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Redox Flow Batteries for Long-Duration Energy Storage: Technology Overview, Market Status, and Sustainable Development Perspectives

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Abstract:
With the acceleration of the global energy transition and ambitious decarbonization targets put forward by various countries, long-duration energy storage (LDES) technology, as a core technology for solving the problem of intermittency of renewable energy sources, realizing the temporal and spatial regulation of the power system as well as supporting the deep decarbonization, has received extensive attention from both the academia and the industry. LDES batteries play an important role in the integration of renewable energy sources, such as wind and solar, due to their advantages of independent configuration of power and energy, high cycling efficiency and long lifetime. In this paper, we systematically sort out the mainstream liquid flow battery technology types such as vanadium, ferrochromium and zinc-bromine, analyze their technical characteristics and performance bottlenecks, and evaluate the market scale and regional development pattern, with a focus on typical. In the future, it is necessary to strengthen material innovation, system optimization and policy support to promote the progress of liquid flow battery technology towards higher performance, lower cost and wider application, and help the green transition and sustainable development of the global energy system.

Keywords: Redox flow battery; Long-duration energy storage; Renewable energy integration.

1. Introduction

Against the backdrop of accelerating global energy transition and countries setting ambitious decarbonization targets, long-duration energy storage (LDES) has been widely recognized by academia and industry as a core technology to address the intermittency of renewable energy, enable spatio-temporal regulation of power systems, and support deep decarbonization [1]. Liquid flow batteries play a crucial role in

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the integration of renewable energy sources. Their characteristics, such as independently configurable power and energy, high cycling efficiency, and long durability, effectively smooth out the output fluctuations of intermittent power sources like wind and solar energy. This enables load balancing, peak regulation, time-sharing storage, and emergency power supply functions [2]. The toxicity and solubility issues of current mainstream vanadium-based electrolytes have driven research toward inorganic aqueous electrolytes such as zinc, iron, and manganese, as well as high-energy-density organic materials. In system design, serpentine flow fields are recognized as the optimal structure, while optimizing carbon electrode compression rates and novel membrane materials (e.g., zeolite-based membranes) is critical for performance improvement. In the future, it will be necessary to balance cost, environmental friendliness, and stability, and extend service life through engineering innovations to adapt to the grid integration of high-proportion renewable energy [3].

The flow battery market is exhibiting a remarkable growth trend, demonstrating strong momentum and broad prospects in the global energy transition process. Additionally, the current regional landscape of the flow battery market shows significant differences: the Asia-Pacific region is currently the largest market, while markets in North America, Europe, and other regions are also experiencing notable growth and possess substantial potential [4]. Redox flow batteries demonstrate comprehensive potential to support the United Nations Sustainable Development Goals (SDGs) by efficiently storing renewable energy, enhancing equitable energy access, promoting material recycling, and enabling cross-regional technological collaboration. These capabilities contribute to sustainable energy transition, reduction of inequalities, climate action, and global cooperation [5]. The research objectives of this paper aim to systematically analyze the technical feasibility of redox flow battery (RFB) technology, characterize the current global market landscape, and forecast future development trajectories. Additionally, this study seeks to explore the synergistic potential of RFBs in advancing the United Nations Sustainable Development Goals (SDGs) through their unique technical and operational attributes.

2. Overview of Redox Flow Battery Technology

2.1 Main Technical Types of Redox Flow Batteries

Flow batteries are energy storage systems based on liquid electrolyte solutions, where electrical energy and chemical energy are converted through redox reactions of active substances in the positive and negative electrode electrolytes. These electrolytes are stored in external tanks and circulated through the cell stack by pumps to facilitate the reactions [6]. Among the main types, vanadium redox flow batteries (VRFBs) store energy in liquid electrolytes containing vanadium ions in multiple oxidation states (e.g., V^{2+} and V^{5+}), utilizing two separate electrolyte tanks to enable electrochemical reactions within the cell stack, which differentiates them from traditional solid-electrode batteries [7]. Iron-chromium redox flow batteries (Fe-Cr) use iron and chromium ions as active materials; these elements are abundant and low-cost, providing significant economic advantages. Their positive and negative electrode couples are Fe^{2+}/Fe^{3+} and Cr^{2+}/Cr^{3+}, respectively [8]. Zinc-bromine flow batteries (Zn-Br) exhibit high theoretical energy density and cost-effectiveness, making them suitable for grid-scale energy storage. However, traditional Zn-Br systems face challenges such as uneven zinc deposition and slow bromide ion reaction kinetics, resulting in short cycle life and low power density. Advances in electrode technology have improved current density, energy efficiency, and cycling stability in these batteries [9] [10].

2.2 Market Status

Flow batteries, as one of the most effective and highly regarded solutions for long-duration energy storage, have experienced rapid market expansion in recent years. The market size is projected to reach USD 340 million in 2024 and surge to USD 118 billion by 2030, with a compound annual growth rate (CAGR) of 23.0%. During the forecast period (2024–2030), the market is expected to expand by over 346 times, highlighting its immense growth potential [11]. The growth drivers can be categorized into two groups: demand-side factors, particularly the integration requirements for renewable energy, as the global surge in wind and solar installations imposes higher demands on grid stability; and competitive advantages, where flow batteries demonstrate scalability, long cycle life (>20,000 cycles), and enhanced safety, leading to significantly increased penetration in grid-scale energy storage applications.

2.3 Global Market Size

The global market distribution is primarily segmented into Asia-Pacific, North America, and Europe/other regions. The Asia-Pacific region dominates the flow battery market with approximately 45% share, driven by policy support and technological breakthroughs in commercializing flow batteries across China, Japan, and South Korea. Notably, Dalian, China is home to the world's largest vanadium redox flow battery (VRFB) project, backed by dedicated national policies to advance this technology. The North American market focuses on developing flow battery applications in microgrids and data center backup power systems, with the U.S. Department of Energy allocating $120 million in 2022 to support long-duration energy storage technologies . European markets, particularly the UK and Germany, prioritize carbon neutrality goals, implementing subsidy mechanisms to accelerate flow battery adoption in industrial and residential energy storage sectors while lowering the investment threshold for end-users .

2.4 Typical Project Cases

Dalian, China: 200 MW/800 MWh All-Vanadium Redox Flow Battery (VRFB) Project

As the world's largest flow battery energy storage facility, this project was developed by Dalian Rongke Energy Storage Technology Co., Ltd. Upon grid connection in 2023, it provides peak shaving services for 400,000 households . Its successful operation has validated the cost advantages of flow batteries in long-duration energy storage exceeding four hours, achieving a 30% lower levelized cost of storage (LCOS) compared to lithium-ion batteries . Key technological breakthroughs include an independently developed 3.5 kW-class stack (energy efficiency exceeding 80%) and low-permeability ion-exchange membranes (40% reduction in cost) .

Invinity 7 MWh Vanadium Flow Battery System, UK

Deployed in 2022 at the Oxford Energy Superhub, the Invinity system generates £2.8 million in annual revenue through dynamic electricity price arbitrage and grid frequency regulation . Featuring a modular design, the system supports hybrid operation with lithium-ion batteries, delivering a comprehensive response time under 500 milliseconds . Studies indicate its lifecycle carbon emissions are 58% lower than lithium-ion batteries, underscoring significant environmental benefits .

3. Literature References

3.1 SDG 7 Affordable clean energy

In the field of renewable energy integration, flow batteries with long-duration energy storage capabilities effectively address the intermittency issues of solar/wind power. For instance, the 700 MWh vanadium flow battery project in Xinjiang has increased wind energy integration rate by 22%, significantly reducing curtailment losses[12]. Additionally, the polysulfide-air flow battery (PSA RFB) utilizes atmospheric oxygen as the positive electrode active material, reducing electrolyte costs to 2.5 $/kWh and providing an economical power supply solution for off-grid communities[13]. In terms of cost advantage, the chlorine flow battery (CFB) achieves a material cost of only ~5 $/kWh, representing a 95% reduction compared to vanadium batteries (~100 $/kWh), thus accelerating the popularization of clean energy [14]. Empirically, a 2.5 kW/10 kWh demonstration project funded by the U.S. DOE has validated the synergistic effect of low-cost proton exchange membranes and electrolytes, achieving a 30% reduction in cost per kWh[15]. These technological innovations and case practices collectively drive dual breakthroughs in renewable energy integration and cost optimization.

3.2 SDG 9 Industrial innovation and infrastructure

In materials breakthroughs, the iron-based flow battery ($FeNTMPA_2$) uses earth-abundant elements (Fe, P), cutting raw material costs by 50% compared to vanadium-based systems and driving the upgrading of South Africa's iron ore processing industry chain[16]. Additionally, the chelated electrolyte ($Zn(PPi)_2^{6-}$) for zinc-iodine batteries has achieved industrial-scale synthesis with ton-level production capacity [17]. In structural optimization, a dual-membrane system (CEM+AEM) blocks polysulfide permeation, extending battery life to 20 years and reducing power plant maintenance costs [13]. For infrastructure enablement, the negatively charged nanoporous membrane (PES/SPEEK) for alkaline zinc-based flow batteries realizes roll-to-roll production, boosting capacity to 100,000 m^2/year [18].

3.3 SDG 12 Responsible consumption and production

In electrolyte recycling, the vanadium electrolyte leasing model achieves a recovery rate >95%, sparing users from 36.50 $/kWh of decommissioning costs[17], while the CCl_4 solvent in chlorine flow batteries can be recycled over 50 times, reducing organic waste emissions[14]. For green manufacturing, membrane-free designs eliminate PFAS pollution from perfluorosulfonic acid membrane (e.g., Nafion) production[14]. Life Cycle Assessment (LCA) shows the iron-based flow battery ($FeNTMPA_2$) has a full-life carbon footprint of 12 kg CO_2-eq/kWh, a 66% reduction from vanadium batteries (35 kg CO_2-eq/kWh)[16].

3.4 SDG 13 Climate action

In carbon reduction pathways, the direct substitution effect

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shows that 1 GWh of flow batteries replacing coal-fired peaking power plants can reduce annual carbon emissions by 100,000 tons (equivalent to planting 5.5 million trees) [12]. Indirect promotion highlights that high-proportion renewable energy grids rely on long-duration energy storage, with flow batteries supporting the penetration rate of solar/wind power to 70% [12]. For climate resilience, flow batteries' water-based electrolytes operate stably at -20°C to 60°C, adapting to extreme climates [17][18].

4. Technical feasibility analysis

4.1 Core advantages

The battery system possesses inherent safety characteristics; aqueous electrolytes such as zinc-iodine, iron-based, and chlorine flow batteries exhibit no thermal runaway risk [14][16][17]. It features long lifespan and flexibility; through its power/capacity decoupled design, a 4-hour system can be expanded to 100 hours by increasing the electrolyte volume [17]. Regarding resource sustainability, key materials iron (crustal abundance: 5.6%) and zinc (0.007%) have significantly higher reserves than vanadium (0.02%) [12][16].

4.2 Technical bottleneck

Regarding energy density shortcomings, except for chlorine flow batteries at 125.7 Wh/L, both iron-based and zinc-based systems fall below 10 Wh/L, merely one-tenth that of lithium batteries[12][16][18]. Within the efficiency loss chain, the AC-AC round-trip efficiency is only 65%, primarily due to inverter and transformer losses, while DC-DC efficiency ranges from 78 to 82%,[17]. Supply chain risks include vanadium price volatility, reaching 352 USD per kWh in 2021 while projected to decrease to 277 USD per kWh by 2030[17], concurrently, carbon tetrachloride has been listed under the POPs Convention for control, necessitating the development of mineral oil alternatives for chlorine flow batteries[14].

4. 3Industrialization path and priority

The short-term focus (pre-2025) involves implementing policies mandating energy storage deployment, such as China's "new energy + storage" model, and establishing a vanadium electrolyte futures trading market [12]. Long-term objectives (by 2030) aim to increase the market share of non-vanadium systems to 50% [12] while reducing system costs to $100/kWh to meet targets set by the U.S. Department of Energy (DOE) [15].

5. Conclusion

As an important technology in the field of long-duration energy storage, flow batteries, with their unique design concepts and excellent operating characteristics, show great potential in meeting the challenges of renewable energy intermittency and enhancing grid flexibility. Current technological advances are driving the commercialization of vanadium-based flow batteries, while the development of new flow battery materials, such as iron-based and zinc-based, provides new paths to reduce costs and enhance environmental friendliness. The market is expanding rapidly, with the Asia-Pacific region leading the global development, and the successful operation of typical projects further validates their economic and technical reliability. Flow batteries not only help realize the UN Sustainable Development Goals of clean energy supply, industrial innovation, responsible consumption and climate action, but also face technical bottlenecks such as low energy density, efficiency loss and supply chain risks. In the future, it is necessary to strengthen material innovation, system optimization and policy support to promote the advancement of flow battery technology towards higher performance, lower cost and wider application, to help the green transition and sustainable development of the global energy system.

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