), lower energy density, potential to mitigate supply chain difficulties

- **Solid-State Li-ion:** High energy density (~300–400 Wh/kg) and safe, expensive with limited modular options today

- **Li-Sulfur:** High energy densities (350–600 Wh/kg), limited cycle life (<1000), making them difficult to use in short-term UPS applications

- **Flow Batteries:** Good cycle life (>10,000) for large stationary UPS, but limited to low energy densities (15–40 Wh/kg) and they are bulky.

For mid-term use in hybrid and standby systems where cost and sustainability matter more than energy density, sodium-ion chemistries are more promising. The safety and compactness of solid-state chemistries make them strong candidates for long-term use despite the current cost issues. Li-S batteries can be classified as high energy density batteries; however, their cycle life prevents them from being used in UPS systems. Flow batteries are great for their durability, but bulky and complex systems can only be used for large-scale stationary UPS installations.

While lithium-ion chemistries receive detailed treatment due to their current market dominance and mature data availability, emerging chemistries such as sodium-ion and flow batteries are covered in proportion to their readiness and published UPS-specific literature. Sodium-ion is a short discussion as commercial cells pertinent to UPS applications are still in the early pilot phase with few published reports regarding performance and durability. However, sodium-ion and flow batteries have sustainability benefits as well as supply security, making them viable mid-term and long-term options, and they should be more closely tracked based on available scale-up and performance innovation data.

5. Effects of Variability: Temperature, DOD, and Duty Modes

Temperature Effects

Battery performance in UPS devices is very sensitive to ambient temperature (heat is a challenge for batteries). Energy that exists in the form of electrochemicals in cells speeds up or slows down depending on temperature. LFP and LTO batteries, with stable capacity retention from −20°C to +55°C, are better suited for UPS in variable temperature environments than VRLA or NMC (see Table 1 and Section 5). All of this to say that LFP and LTO batteries are much more appropriate for mission critical UPS systems that will be subjected to uncontrolled or wide temperature fluctuations (e.g., industrial applications or outdoor installations) [20].

Depth of Discharge (DoD) Effects

Depth of discharge is considered to be one of the most important factors influencing battery life. Although a higher depth of discharge allows more energy to be tapped from the available energy, it also leads to increased stress and decay on the electrodes and thus decreased overall cycle life. For conventional batteries, such as LFP and LTO cells, which are much more resistant to battery degradation, they can operate with greater than 80% DoD with very little cycle loss. Consequently, these attributes afford them compatibility with grid-interactive UPS systems, particularly when cycling across cells and experiencing discharge events with a depth of discharge (DoD) greater than 80%. By contrast, Lead-Acid and Nickel-Cadmium batteries will degrade rapidly under high DoD rates as they will lose capacity and efficiency within hundreds of cycles if used regularly with over 50% DoD. The potential for the two lithium-ion chemistries distinctly differs from Lead-Acid and Ni-Cd, which explains why LFP and LTO chemistries are increasingly being used in renewables-integrated UPS and real-time microgrid battery support systems where deep cycling is often encountered [21].

Duty Cycle and Operational Modes

UPS batteries face different aging trajectories when operating systems in standby or cyclical/continuous cycling mode. Under standby duty, most battery chemistries can probably tolerate one to two full cycles annually with some degree of confidence when grid outages occur, without significant degradation as their rate of aging is dominantly influenced on a calendar aging basis and cycling has very little impact on their actual lifespan. Under continuous or daily cycling duty cycles, especially when electrochemical stability is stressed, a sharp difference can certainly be noticed. To repeat, LFP and LTO will again excel, as they can maintain cycle integrity after literally thousands of deep discharge cycles. Here, flow systems will also be beneficial since they are purposely designed for continuous cycling and minimal degradation rates that would be a game changer - that could fit in to data center and renewable-energy-coupled UPS systems. Of course, variability in temperature, DoD and duty cycles represent frustrating limitations on VRLA and Ni-Cd usability, while LFP and LTO chemistries demonstrate much more robust properties under more severe real-world UPS conditions. As literature has consistently demonstrated, their improved cycle stability, thermal tolerance, and tolerance for deep discharge make them the frontrunners for next-generation high reliability UPS deployment. Typically, UPS batteries will experience different cycling regimes depending on the UPS operating mode/system. Standby UPS generally experience a very low duty cycle, averaging around 1-2 full discharge events/year, where calendar aging is the leading degradation mechanism. Continuous or grid-interactive UPS systems could undergo cycling on a daily basis - possibly 250-365 cycles/year, with a depth-of-discharge (DoD) value in the range of 30%-80% per discharge event. Hybrid configurations are likely to have a moderate cycling frequency and perhaps experience some combination of shallow and deep cycles.

6. Grid-Interactive vs. Standalone UPS: Comparative Results

Grid-interactive UPS systems require batteries that can handle fast charge/discharge cycles, deep cycling, and stable output. LFP and LTO chemistries fit those requirements by exhibiting flat discharge curves indicating deep cycling and negligible memory effect. The standalone UPS is almost entirely reliant on VRLA sources because of the costs of more suitable chemistries and cycles, but also due to their rapid degradation under the 'cycling' that VRLA systems are subjected to over time. With the advent of new technologies, sodium-ion batteries have been touted as having longer life cycles and stability in performance over time on their own [22].

7. Resource Availability, Ethical Concerns, and Recyclability in UPS Battery Technologies

Nickel-Manganese-Cobalt (NMC) lithium-ion batteries face significant challenges due to resource constraints and ethical concerns associated with cobalt and nickel mining, which are concentrated in geopolitically sensitive regions and often raise human rights issues. Meanwhile, lithium itself is geographically concentrated primarily in a few countries such as Australia, Chile, and China, creating supply vulnerabilities. Although recycling and second-life battery programs for lithium-ion technology are developing, their progress remains relatively slow, limiting immediate relief for raw material demand and environmental impacts.

In contrast, Lithium Iron Phosphate (LFP) and Lithium Titanate Oxide (LTO) chemistries offer low toxicity and higher recycling rates, which reduce risks related to critical material availability and environmental harm. Advances in recycling technologies for these chemistries contribute to mitigating supply chain concerns and enhancing circular economy strategies.

Sodium-ion batteries leverage the global abundance and wide geographic distribution of sodium, enabling a robust and low-environmental-impact supply chain despite their comparatively lower energy density. This abundance offers a promising solution to the resource criticality issues facing lithium-ion batteries.

Flow batteries, utilize non-toxic and easily sourced raw materials, further supporting sustainable material use. NMC lithium-ion batteries are viewed as dominating chemistries in the medium term, though they do face challenges associated with resource limitations, particularly those related to cobalt and nickel, which are mined in geopolitically sensitive areas and raise many concerns over human rights (i.e., labor issues). In addition, lithium is also a geographically concentrated mineral and is mined or extracted from Australia, Chile, and China, leading to supply vulnerabilities as well. Many lithium-ion technologies are also exploring recycling and second-life programs, but thus far the overall progress has been relatively slow and provides limited immediate relief from raw material demands and environmental impacts.

LFP and LTO chemistries are very low in toxicity and can be recycled and reused at a high rate, making LFP and LTO materials less risky in terms of both critical material availability and environmental impact. Better recycling technologies and improvements for these chemistries have enhanced the robustness of supply chain related concerns and circular economy strategies.

Sodium-ion batteries benefit from the abundance and wide geographic distribution of sodium. Even with lower energy density than lithium-ion batteries, sodium's prominence allows for a strong supply chain with less environmental impact. Sodium is another potential remedy for the resource criticality associated with lithium-ion batteries [23].

Out of all battery chemistries, LFP and LTO stand out as the easiest to recycle and the least toxic options currently available. Meanwhile, sodium-ion batteries offer a sustainable choice with dependable supply chains, though they don't pack as much energy.

8. Advancing Battery Management Systems

New BMS AI-based controls offer active control of charging and discharging, thermal management and predictive maintenance - all of which improve the reliability and longevity of UPS batteries. It is even more valuable to manage new chemistries (for example, solid state and sodium-ion), that extend the cycle life and provide greater safety margin for end users in their operations [24].

9. Real-World Deployment Challenges of UPS Battery Technologies

Thermal management and modularity are significant factors in the real-world deployment of UPS battery technologies. Lithium-ion systems, and most notably Lithium Iron Phosphate (LFP) and Lithium Titanate Oxide (LTO) chemistries, require integrated heating and cooling for large UPS installations to satisfy constant performance and safety requirements. Without effective thermal control the performance of these batteries will degrade significantly, and simultaneously create unacceptable safety parameters to operate under variability of environmental conditions. Flow batteries and even metal–air chemistries have factors of constituent bulkiness and complexity that do not create an opportunity for modularity and diminish their viability for smaller to mid-size UPS systems. These factors of form and physical and engineering limits on their deployment are mainly relegated to essentially large stationary installations. Maintenance and replacement cycles are also critical factors related to the continued viability of UPS systems in natively maintenance susceptible environments [25].

From a maintenance and replacement perspective, LFP and LTO batteries are advantageous regarding service requirements and replacement intervals, often 8–15 years in normal UPS cycling. VRLA and Ni-Cd batteries require frequent inspections and short replacement periods (typically 3–5 years) and can require replacement in neon terms if used at high DoD or subjected to thermal stress. These distinctions also significantly affect the total cost of ownership and operational expenses on the part of institutional and industrial UPS customers. LFP and LTO chemistries have little to no ongoing maintenance and have replacement cycles that account for a much longer period of time, which revolves directly around OPEX factors for UPS operators and regions with a need for maintenance. Conversely, traditional technologies, such as lead-acid, Valve-Regulated Lead Acid (VRLA), and Nickel-Cadmium (Ni-Cd) batteries require continuous inspections, and closely timed replacement cycles, that make them entirely unsuitable for next-generation UPS systems that revolve around consistence, reliability, and uninterruptible performance.

10. Technology Roadmap: Prioritizing Chemistries for UPS

The Table 3 represents a progressive timeline of UPS battery chemistries, classifying them based on their anticipated adoption timing, and expressing their primary benefits and drawbacks related to real-world deployment.

Table 3. Technology Roadmap for Prioritizing UPS Battery Chemistries

Timeframe	Technology	Benefits	Limitations/Challenges
Short-term	LFP, LTO, VRLA	Stable, reliable, scalable	Energy density/toxicity (VRLA), cost (LTO)
Medium-term	Sodium-ion, Solid-state	Sustainability, safety, cycle life	Energy Density (Na-ion), cost (SSB)
Long-term	Li-S, Flow, Hybrid	High density, long cycle, rapid power	Cycle life (Li-S), system bulk (flow)

The technology roadmap for UPS batteries organizes chemistries relative to their level of maturity, performance benefits, and deployment challenges into three horizons: short, medium, and long-term. In the short term, VRLA chemistries continue to be widely used because of their proven history, reliability, availability, and modularity. Both LFPs and LTOs offer better safety and cycle life characteristics, while VRLA is cost-advantageous; however, the cost-associated energy density and toxicity of LTO limits its application. Looking to the medium term, sodium-ion batteries utilize numerous abundant materials and have lower environmental impacts, but less energy density than lithium-ion. Solid-state batteries have superior safety and energy densities but have high-cost manufacturing and scale-up limitations.

In the long term, lithium-sulfur, flow, and hybrid systems are expected to be some of the most transformational technologies, with attractive energy density, long cycle life, and potential for high-rate discharge. Unfortunately, Li-S batteries today are deeply constrained by overall cycle life, and flow storage systems tend to be too large, cumbersome, and complex to be flexible enough for wider adoption in smaller UPS applications. This evolving roadmap shows a balanced shift from well-established, low-cost chemistries to solution-based chemistries that can address sustainability, performance, and integration challenges that will be critical in developing the UPS technology of the future.

11. Conclusion and Future Work

The shift happening now from traditional UPS battery technologies to the next generation of chemistries is being driven primarily by the demand for greater reliability, modularity, and environmental sustainability. Lithium Iron Phosphate (LFP) and Lithium Titanate Oxide (LTO) batteries currently offer the best performance, safety, and lifecycle costs for current and prospective UPS applications. On the other hand, sodium-ion and solid-state battery technologies are evolving quickly. They have tremendous advantages with respect to a more plentiful and safe supply chain, as well as a better environmental footprint. Both technologies will be significant contenders in future UPS systems.

References

[1] Gouglidis, Antonios, Benjamin Green, David Hutchison, Ali Alshawish, and Hermann de Meer. "Surveillance and security: protecting electricity utilities and other critical infrastructures." Energy Informatics 1, no. 1 (2018): 15.

[2] Mahadevan, Vaishnavi, Maher Ali Rusho, and Simon Yishak. "Critical review of Energy Storage Systems: A comparative assessment of Mechanisms, Advantages, Challenges, and Integration with Renewable Energy." Results in Engineering (2025): 105589.

[3] Evro, Solomon, Abdurahman Ajumobi, Darrell Mayon, and Olusegun Stanley Tomomewo. "Navigating battery choices: A comparative study of lithium iron phosphate and nickel manganese cobalt battery technologies." Future Batteries 4 (2024): 100007.

[4] Cicconi, Paolo, Leonardo Postacchini, Emanuele Pallotta, Andrea Monteriù, Mariorosario Prist, Maurizio Bevilacqua, and Michele Germani. "A life cycle costing of compacted lithium titanium oxide batteries for industrial applications." Journal of Power Sources 436 (2019): 226837.

[5] Poullikkas, Andreas. "A comparative overview of large-scale battery systems for electricity storage." Renewable and Sustainable energy reviews 27 (2013): 778-788.

[6] Tournaviti, Maria, Alexandra V. Michailidou, Christodoulos Savva, and Christos Vlachokostas. "Bridging the gap between life cycle assessment and lithium-ion batteries for electrification of vehicles: A critical review towards unified frameworks." Future Batteries (2025): 100047.

[7] Orangi, Sina, Nelson Manjong, Daniel Perez Clos, Lorenzo Usai, Odne Stokke Burheim, and Anders Hammer Strømman. "Historical and prospective lithium-ion battery cost trajectories from a bottom-up production modeling perspective." Journal of Energy Storage 76 (2024): 109800.

[8] Wagner, R. "Valve-regulated Lead-Acid Batteries for Telecommunications and UPS Applications." In Valve-Regulated Lead-Acid Batteries, pp. 435-465. Elsevier, 2004.

[9] Lecompte, Matthieu, Julien Bernard, Elisa Calas, Lucas Richardet, Aurelien Guignard, François Duclaud, Damien Voyer et al. "Experimental assessment of high-energy high nickel-content NMC lithium-ion battery cycle life at cold temperatures." Journal of Energy Storage 94 (2024): 112443.

[10] Xia, Kang, Zhengyin Yao, Pengfei Zhao, Zhen Liu, Shuo Zhao, Zheng Peng, and Peng Zhang. "Enabling 10C-rate fast charging in LiFePO4 based lithium-ion battery by balancing the electronic and ionic conductivity paths in cathode." Chemical Engineering Journal 506 (2025): 160290.

[11] Mahek, Mehwish Khan, Mohamad Ramadan, Daniel S. Choi, Mohammed Ghazal, Mohammad Alkhedher, and Abdel Hai Alami. "Lithium titanate batteries for sustainable energy storage: A comprehensive review of safety, performance, and environmental impact." Journal of Energy Storage 132 (2025): 117573.

[12] Jia, Zhuangzhuang, Huang Li, and Qingsong Wang. "Experimental study on heat and gas generation characteristics of commercial sodium-ion batteries during thermal runaway." Journal of Energy Chemistry (2025).

[13] Kızılaslan, Abdulkadir, Recep Kızılaslan, Akira Miura, and Kiyoharu Tadanaga. "Mixed ion-electron conductive materials: A path to higher energy density all-solid-state lithium-ion batteries." Nano Today 60 (2025): 102556.

[14] Ding, Qian, Tianli Han, Ting Zhou, Xirong Lin, and Jinyun Liu. "A Temperature-Tolerant Magnesium-Ion Battery Using Ball Cactus-like MgV2O4 as High-Performance Cathode." Chemistry–A European Journal 30, no. 16 (2024): e202302978.

[15] Phogat, Peeyush, Subhadeepa Dey, and Meher Wan. "Powering the sustainable future: a review of emerging battery technologies and their environmental impact." RSC Sustainability (2025).

[16] He, Zidong, Yujie Huang, Huaxin Liu, Zhenglei Geng, Yujin Li, Simin Li, Wentao Deng, Guoqiang Zou, Hongshuai Hou, and Xiaobo Ji. "Anode materials for fast charging sodium-ion batteries." Nano Energy 129 (2024): 109996.

[17] Liu, Jiaxuan, Yajie Song, Qingsong Liu, Wei Zhao, Hanwen An, Zinan Zhou, Zihan Xu, Menglu Li, Biao Deng, and Jiajun Wang. "Origin of fast charging in solid-state batteries revealed by Cryo-transmission X-ray microscopy." Proceedings of the National Academy of Sciences 121, no. 51 (2024): e2410406121.

[18] Offermann, Jakob, Sheikh Najeeb Ul Haq, Kai-Xing Wang, Rainer Adelung, Shu-Hao Chang, Binson Babu, and Mozaffar Abdollahifar. "Fast-Charging Lithium–Sulfur Batteries." Advanced Energy Materials (2025): 2404383.

[19] Sharmoukh, Walid. "Redox flow batteries as energy storage systems: materials, viability, and industrial applications." RSC advances 15, no. 13 (2025): 10106-10143.

[20] Mahmud, Saifullah, Mostafizur Rahman, Md Kamruzzaman, Md Osman Ali, Md Shariful Alam Emon, Hazera Khatun, and Md Ramjan Ali. "Recent advances in lithium-ion battery materials for improved electrochemical performance: A review." Results in Engineering 15 (2022): 100472.

[21] Teague, Tyler, Shady S. Refaat, Mostafa Farrag, and Anas Karki. "A Comparative Study of UPS Batteries for Data Center Applications." In 2025 IEEE 19th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), IEEE, (2025): 1-6.

[22] Dunn, Donald G. "Lithium-Ion Battery Systems: Risk Management, Operations and Maintenance Considerations." In 2024 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC), IEEE, (2024): 1-7.

[23] Sada, Krishnakanth, Joe Darga, and Arumugam Manthiram. "Challenges and prospects of sodium-ion and potassium-ion batteries for mass production." Advanced Energy Materials 13, no. 39 (2023): 2302321.

[24] Gundebommu, Sree Lakshmi, E. Sreeshobha, and Sharvani Chapala. "Emerging Technologies in Battery Management System for Next-Generation Electric Vehicles." In 2024 IEEE International Conference on Intelligent Systems, Smart and Green Technologies (ICISSGT), IEEE, (2024): 12-17.

[25] Dilshad, Maham, Tao Li, Shern-Long Lee, and Lei Qin. "Next-Generation Aluminum-Air Batteries: Integrating New Materials and Technologies for Superior Performance." ACS Applied Energy Materials 8, no. 6 (2025): 3248-3275.