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Status and Prospects of Redox Flow Batteries for Sustainable Energy Systems

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Abstract

Redox flow batteries (RFBs) present a viable option for long-duration, large-scale energy storage, which is necessary for the system to include renewable energy. Their distinct architecture allows for adjustable and adaptable storage capacity by separating the energy and power components. This study highlights developments in electrolyte formulation, membrane and electrode materials, and system design while examining important RFB chemistries, such as organic, aqueous metal-based, non-aqueous, and hybrid systems. Efficiency, stability, and affordability are increasing due to continuous advancements in molecular engineering and modular designs, despite obstacles such as high prices and low energy density. For broad adoption, market preparedness, legislative incentives, and techno-economic considerations are also essential. RFBs are positioned as a key technology for sustainable energy transitions due to their safety benefits and rapidly expanding global usage. Overcoming the last obstacles and realising RFBs' full potential for a cleaner, more resilient energy future will need sustained research and cross-sector cooperation.

Keywords: Electrode, Electrolyte, Energy Storage Devices, Membrane, Redox-Flow Battery

1. Introduction

The global transition towards sustainable energy is critical for reducing environmental deterioration and the depletion of resources[1]. In this context, the advancement of renewable energy technology has emerged as a key component of both scientific exploration and the worldwide marketplace[2,3]. To minimise the negative impacts of carbon dioxide (CO_2) emissions on the environment, it is imperative to create carbon-free power systems[4,5]. Hence, effective energy storage systems are significant in tackling issues such as rising global temperatures and increased greenhouse gas emissions produced by fossil fuel usage[6]. Energy storage devices that are affordable, highly effective, and have a long-life span are in great demand. Redox flow batteries (RFBs) are a new, large-scale energy storage technique that can efficiently connect sustainable power production and utilisation. They solve the volatility and erratic nature of renewable energy suppliers by allowing for both long-term storage and on-demand discharge[7].

RFBs are a kind of electrochemical system that uses a solution of electrolytes flowing over an electrode surface to transform chemical energy into electrical energy. A redox species undergoes reduction or oxidation at the electrode surface. An ion-exchange membrane divides the RFB into two half-cells. These membranes keep the active species from passing while permitting some ions to move easily,

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balancing the charge of the cell. The electrolyte solution is called the anolyte in the half-cell with the anode, and the catholyte in the half-cell with the cathode. Electricity is brought in, stored, or released through electrolyte flow, redox reactions, and ion-exchange processes that propel electrons across an external circuit[8]. A general schematic of a redox flow battery is displayed in Figure 1.

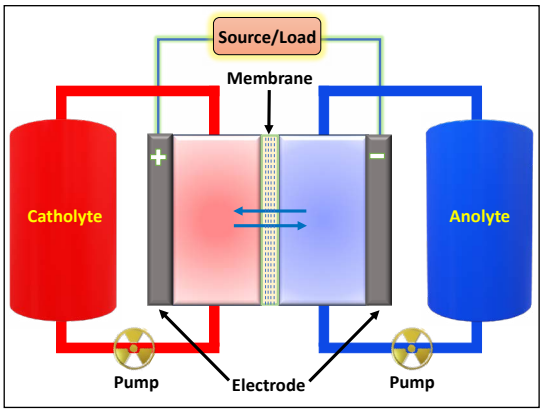


Figure 1. General schematic of a redox flow battery.

RFBs can function similarly to a fuel cell, which continuously supplies fresh fuel for conversion into power; however, they are usually used as a secondary battery. The capacity to store the electrolyte solution externally, apart from the electrochemical cell, is the primary distinction between RFBs and secondary batteries. This special characteristic makes it possible to separate power and energy, allowing each to be adjusted independently. In this manner, simply adding more electrolyte solution can boost the energy storage capacity. As RFBs are readily scalable to satisfy expected energy storage requirements, they have a clear benefit in grid energy storage of intermittent sources[8]. However, other areas, including energy density, the creation of cost-effective components and flow system optimisation, need further research before they are massively scaled up and implemented. Going forward, the next generation of redox flow battery designs will rely on innovative molecular engineering, advanced membranes, and cost-effective scale-up strategies that reduce complexity while boosting energy density. Designing high-energy materials with tunable thermodynamics and stability (such as bio-inspired or computationally guided scaffolds) is a promising pathway[9].This article presents the fundamental concepts, specifications, and recent research findings for each system component, along with the future outlook and promising research avenues for RFBs. A comparative evaluation of different electrolyte chemistries, highlighting variations in voltage windows, energy-related metrics, and operational constraints, is also provided. This is followed by a techno-economic discussion emphasising capital expenditure (CAPEX), operating expenditure (OPEX), and levelised cost of storage (LCOS), with identification of key cost-driving components. Finally, the article outlines the current technology readiness levels (TRLs) of major systems and summarises future research directions.

2. Chemistries of Redox Flow Batteries

Based on electrolyte chemistry and system architecture, redox flow batteries can be classified into organic redox

Table 1. Comparative summary of different RFB electrolyte systems[10,11]

Electrolyte Type	Voltage Range	Energy Metrics	Advantages	Disadvantages	TRL Level
ORFBs	~1.0–2.0 V	Moderate energy density and tunable	Low-cost, tunable Redox molecules and sustainable	Stability issues and solubility limits	2–4 (early stage to lab-scale)
AMBRFBs	~0.8–1.5 V	Low, moderate and high power	Safe, non-flammable and high ionic conductivity	Low cell voltage and large tank volume	7–9 (commercial/near-commercial
NARFBs	~2.0–3.5 V	High potential energy density	Higher cell voltage and flexible design	Expensive, flammable and low conductivity	3–4 (lab-scale)
HRFBs	~1.3–1.8 V	Improved energy density	High energy density and reduced crossover	Electrolyte imbalance and complex design	5–7 (pilot scale)

flow batteries (ORFBs), aqueous metal-based redox flow batteries (AMBRFBs), non-aqueous redox flow batteries (NARFBs), and hybrid redox flow batteries (HRFBs). Each system has its own redox chemistry, depending on the electrolyte (either the catholyte or the anolyte) and the electrode materials. Table 1 summarises the RFBs with their electrolyte type, voltage range, energy metrics, pros and cons, and current TRL level.

2.1 Organic Redox Flow Batteries (ORFBs)

ORFBs have emerged as a promising candidate due to the cost-effectiveness, abundance, and flexible structure of organic redox-active molecules[12]. Thanks to advances in synthetic chemistry, researchers have developed various organic compounds, such as quinones, viologens, and TEMPO derivatives, with improved solubility, stability, and redox kinetics[13]. Organic systems can be tailored to enhance electrochemical performance, including multi-electron transfer reactions and broader voltage ranges[14]. Non-aqueous systems offer access to higher voltages by avoiding water decomposition and limits. However, challenges remain in maintaining long-term molecular stability, reducing crossover through membranes, and developing cost-effective synthesis techniques at scale. Continuous innovation in materials and electrolyte design is crucial to unlocking the full potential of ORFBs for grid-scale and decentralised energy storage[15].

2.2 Aqueous Metal-based Redox Flow Batteries (AMBRFBs)

AMBRFBs are among the most mature and widely researched flow battery systems, particularly for grid-scale energy storage[8]. AMBRFBs continue to represent a strong candidate for stationary energy storage, particularly in applications where safety, scalability, and cost-effectiveness are prioritised over energy density[16]. These systems employ metal ions dissolved in water-based electrolytes, benefiting from the safety, non-flammability, and low cost of water as a solvent[17]. One of the best-known examples is the all-vanadium redox flow battery (VRFB), where vanadium ions in different oxidation states act as both anolyte and catholyte. This symmetric configuration minimises capacity loss due to crossover and simplifies electrolyte management[18]. The use of other metal pairs, such as Fe/Cr, Zn/Br, and Fe/V, has also attracted attention due to their abundance and potential cost advantages. Iron-based systems, in particular, offer high reversibility and low toxicity, while zinc-based chemistries enable high theoretical energy densities and are often used in hybrid formats with solid plating on the anode[19]. Despite these advantages, aqueous systems face critical challenges, among them being the limited electrochemical stability window of water (~1.23 V), which constrains the cell voltage and, consequently, the overall energy density. Furthermore, issues such as hydrogen evolution at low potentials and oxygen evolution at high potentials can lead to efficiency losses and degradation of cell components over time[20]. To address these limitations, recent efforts have focused on improving electrolyte formulations, such as the addition of mixed acids (e.g., sulfuric and hydrochloric acid) to enhance solubility and suppress precipitation. Advanced membrane materials with lower ionic resistance and reduced crossover are also being developed to improve cycle life and coulombic efficiency[21].

2.3 Non-aqueous Redox Flow Batteries (NARFBs)

To achieve a leap in energy density and reach low-cost targets, attention has increasingly shifted to nonaqueous systems. NARFBs offer a wider electrochemical potential window, often exceeding 4 V, due to the absence of water electrolysis limits[22]. This opens the door for high-voltage redox couples and multielectron transfer reactions, both of which directly enhance energy density. For instance, functionalized organic molecules and metal-ligand complexes dissolved in solvents like acetonitrile or dimethyl sulfoxide (DMSO) have shown impressive redox performance, including stable multi-electron storage and tunable redox potentials[23,24]. Moreover, many organic active species can form unstable radical intermediates or degrade over time unless stabilised via resonance or steric hindrance. This remains a critical challenge in NARFB design, requiring engineered molecular scaffolds for chemical stability. However, these advantages come at a cost. Nonaqueous solvents typically exhibit lower ionic conductivity and higher viscosity compared to water, resulting in greater internal resistance and less efficient mass transport. Additionally, many organic active species form unstable radicals or degrade over time unless chemically stabilised through steric hindrance or resonance effects[9]. Material compatibility is also a concern, as nonaqueous electrolytes can degrade polymer-based components and require more robust containment infrastructure, increasing system complexity

and cost. Hybrid approaches and additives (e.g., ionic liquids or deep eutectic solvents) have been explored to mitigate these issues, though trade-offs exist in solubility, viscosity, and safety[25].

2.4 Hybrid Redox Flow Batteries (HRFBs)

Recent research explores hybrid systems that combine aqueous safety and conductivity with nonaqueous voltage and energy advantages, such as semi-aqueous solvents, hybrid metal-organic redox couples, and redox targeting schemes. These approaches aim to regenerate solid active materials via flowable mediators and improve performance while containing complexity[26]. Hybrid Redox Flow Batteries (HRFBs) occupy a unique middle ground between traditional flow batteries and solid-state systems, offering a promising pathway to balance energy density, operational simplicity, and cost. Unlike conventional redox flow batteries, which use fully soluble redox couples in both half-cells, HRFBs utilize a combination of one soluble redox couple and one solid-state electrode. This design enables the use of high-capacity, metal-based anodes such as zinc, iron, or lithium, while retaining the scalability and decoupled power/energy design advantages of flow systems[27]. One of the most widely studied HRFB systems is the zinc-bromine battery. In this system, energy is stored via the plating and stripping of zinc metal at the anode, while bromine undergoes a redox reaction in the catholyte. The use of solid zinc dramatically enhances the theoretical energy density compared to fully dissolved systems, making HRFBs suitable for stationary storage applications where footprint and cost per kWh are key considerations[28]. Despite these advantages, HRFBs face unique technical hurdles. Dendrite formation during metal deposition, particularly for zinc and lithium, poses risks for short-circuiting and long-term stability. The reactivity of metallic species also demands careful selection of separator and electrolyte materials to suppress parasitic reactions and self-discharge[29]. Furthermore, managing the interface between solid and liquid phases is critical for ensuring efficient charge transfer and minimising polarisation losses. To address these challenges, recent research efforts have focused on electrolyte additives that promote uniform plating, the development of self-healing or three-dimensional electrode architectures, and advanced separators with selective ion transport properties[30]. Additionally, integrating HRFB systems with real-time monitoring and control algorithms can mitigate operational risks and extend cycle life. From a techno-economic perspective, HRFBs have the potential to reduce material costs by utilising abundant metals and avoiding the costly ion-exchange membranes used in symmetric flow batteries[31]. Their simplified stack design, paired with modular tank-based energy scaling, makes them attractive candidates for behind-the-meter storage, microgrids, and backup systems.

3. Design Innovations and System Integration in RFBs

3.1 Membrane and Electrode Materials

The performance and longevity of RFBs are fundamentally governed by the nature and compatibility of the membrane and electrode materials used within the electrochemical cell. A well-designed membrane serves as a selective barrier, allowing ion conduction while minimising active species crossover, thus preserving coulombic efficiency and mitigating capacity decay. Advanced ion-exchange membranes like sulfonated poly(ether sulfone) (SPES) or composite SPES/PVA have shown better selectivity and stability compared to Nafion in vanadium RFBs[32]. Traditionally, perfluorosulfonic acid (PFSA) membranes have been widely used in vanadium redox flow batteries due to their chemical stability and proton conductivity. However, their high cost, limited selectivity for non-proton-conducting ions, and susceptibility to swelling in organic or nonaqueous systems have prompted the search for alternatives[32,33]. Emerging strategies focus on low-cost hydrocarbon-based membranes, composite ion-conducting films, and microporous separators, each tailored for specific chemistries like organic or nonaqueous redox couples. Examples include porous polyethene Daramic membranes coated with poly(vinyl alcohol) or ceramic-S-x hybrids in iron-based systems, offering better chemical resistance and reduced crossover[34]. These designs aim to enhance ion selectivity, reduce electrolyte crossover, and withstand aggressive chemical environments, especially in hybrid and nonaqueous RFBs. Composite or mixed-matrix membranes embedding graphene oxide, MoS_2, or MOFs have been shown to suppress active species diffusion while maintaining good proton conductivity[35]. Functional modifications, such as sulfonation, cross-linking, or the incorporation of ionic liquids and nanofillers, have shown promise

in improving ion transport while retaining structural integrity under diverse operating conditions. Surface-coating techniques (e.g., Ag nanolayers, polyelectrolyte coatings) and nanofillers (e.g., g-C_3N_4 nanosheets) have successfully enhanced selectivity and reduced swelling[36]. Simultaneously, electrode development has advanced from using simple carbon felts to engineered structures with enhanced surface area, tailored porosity, and catalytic activity. Thermal activation of carbon felts significantly increases their surface area and introduces oxygen functional groups, boosting vanadium redox kinetics. Modifications such as thermal activation, doping with heteroatoms (e.g., nitrogen or phosphorus), and coating with metal or metal oxide catalysts significantly improve reaction kinetics, especially for sluggish redox couples. Graphene-enhanced felt electrodes treated via low-pressure gas plasma have achieved energy efficiencies above 90 % at high current densities[37]. Additionally, compressibility, wettability, and electrical conductivity are essential considerations in optimising electrode performance, particularly in flow-by and zero-gap cell designs.

3.2 Modular System Architectures

The scalability and flexibility of RFBs derive from their inherently decoupled power and energy components. Modular architectures enable independent scaling of tank volume and stack size, allowing flexible adaptation to residential or utility needs[35]. However, effective system integration, especially at scale, demands innovative modular architectures that can maintain high efficiency while minimising system complexity. Uniform electrolyte distribution and low pressure drop across stacks are essential; recent topology optimisation efforts help reduce flow-channel maldistribution[38]. Flow battery stacks, which comprise multiple repeating cells sandwiched between bipolar plates, must ensure uniform electrolyte distribution, low internal resistance, and minimal pressure drop across the entire stack. Interdigitated, serpentine, and spiral channel geometries have been optimised to support these requirements at scale[39]. Recent innovations in flow field design, such as interdigitated, serpentine, and spiral geometries, seek to optimise mass transport and reduce electrolyte maldistribution. These designs enhance reactant penetration and raise limiting current densities in zero-gap configurations[38]. Flow-by configurations have emerged as superior to flow-through designs in large-scale systems due to their reduced pressure drop and compatibility with thinner electrodes. Comparative studies show that flow-by systems enable the use of thinner electrodes and better pumping efficiency in large-scale vanadium setups. The development of zero-gap architectures, where the membrane and electrode are pressed tightly together, further enhances volumetric efficiency and reduces ohmic losses[39]. Additionally, modularity in tank and stack configuration offers flexibility for a wide range of applications, from residential backup to utility-scale grid support. Smart system control strategies that adapt flow rate, temperature, and voltage in real time have begun to integrate with digital twin models and AI-driven diagnostics to predict maintenance needs and optimise performance over long durations[34]. As the RFB field progresses, future system architectures will likely emphasise plug-and-play modules, self-healing components, and cross-platform compatibility, all geared toward reducing installation and operational costs while enhancing reliability.

4. Techno-economic Considerations for RFBs

4.1 Cost Drivers in Novel RFB Systems and Levelised Cost of Storage (LCOS)

The adoption of RFBs for large-scale energy storage hinges primarily on cost. Among the key determinants are electrolyte costs, membrane durability, stack manufacturing, and balance-of-plant components such as pumps and power electronics. Sensitivity analyses of a 10 kW/120 kWh VRFB system show that stack components (gaskets, bipolar plates, felts) and electrolyte costs dominate the total system cost[40]. Traditional systems like vanadium RFBs face challenges due to the high and volatile prices of vanadium salts, which contribute significantly to capital costs, prompting a shift toward lower-cost alternatives such as iron, organic molecules, or hybrid systems[41]. One of the most holistic metrics to evaluate economic viability is the LCOS, which accounts for total lifetime costs, including capital, operation, maintenance, and replacement, divided by total energy delivered over the battery's lifespan[42]. Achieving an LCOS below $150/kWh is often cited as a target for grid-scale viability, especially for durations beyond four hours[43]. Systems leveraging low-cost, earth-abundant materials (e.g., iron, sulfur, or organics) show potential to meet

these targets, especially when integrated with efficient system design, modular stacks, and longer cycle life[41]. Electrolyte stability, membrane fouling, and degradation are other significant cost drivers. Membrane innovations that reduce crossover while maintaining low resistance and long-term stability are vital to lowering LCOS. Similarly, innovations such as slurry-based electrodes, as explored in all-iron flow systems, aim to decouple energy and power scaling, offering a path to lower material and component costs without compromising performance[40].

4.2 Market Readiness and Deployment Barriers

While RFBs have achieved commercial demonstrations, their market share remains limited compared to lithium-ion technologies. One of the main barriers is their relatively lower energy density, which restricts use in space-constrained applications. Additionally, the market's familiarity with and established infrastructure around lithium-ion technology create inertia that RFBs must overcome by offering better value propositions for long-duration storage[43]. Another challenge is the technology readiness level (TRL). Many promising RFB chemistries remain at the lab or pilot scale. The transition from lab demonstration to field deployment is often hindered by the so-called 'valley of death', where funding for scale-up is difficult to secure[44]. As observed in recent ARPA-E-funded projects, the lack of flexible funding models and the pressure to quickly demonstrate large-scale prototypes can lead to premature scale-ups, design inefficiencies, or failed demonstrations due to unoptimized materials or system integration issues[45].

4.3 Incentives for Long-duration Storage

To encourage adoption, policy-level incentives are essential, especially those targeting long-duration storage (>8 hours), where RFBs naturally excel. Time-of-use electricity pricing, grid stabilisation programs, and renewable energy integration mandates can all support the economic case for RFBs[46]. Furthermore, tax credits, like the Investment Tax Credit (ITC) in the United States or feed-in tariffs in other regions, have the potential to reduce upfront investment burdens. Government-supported pilot programs and guaranteed procurement contracts for stationary storage solutions can also provide the necessary pull for private investment, helping novel RFB systems bridge the commercialisation gap[47].

4.4 Standardisation and Safety Guidelines

Unlike the lithium-ion industry, which has well-established standards for safety, manufacturing, and testing, the RFB sector still lacks universal guidelines[43]. The absence of standardised testing protocols, certified safety benchmarks, and performance reporting formats makes it difficult for stakeholders to compare technologies or evaluate vendor claims. As the industry matures, harmonising standards will be crucial for large-scale procurement and bankability. RFBs offer inherent safety advantages, such as non-flammable electrolytes, low risk of thermal runaway, and ease of monitoring, but still require robust safety validation to meet regulatory requirements. Accelerated life-cycle testing, real-world field trials, and third-party certification will play essential roles in establishing trust in the technology.

4.5 Global Deployment Trends

Globally, several countries are recognising the strategic importance of long-duration energy storage and are initiating deployment programs for RFBs. China currently leads in large-scale vanadium flow battery projects, including multi-megawatt installations for grid support[48]. Europe and the United States are investing in R and D for organic and hybrid RFB chemistries, often tied to decarbonisation and grid flexibility goals[49]. However, sustained growth in RFB deployment depends on collaborative efforts between academia, industry, and policymakers. Investment in local supply chains, modular manufacturing capabilities, and international partnerships can catalyse broader adoption, especially in regions with high renewable energy penetration and variable grid demands. Figure 2 highlights the techno-economic breakdown of RFB systems[50].

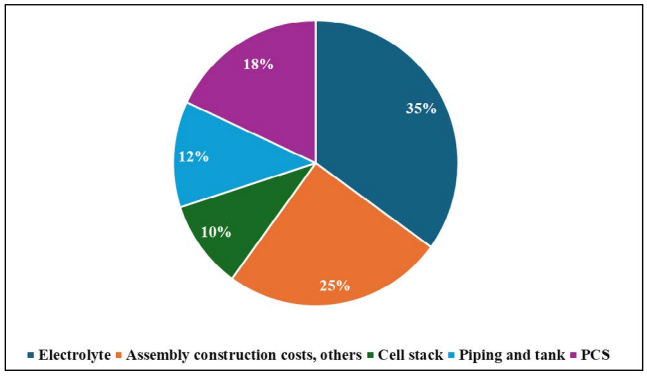


Figure 2. Techno-economic breakdown of RFB systems.

5. Conclusion

Redox flow batteries are at the forefront of environmentally friendly energy storage technologies and are ideally positioned to handle the pressing issues brought on by the growing use of intermittent renewable energy sources. They offer unmatched versatility for a variety of grid and decentralised applications because of their modular architecture, scalability, and capability to separate power from energy. There are still plenty of chances to increase energy density, lower prices, and improve long-term durability despite the impressive advancements in electrolyte chemistries, membrane and electrode materials, and system topologies. New developments in membrane technology, organic and hybrid redox systems, and intelligent system integration are opening the door to next-generation RFBs that blend excellent performance with financial feasibility. However, achieving their full potential would need concerted efforts across material science, techno-economic optimisation, molecular engineering, and supporting policy frameworks. Redox flow batteries have the potential to become a key technology for dependable, secure, and reasonably priced long-duration energy storage by encouraging cooperation between government, business, and academia. This would enable a planet with a cleaner and more resilient energy future.

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