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Modern Technologies for Uninterrupted Power Supply: Breakthroughs, Significance, Vulnerabilities, Environmental Sustainability and Global Best Practices

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***Abstract* – This paper systematizes the technological landscape of assured and uninterrupted power supply systems as it stood in the mid-2020s. It shows that the industry's center of gravity has shifted from the conventional combination of "diesel generator + static UPS" toward four interrelated areas: grid-scale battery energy storage systems (BESS), grid-forming inverters, self-healing distribution networks based on FLISR algorithms, and independently operating microgrids. Quantitative evidence of this turning point is drawn from reports by the International Energy Agency, BloombergNEF, EPRI and ENTSO-E: global storage additions reached a record 108 GW in 2025 (+40 % compared with 2024), lithium-ion battery pack prices fell to USD 108/kWh, and the storage failure incident rate declined by 97 % over 2018–2023. At the same time, systemic vulnerabilities are identified: a shift in failures from cells to integration and installation, insufficient voltage and reactive power control capabilities (as confirmed by the final ENTSO-E report on the Iberian blackout of 28 April 2025), geographical concentration of manufacturing supply chains, a shortage of storage technologies with durations exceeding eight hours, and grid connection queues totaling more than 2500 GW. Environmental issues are examined through the lens of Regulation (EU) 2023/1542, which establishes mandatory recycling efficiency targets and a digital battery passport. Global best practices are summarized in tables with verified numerical results.**

***Keywords* - uninterrupted power supply; energy storage systems; grid-forming inverters; microgrids; power supply reliability; SAIDI and SAIFI; sodium-ion batteries; vanadium flow batteries; circular economy; energy transition.**

I. INTRODUCTION

1. The Cost of Unreliability

The advent of the "Age of Electricity" has changed the requirements for continuity of power supply. Global electricity consumption is growing by approximately 4 % annually, while grid infrastructure is developing more slowly: annual grid investment is around USD 400 billion and needs to increase by approximately 50 % by 2030, while more than 2500 GW of generation, storage and large electricity demand projects remain in connection queues [3, 4]. The IEA estimates direct economic losses from power outages at approximately USD 100 billion per year, equivalent to 0.1 % of global GDP [5]. At the facility level, the cost of failure is equally revealing: according to the Uptime Institute, power remains the leading cause of significant data center outages, with 57 % of respondents estimating the cost of their most recent major outage at more than USD 100,000, and one in five at more than USD 1 million [13]. The relationship between the cost of failure and the cost of backup provision has been the decisive factor in the commercial appeal of new technologies.

II. TECHNOLOGICAL BREAKTHROUGHS IN 2020–2026

1. Storage as the New Foundation of Backup Power

In 2025, global storage additions reached 108 GW, exceeding the historical peak in annual gas-fired capacity additions (approximately 107 GW in 2002). Approximately 87 GW (four fifths) came from grid-scale projects, led by China (≈60 % of additions), the United States (≈19 GW) and Europe (≈6.2 GW) [1, 2]. The functional shift is fundamental: whereas only around 40 % of projects were designed for energy shifting in 2015, the share exceeded 90 % in 2025, while the average discharge duration of new installations increased from two hours in 2023 to three hours [1]. Storage has evolved from a narrowly specialized frequency regulation device into a versatile asset that simultaneously provides backup power, relieves grid congestion and enables arbitrage.

2. An Economic Turning Point

Lithium-ion battery pack costs fell by 93 % relative to 2010, reaching USD 108/kWh in 2025; stationary storage became the lowest-cost segment for the first time, at USD 70/kWh (−45 % year on year), while the average turnkey system price fell to USD 117/kWh [7, 8]. The key drivers are the almost industry-wide transition to lithium iron phosphate (LFP) chemistry, larger cells (systems using cells of 300 Ah or more were half as expensive), and excess manufacturing capacity.

3. Grid-Forming Control

The widespread replacement of synchronous machines with inverter-based generation has required a transition from grid-following operation, in which the converter merely follows the existing grid voltage, to grid-forming operation, which establishes its own voltage and frequency reference phasor. These devices can provide synthetic

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inertia, reactive power support, islanded operation and participation in black-start procedures. This area became the main focus of regulatory discussions in Europe and Australia after 2025.

4. Diversification of Chemistries and Long-Duration Storage

Sodium-ion technology has reached industrial scale: the 50 MW / 100 MWh Datang Hubei plant maintains a round-trip efficiency of 85 % at −20 °C and withstands 1500 cycles at 60 °C, which is critical for regions with extreme climates [16]. Vanadium flow batteries have established a niche in long-duration storage: installations in Dalian (100 MW / 400 MWh) and Xinjiang (175 MW / 700 MWh) provide discharge durations of four hours or more without electrolyte degradation [17].

5. Self-Healing Grids

FLISR (fault location, isolation and service restoration) algorithms, combined with advanced distribution management systems, reconfigure the network within seconds, turning a prolonged outage into a momentary interruption for most customers.

Table 1. Trends in Key Market Indicators for Uninterrupted Power Supply Technologies [1, 2, 7, 8, 9]

Indicator	Baseline year	2025	Δ
Global annual BESS additions, GW	77 (2024)	108	+40 %
Cumulative BESS capacity relative to 2021	1.0 (2021)	≈11.0	×11
Average Li-ion pack price, USD/kWh	1474 (2010)	108	−93 %
Stationary storage battery packs, USD/kWh	≈127 (2024)	70	−45 %
Turnkey BESS, USD/kWh	169 (2024)	117	−31 %
LFP share of new additions, %	≈50 (2020)	≈90	+40 pp
Average discharge duration of new projects, h	2.0 (2023)	3.0	+50 %
Share of energy-shifting projects, %	≈40 (2015)	>90	+50 pp
BESS failure incident rate, incidents per GW	9.2 (2018)	≈0.2 (2023)	−97 %
Battery UPS additions in data centers, GW/year	≈35 (2024)	45	+30 %

III. GLOBAL BEST PRACTICES

The value of a technology is determined by reproducible, measurable outcomes rather than equipment nameplate specifications. Table 2 presents projects whose benefits have been confirmed by independent audits or operators reports.

Table 2. Verified Results of Implementing Uninterrupted Power Supply Technologies [1, 12, 13, 15, 16, 17, 18]

Practice, country	Technology and specifications	Verified quantitative result	Years
Hornsdale Power Reserve, Australia	Li-ion BESS 100→150 MW / 193.5 MWh	Consumer savings of AUD 40 million (2018) and AUD 116 million (2019), totaling >AUD 150 million over two years; reduction in frequency control ancillary services (FCAS) prices of more than 90 %; response time <150 ms	2018 – 2020
National power system, Australia	Large-scale deployment of grid storage	≈8 GW added in 2025 (9 times the 2024 level); storage accounts for ≈18 % of the country's dispatchable capacity, compared with 7 % in China, 5 % in the United States and 4 % in Europe	2025
ComEd, United States (Illinois)	Distribution grid digitalization: automatic sectionalizing switches, FLISR, ADMS	Since 2012, ≈24.7 million customer interruptions and >USD 4.3 billion in losses avoided; in 2024 alone, >400,000 interruptions avoided during a series of storms	2012 – 2025
Blue Lake Rancheria microgrid, United States	420 kW solar PV + 500 kW storage, islanded operation	Independent power supply for ≈10,000 people for 30 h during a public safety power shutoff (PSPS); savings of ≈USD 200,000/year	2019 – 2025
Datang Hubei, China	50 MW / 100 MWh sodium-ion ESS (Phase I of 100 MW / 200 MWh)	Round-trip efficiency of 85 % at −20 °C; 1500 cycles at 60 °C; meets the daily demand of ≈12,000 households; emissions reduction of ≈13,000 t CO_2/year	2024 – 2026

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Xinjiang (Ushi) and Dalian, China	Vanadium flow batteries, 175 MW / 700 MWh and 100 MW / 400 MWh	Discharge duration of 4 h or more without electrolyte degradation; the world's largest installations of this type at commissioning	2022 – 2026
Data centers (Uptime Institute global sample)	2N redundancy, lithium-ion UPS systems, software-based failure management	Frequency and severity of significant outages declining for the fourth consecutive year; share of data centers experiencing at least one significant outage over 3 years fell from 53 % to 50 %	2022 – 2026

These practices support three conclusions. The greatest returns come from combining storage with grid automation, rather than from individual installations. Savings arise primarily from ancillary services markets and avoided losses, rather than energy sales. Microgrids remain the most cost-effective solution for critical infrastructure in areas with a high probability of prolonged outages.

IV. WEAKNESSES AND UNRESOLVED ISSUES

Stability of Systems with High Shares of Inverter-Based Generation. The Iberian blackout of 28 April 2025, which left approximately 47 million people without power, was the first event of this scale in a system dominated by inverter-based resources. The ENTSO-E expert panel's final report of 20 March 2026 attributes the incident to a combination of interacting factors rather than the generation type: oscillations, gaps in voltage and reactive power control, differences in control practices, rapid reductions in power output and cascading generator disconnections [11]. The practical implication is that facility-level backup cannot compensate for a shortage of ancillary services at the power system level.

A Shift in the Nature of Failures. The storage failure incident rate declined from approximately 9.2 to 0.2 incidents per gigawatt of capacity, but the distribution of causes changed: integration, assembly and installation were the most frequent causes among classified incidents (10 out of 26 cases), rather than cells and modules [9]. Risk management is shifting its focus from cell supplier selection to the quality of engineering and commissioning. Supply Concentration and a Shortage of Long-Duration Storage. The dominance of a single region in LFP and sodium-ion cell manufacturing means that diversification of chemistries does not provide geographical supply diversification: critical infrastructure operators must incorporate spare parts inventories and maintainability into their designs, alongside unit costs. The predominance of two- and four-hour systems leaves scenarios involving multi-day generation shortfalls unaddressed, while grid connection queues remain the main constraint on the pace of deployment [3, 6].

V. ENVIRONMENTAL CONSIDERATIONS

The environmental sustainability of uninterruptible power systems has moved beyond reputation and become subject to direct regulation. Regulation (EU) 2023/1542 sets mandatory recycling efficiency targets for lithium batteries of 65 % by mass by the end of 2025 and 70 % by the end of 2030, lithium recovery targets of 50 % by 2027 and 80 % by 2031, and recovery targets for cobalt, copper, nickel and lead of 90 % by 2027 and 95 % by 2031. From 18 February 2027, a digital passport becomes mandatory for industrial batteries with a capacity above 2 kWh, while a carbon footprint declaration for industrial batteries is introduced from February 2026 [14].

Technological development is aligned with regulation. The transition to LFP chemistry has eliminated cobalt from the stationary storage supply chain; sodium-ion and vanadium systems rely on abundant raw materials, while flow battery electrolytes allow almost complete reuse. Replacing diesel backup with storage delivers direct benefits: for the Datang Hubei plant, the estimated reduction is 13,000 t CO_2 per year [16]. A sound assessment nevertheless requires a full life-cycle perspective: operational gains are partially offset by the carbon intensity of cell manufacturing, which prompted the introduction of mandatory carbon footprint declarations.

VI. CONCLUSION

The period 2020–2026 has established a new architecture for uninterrupted power supply, in which backup capability is provided through the interaction of storage, intelligent grid management and microgrids, rather than stand-alone equipment at individual facilities. The economic foundations of this transition are now in place: a 93% reduction in storage costs over fifteen years and additions of 108 GW in 2025 shift the discussion from technical feasibility to engineering quality and regulatory readiness.

The principal conclusion is that the critical point of risk has shifted: the reliability of an individual device is no longer the bottleneck; integration, ancillary services and the pace of grid infrastructure development have taken its place. The resulting priorities for practical policy are mandatory grid-forming requirements for new inverter-

based installations, independent audits of storage installation quality, development of storage with durations exceeding eight hours, and shorter grid connection lead times.

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