# Flow Batteries as Energy Storage Systems: A Survey

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## Abstract

Flow batteries, particularly redox flow batteries (RFBs), are pivotal in advancing energy storage solutions due to their scalability, safety, and cost-effectiveness. These systems facilitate the efficient conversion and storage of electrical energy through reversible redox reactions, making them ideal for integrating intermittent renewable energy sources into the grid. Recent advancements, such as the use of bromide ions to enhance iodide capacity, have achieved record energy densities, underscoring their potential in robust energy storage applications. The development of novel electrolyte systems and the visualization of energy dynamics within redox-active colloids offer new insights into optimizing flow battery performance. Despite their promise, flow batteries face challenges related to material limitations, electrochemical stability, and complex modeling requirements. Addressing these issues is critical for enhancing their efficiency and scalability. Future research should focus on developing cost-effective materials, optimizing micro-emulsion compositions, and improving membrane technologies to overcome current limitations. As these technologies evolve, flow batteries are set to play a transformative role in creating sustainable and resilient energy infrastructures, supporting the transition to cleaner energy systems and the widespread adoption of renewable resources. This survey highlights the significance of ongoing advancements and the necessity for continued innovation to fully realize the potential of flow batteries in modern energy systems.

## 1 Introduction

### 1.1 Concept of Flow Batteries

Flow batteries, commonly referred to as redox flow batteries (RFBs), represent a pivotal advancement in electrochemical energy storage systems, distinguished by their capacity for efficient and cost-effective large-scale energy storage [1]. These systems operate on the principle of electrochemical cells where two chemical components, dissolved in liquid electrolytes, are separated by a membrane, facilitating the conversion and storage of electrical energy via reversible oxidation and reduction reactions. The modularity and durability of RFBs render them particularly promising for stationary energy storage applications [2].

The importance of flow batteries in energy storage is further accentuated by their role in integrating renewable energy sources into the electrical grid. Given the intermittent nature of renewable energy generation, flow batteries are crucial for storing surplus energy produced during peak times and discharging it during periods of low production, thereby ensuring grid stability and reliability [3]. Recent advancements in redox flow battery chemistries, such as the Nickel Vanadium Redox Flow Battery (NVRFB) and Titanium Manganese Redox Flow Battery (TMRFB), demonstrate the potential for higher charge densities and environmentally friendly properties .

Aqueous polysulfide/iodide redox flow batteries are particularly noteworthy for their high energy density and cost-effectiveness, broadening their applicability across diverse sectors [4]. The continuous development and commercialization of RFBs for utility-scale energy storage highlight both the technical progress and the challenges inherent in optimizing these systems for widespread adoption

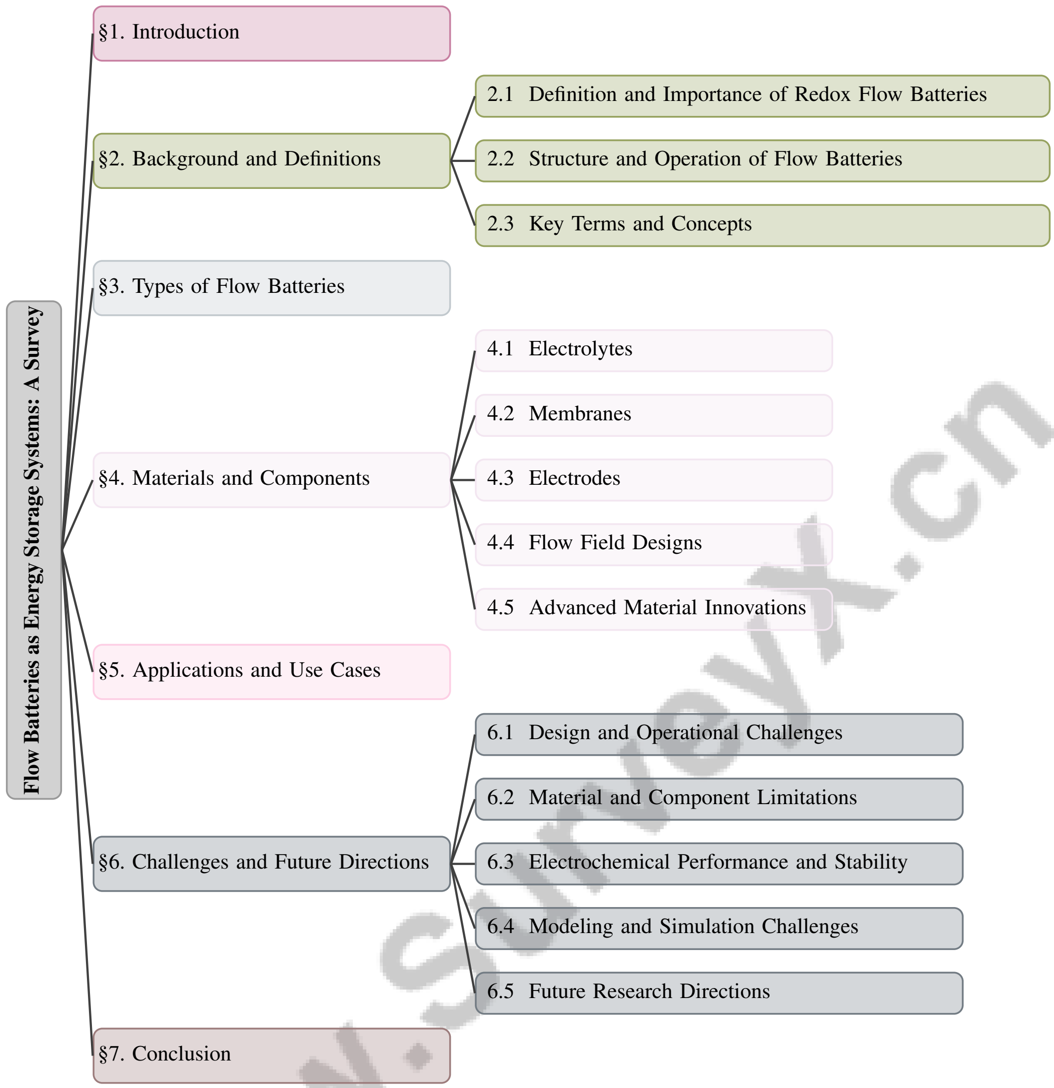


Figure 1: chapter structure



[5]. The adaptability and robustness of flow batteries in managing various operational constraints further solidify their potential as a foundational technology for future energy infrastructure [6]. Additionally, the drive to reduce the cost of redox-flow battery systems, especially in comparison to lithium-ion batteries, remains a significant focus in the field [7]. This is complemented by efforts to enhance the performance and stability of polymer membranes specifically designed for all-vanadium redox flow batteries, which are crucial for renewable energy storage [8].

Moreover, aqueous organic redox flow batteries (AORFBs) are gaining momentum in renewable energy storage due to their cost-effectiveness, environmental benefits, and scalability [9]. Non-aqueous redox flow batteries also present a promising avenue for large-capacity, reversible energy storage capable of responding to the dynamic demands of the electrical grid [10].

### 1.2 Role in Energy Storage Systems

Flow batteries, particularly redox flow batteries (RFBs), are integral to modern energy storage solutions due to their scalability and ability to efficiently manage the variability of renewable energy sources . These systems provide a crucial mechanism for storing excess energy generated during peak production periods and releasing it during times of low generation, thereby ensuring a stable and reliable electricity supply [11]. The vanadium redox flow battery (VRFB) stands out as the most commercially mature RFB technology, valued for its robust chemical stability and performance, despite challenges related to cost and efficiency .

Addressing the limitations of traditional systems, such as the limited energy density and stability of charge carriers in non-aqueous redox flow batteries, remains a critical area of research [10]. Innovations in modeling complex transport and electrochemical processes within flow batteries are pivotal for enhancing their performance and reducing costs . Furthermore, the discovery and integration of aqueous soluble organic redox-active materials, supported by machine learning techniques, are advancing the predictive capabilities and efficiency of these systems [9].

The advancements in redox flow batteries (RFBs) highlight their critical role in energy storage systems, especially for medium to large-scale applications, as they offer unique advantages such as peak shaving, frequency regulation, and enhanced grid stability in conjunction with renewable energy sources. Recent progress in standardization, safety, and recycling regulations has bolstered their commercial viability, while ongoing research into flow field designs and the optimization of electrolyte and electrode materials promises to further improve their efficiency and longevity. As a result, RFBs are emerging as indispensable elements in the transition towards a sustainable and resilient energy infrastructure, capable of supporting the integration of intermittent renewable energy sources like solar and wind power. [12, 13, 5, 14]. The ongoing research and technological advancements are expected to overcome existing challenges, facilitating the broader adoption and integration of flow batteries into the energy grid.

## 1.3 Importance in Renewable Energy Integration

Flow batteries play a pivotal role in the integration of renewable energy sources into the electrical grid, offering a solution to the challenges posed by the intermittent nature of energy generation from renewables. The Nickel Vanadium Redox Flow Battery (NVRFB) and the Titanium Manganese Redox Flow Battery (TMRFB) exemplify advancements in flow battery technology that provide high energy density and reduced costs, which are critical for effective renewable energy integration . Revised Sentence: "These advanced energy storage systems, such as alkaline zinc-based flow batteries, effectively capture and store surplus energy generated during peak periods of renewable energy production, allowing for its efficient release during times of low generation. This capability not only enhances the reliability of the energy supply but also contributes to the stability of the electrical grid by mitigating the challenges posed by intermittent renewable sources." [15, 14]

Moreover, the integration of advanced laboratory automation systems, such as ORGANA, supports the evolution of flow battery chemistries by enabling rapid adaptation to new experimental conditions and enhancing the efficiency of research and development processes [16]. This technological synergy accelerates the advancement of flow battery systems, making them more adaptable and robust for large-scale deployment in renewable energy applications.

The advancement of redox flow batteries, which are designed for medium to large-scale stationary energy storage, is crucial for effectively integrating renewable energy sources into the electrical grid. These batteries not only enhance grid stability by accommodating the intermittent nature of renewable energy but also offer multiple service functions, such as peak shaving and rapid response to frequency and voltage fluctuations. Addressing global energy constraints and reducing environmental pollution will require ongoing research into the optimization of flow battery components, including electrolyte flow dynamics, electrode design, and system scalability, to ensure their commercial viability and environmental sustainability. [5, 14]. By providing a scalable and sustainable energy storage solution, flow batteries contribute significantly to the transition towards a cleaner energy future, underscoring their importance in modern energy infrastructures.

## 1.4 Structure of the Survey

This survey paper is systematically organized to provide a comprehensive overview of flow batteries, focusing on their significance as energy storage systems in the context of renewable energy integration. The paper opens with a comprehensive overview of flow batteries, emphasizing their pivotal role in contemporary energy storage systems and their essential function in facilitating the integration of intermittent renewable energy sources into the electrical grid. It discusses the unique operating principles of rechargeable redox flow batteries, which distinguish them from traditional battery technologies. Additionally, the paper highlights recent advancements in flow battery design,



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including considerations related to electrolyte flow velocity, mass transfer, and the importance of long-term evaluations of electrode and membrane durability for utility-scale applications. Through this exploration, the paper underscores the growing significance of flow batteries in enhancing grid stability and supporting the transition to renewable energy. [5, 14]. Following this, the paper delves into the background and definitions, offering detailed explanations of flow batteries, including their structure, operation, and key terminologies.

The subsequent section explores the various types of flow batteries, such as vanadium redox flow batteries, zinc-bromine flow batteries, and organic redox flow batteries, each with its unique characteristics, advantages, and limitations. This is followed by a discussion on the materials and components integral to flow batteries, examining the roles of electrolytes, membranes, electrodes, and flow field designs, as well as recent material innovations that enhance battery performance.

The paper then transitions to applications and use cases, highlighting the diverse roles flow batteries play in grid-scale energy storage, electric vehicles, and energy market participation. The penultimate section addresses the challenges and future directions in flow battery technology, identifying current limitations and potential research avenues to overcome these obstacles. Finally, the conclusion synthesizes the key points discussed, reflecting on the transformative potential of flow batteries in future energy systems.The following sections are organized as shown in Figure 1.

# 2 Background and Definitions

## 2.1 Definition and Importance of Redox Flow Batteries

Redox flow batteries (RFBs) represent a unique class of electrochemical energy storage systems, characterized by the use of liquid electrolytes with dissolved redox-active species stored in separate tanks. These electrolytes circulate through an electrochemical cell, where they are divided by a membrane, facilitating energy storage and conversion via reversible redox reactions [17]. A notable advantage of RFBs is their ability to independently scale power and energy capacities, making them ideal for large-scale applications [5].

RFBs are strategically important for managing the variability of renewable energy sources by storing excess energy during peak periods and releasing it when generation is low, thereby supporting grid stability and reliability [7, 5]. Among RFB types, vanadium redox flow batteries (VRFBs) are the most commercially advanced, though often limited by the low electrochemical activity of graphite felt electrodes [18]. Innovations like micro emulsion electrolytes enhance the safety and performance of organic redox flow batteries (ORFBs) [19], and 3D printed conductive static mixers address power density limitations by improving redox kinetics [20].

Challenges persist, such as capacity loss due to inefficient mixing, impacting charge utilization [21]. Optimizing polymer membranes is critical for improving ion exchange and chemical stability in VRFBs [8], while capacity losses in aqueous organic-organometallic RFBs limit efficiency [22]. Research continues to address these issues, with innovations like polyoxovanadate-alkoxide clusters offering promising performance improvements for non-aqueous RFBs [10]. As these technologies advance, RFBs are poised to play a transformative role in renewable energy adoption.

## 2.2 Structure and Operation of Flow Batteries

Flow batteries, particularly RFBs, feature a distinctive structural design that enhances energy storage and conversion efficiency. The flow field is engineered to optimize electrolyte distribution across electrodes, boosting electrochemical reactions and overall performance [23]. Porous electrodes facilitate fluid, mass, and charge transport, which are crucial for maximizing efficiency.

The operation involves circulating liquid electrolytes through an electrochemical cell, where they undergo redox reactions at electrodes separated by a membrane. This setup allows for independent scaling of power and energy capacities, making RFBs suitable for medium to large-scale applications [24]. In VRFBs, vanadium electrolyte solutions undergo redox reactions to store and release energy [21].

Innovations like micro-emulsion-based electrolytes, which are stable dispersions of immiscible liquids, enhance electrochemical characteristics in ORFBs [10]. Additionally, 3D-printed conductive static mixers improve charge transfer and performance by enhancing slurry electrode mixing [25].

Electrolyte viscosity influences flow properties and battery performance [9], with flow dynamics being critical for performance in alkaline zinc-based flow batteries [15].

The modular design, strategic use of electrolytes and electrodes, and continuous component optimization define flow batteries. Advanced design considerations, such as optimized flow fields and effective electrolyte management, enhance their versatility and effectiveness as energy storage solutions, supporting renewable integration and grid stability [26, 12, 5, 14].

### 2.3 Key Terms and Concepts

Understanding flow batteries involves several key terms and concepts. 'Redox-active colloids' (RAC) and 'charge transfer kinetics' are vital for understanding energy dynamics in colloidal systems, where colloid-electrolyte interactions impact energy transfer efficiency [27]. The 'Nernst relation' and 'open-circuit voltage (OCV)' are fundamental principles describing the relationship between reactant and product concentrations in electrochemical cells, influencing voltage output [28].

'Porous carbon' and 'nitrogen doping' techniques enhance electrochemical performance by increasing electrode surface area and conductivity, improving energy storage [29]. The non-linear nature of battery efficiency functions, dependent on variables like charging power and state of charge, complicates optimization [2].

The 'flow field' is critical, affecting electrolyte distribution across electrodes to enhance reactions. Optimizing flow fields and stacks is crucial for improving rechargeable RFB performance in large-scale applications [14]. The 'Mixed-Convection Flow Model' (MCFM) simulates mixed-convection flow of vanadium electrolytes, optimizing mixing and efficiency [21].

Additionally, using gallium-indium eutectic alloy (EGaIn) as a moldable electrode contact improves measurement accuracy of through-plane electrical conductivity (tp), independent of pressure, enhancing electrode characterization [30]. Understanding these concepts is essential for advancing flow battery technologies and optimizing performance for various energy storage applications.

## 3 Types of Flow Batteries

Flow batteries are critical in energy storage, offering unique advantages and diverse applications. This section examines various types, focusing on their operational mechanisms and materials. As illustrated in Figure 2, the hierarchical classification of various types of flow batteries details their characteristics, challenges, and innovations. Notably, it highlights the specific advantages and challenges associated with Vanadium Redox Flow Batteries (VRFBs), Zinc-Based Flow Batteries, Organic Redox Flow Batteries, Disproportionation and Hybrid Flow Batteries, and Emerging and Specialized Flow Batteries. Table 1 offers a comparative analysis of the primary features of Vanadium Redox Flow Batteries (VRFBs), Zinc-Based Flow Batteries, and Organic Redox Flow Batteries (ORFBs), emphasizing their energy densities, scalability, and recent technological innovations. This comprehensive overview not only underscores the scalability and longevity of VRFBs, making them ideal for large-scale energy storage, but also lays the groundwork for exploring other flow battery technologies. Understanding VRFBs within this broader context enhances our grasp of the diverse landscape of flow battery technologies.

### 3.1 Vanadium Redox Flow Batteries (VRFBs)

Vanadium Redox Flow Batteries (VRFBs) enable independent scaling of power and energy, making them suitable for large-scale applications [9]. They use vanadium ions in both electrolytes, minimizing cross-contamination and enhancing reliability [31]. Despite this, challenges like capacity degradation due to ion crossover persist [31]. Optimizing energy capacity restoration through algorithms, such as mixed integer linear programming (MILP), and managing electrolyte flow rates are crucial for performance [21].

Innovations include slurry electrodes and advanced flow field designs, improving mass transfer and performance [20, 32]. VRFBs' low specific energy density is addressed by hybrid systems and calibration techniques, enhancing measurement accuracy and understanding of vanadium ions [33, 34, 31, 12]. Membrane quality significantly influences VRFBs' effectiveness, with research focused on enhancing membrane technology to improve durability and scalability [26, 5].

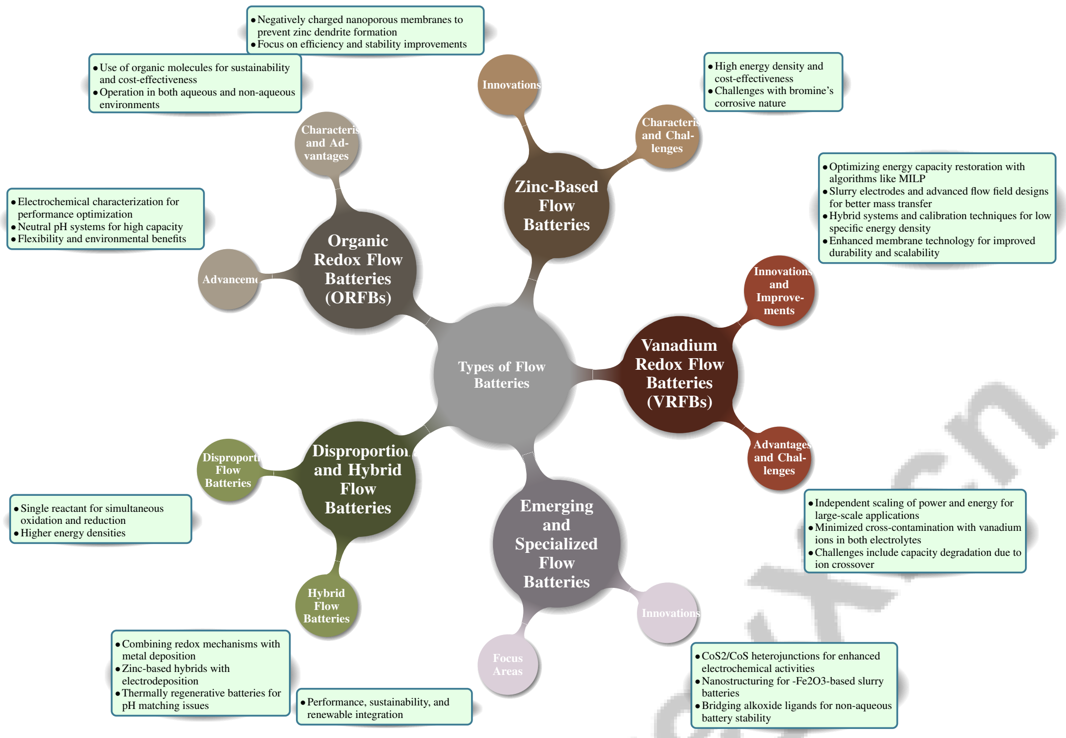


Figure 2: This figure illustrates the hierarchical classification of various types of flow batteries, detailing their characteristics, challenges, and innovations. It highlights the specific advantages and challenges associated with Vanadium Redox Flow Batteries, Zinc-Based Flow Batteries, Organic Redox Flow Batteries, Disproportionation and Hybrid Flow Batteries, and Emerging and Specialized Flow Batteries, providing a comprehensive overview of their respective operational mechanisms and materials.



### 3.2 Zinc-Based Flow Batteries

Zinc-based flow batteries, notably zinc-bromine, are characterized by the deposition and dissolution of zinc and bromine generation, central to their energy storage capabilities [35]. A transient two-dimensional model enhances understanding of these processes, improving predictive accuracy [35]. These batteries offer high energy density and cost-effectiveness, suitable for diverse applications [13].

Challenges include managing bromine's corrosive nature. Innovations like negatively charged nanoporous membranes prevent zinc dendrite formation, enhancing cycle life and efficiency [15, 26, 14]. Research focuses on improving zinc-bromine batteries' efficiency and stability, ensuring their viability as scalable solutions.

### 3.3 Organic Redox Flow Batteries (ORFBs)

Organic Redox Flow Batteries (ORFBs) use organic molecules as active materials, offering sustainability and cost-effectiveness [36]. They operate in both aqueous and non-aqueous environments, with ferrocene derivatives as catholytes in AORFBs, showcasing potential for high energy density [37]. ORFBs' adaptability is highlighted in surveys of various systems [38].

Advancements in electrochemical characterization enhance understanding of ORFBs, crucial for optimizing performance [17]. Neutral pH systems maintain high capacity, addressing key challenges [22]. ORFBs' flexibility and environmental benefits position them as compelling choices for sustainable solutions [15, 36].

### 3.4 Disproportionation and Hybrid Flow Batteries

Disproportionation Redox Flow Batteries (DRFBs) use a single reactant for simultaneous oxidation and reduction, offering higher energy densities. Accurate estimation of charge state and crossover flux is essential, with state observer designs improving accuracy in real-world scenarios [1, 14, 39, 40, 41].

Hybrid flow batteries combine traditional redox mechanisms with metal deposition, enhancing energy density and power output. Zinc-based hybrids use electrodeposition, with flow field design playing a crucial role [13, 14]. Thermally regenerative batteries resolve pH matching issues, highlighting hybrids' versatility in energy storage [42].

### 3.5 Emerging and Specialized Flow Batteries

Emerging flow batteries focus on performance, sustainability, and renewable integration. ORFBs, using sustainable organic compounds, are categorized by active materials and electrolyte types [38]. Novel compounds improve performance and environmental benefits, aligning with renewable energy adoption [36].

Materials science innovations, like $CoS_2$/CoS heterojunctions, enhance electrochemical activities, while nanostructuring improves -$Fe_2O_3$-based slurry batteries [4, 25]. Bridging alkoxide ligands improve polyoxovanadate clusters' stability, addressing non-aqueous battery challenges [10]. These advancements enhance flow batteries' applicability, offering cost-effective, renewable-compatible solutions [15, 5, 14, 7, 36].

| Feature | Vanadium Redox Flow Batteries (VRFBs) | Zinc-Based Flow Batteries | Organic Redox Flow Batteries (ORFBs) |
|---|---|---|---|
| **Energy Density** | Low Specific Energy | High Energy Density | Potential High Density |
| **Scalability** | Independent Scaling Possible | Cost-effective Scalability | Adaptability, Sustainability |
| **Innovations** | Slurry Electrodes, Flow Fields | Nanoporous Membranes | Electrochemical Characterization |

Table 1: Table comparing the key features of Vanadium Redox Flow Batteries (VRFBs), Zinc-Based Flow Batteries, and Organic Redox Flow Batteries (ORFBs). The comparison highlights differences in energy density, scalability, and recent innovations, providing insights into the advantages and challenges of each battery type in the context of energy storage applications.

## 4 Materials and Components

The optimization of materials and components in flow batteries is crucial for enhancing system performance and efficiency. This section focuses on critical materials, starting with electrolytes, whose properties and innovations directly impact the electrochemical processes essential for energy storage and conversion.

### 4.1 Electrolytes

Electrolytes are fundamental to flow battery operations, influencing ion transport, energy density, stability, and overall efficiency. In Vanadium Redox Flow Batteries (VRFBs), vanadium ions serve as active species, with molecular dynamics simulations providing insights into their solution behavior, crucial for efficiency improvements [34]. Innovations like micro-emulsion electrolytes enhance solubility, electrochemical windows, and safety, benefiting organic redox flow batteries [19]. MXene-N's crumpled structure, with nitrogen doping, improves ion transport and conductivity [23].

Non-aqueous electrolytes offer higher energy densities, with vanadium acetylacetonate demonstrating versatility in different solvent environments. Hybrid systems, where zinc oxidizes in alkaline media and iodide reduces in catholytes, show performance promise [43]. In zinc-bromine batteries, bromide ions enhance iodide capacity, increasing energy density [44]. Surfactants like Triton X-100 optimize carbon black suspension stability, exemplifying electrolyte optimization's importance [45].

Electrolyte degradation impacts battery longevity; understanding degradation mechanisms is vital for durability improvements. UV-Visible spectroscopy offers non-invasive monitoring, improving traditional methods [33]. Electrolyte choice and optimization are central to advancing flow batteries, crucial for large-scale energy storage and renewable integration [12, 13, 5, 14].

## 4.2 Membranes

Membranes are vital for flow batteries, separating electrolytes while allowing selective ion transport to maintain charge balance and prevent active species crossover. Their optimization is crucial for VRFB performance, economic viability, and large-scale application efficiency [26, 3, 14, 8]. In VRFBs, membrane material choice affects efficiency and durability. Traditional membranes like Nafion offer proton conductivity and stability but are costly and permeable to vanadium ions, prompting alternative material exploration [8].

Polymer membranes designed for VRFBs improve ion selectivity and reduce vanadium ion permeability, enhancing efficiency and cycle life [8]. Nanocomposite membranes, combining polymers with inorganic fillers, enhance ion selectivity and mechanical strength [18]. Asymmetric membrane structures optimize ion transport and minimize crossover, balancing conductivity and selectivity [21].

Advancing membrane technologies is essential to overcoming flow battery limitations like capacity fade and efficiency loss. Improved membranes enhance VRFBs' performance and economic viability, crucial for large-scale energy storage and renewable energy integration [26, 8].

## 4.3 Electrodes

Electrodes are critical in flow batteries, facilitating electrochemical reactions for energy storage and conversion. Their design significantly affects battery performance, particularly current density and efficiency. Advanced electrode structures, like porous designs and specific flow fields, enhance reactant penetration and mass transfer, crucial for scalability and grid stability alongside renewables [12, 13, 14, 5].

In RFBs, electrodes facilitate oxidation and reduction of active species, affecting efficiency, power density, and longevity. Graphite felt, common in VRFBs, offers stability and conductivity but limited electrochemical activity. Treatments like low-pressure plasma enhance graphite felts by increasing surface area and activity [18]. Advanced designs aim for higher current extraction with reduced reactive areas, improving performance without typical trade-offs [46]. Graphene-based materials further enhance performance due to superior conductivity and surface properties [18].

Optimizing ion diffusion coefficients in charged membranes provides insights for electrode design, enhancing ion transport and battery performance [47]. Electrode advancements are crucial for improving flow battery efficiency, cost-effectiveness, and large-scale energy storage, particularly for renewable integration [26, 14, 3].

## 4.4 Flow Field Designs

Flow field designs are crucial for optimizing electrolyte distribution across electrodes, enhancing electrochemical reaction efficiency and battery performance. Design influences cell hydrodynamics, affecting pressure drop, flow distribution, and reactant utilization. Topology optimization refines designs to minimize power losses and ensure effective reactant distribution [3].

Serpentine, interdigitated, and parallel flow fields impact RFB performance. Serpentine fields enhance current and power density by optimizing reactant penetration, while interdigitated designs improve mass transport with uniform flow patterns, influencing limiting and peak power densities [12, 3]. Advanced manufacturing, like 3D printing, enables intricate flow fields, enhancing mass transfer and reducing pressure drop [32, 20, 3].

Flow field optimization is essential for maximizing flow battery performance and efficiency. Cutting-edge designs and manufacturing improve redox flow battery capabilities for large-scale storage, supporting grid stability with renewables [5, 14].

## 4.5 Advanced Material Innovations

Advancements in material science enhance flow battery performance, focusing on robust redox-active materials, membrane optimization, and innovative organic compounds. These efforts improve Organic Redox Flow Batteries (ORFBs), recognized for sustainable, cost-effective storage [36]. Nanoporous membranes with negative charges improve cycling performance in zinc-based batteries, enhancing reliability and longevity [15].

Multi-material printing transforms flow battery component fabrication, offering advantages in conductivity and strength. This technique tailors material properties for demanding conditions, enhancing performance [48]. Exploring new organic compounds remains a focus, with innovative molecules offering higher energy densities and stability, reducing reliance on costly metal-based species. Machine learning, like the MultiDK method, optimizes molecular design, achieving performance comparable to traditional systems [49, 22, 38].

Material innovations in redox-flow batteries drive cost reduction and efficiency, essential for scalable energy storage and renewable integration. Enhancements in membranes, separators, and electrolyte flow dynamics ensure grid reliability as renewables become a significant electricity source [5, 7].

## 5 Applications and Use Cases

Flow batteries are pivotal in grid-scale energy storage, addressing the integration challenges of renewable energy sources into existing power systems. Their scalability and adaptability make them ideal for modern energy grids' dynamic demands, enhancing large-scale energy storage solutions.

### 5.1 Grid-Scale Energy Storage

Redox flow batteries (RFBs) are particularly suited for grid-scale energy storage, offering independent scaling of energy and power capacities to meet specific grid requirements [5]. This characteristic is crucial for managing the variable output of renewable sources like wind and solar, facilitating energy arbitrage and load-shifting [2]. Zinc-based systems, such as zinc-iron and zinc-bromine flow batteries, are emerging as cost-effective solutions due to their high energy densities and low material costs [13]. The alkaline zinc-iron flow battery, for example, demonstrates stable performance over numerous cycles without zinc dendrite formation, attributed to negatively charged nanoporous membranes [15]. Enhancements in electrode materials, such as N-doped porous carbon, further improve these systems' reversible specific capacity and scalability [29]. Advanced modeling techniques optimize charge and discharge behaviors, enhancing grid-scale applications [35]. Surfactants like Triton X-100 improve the stability of carbon black suspensions, enhancing flow battery performance and reliability [45]. Despite advancements, high capital costs for electrolytes and membranes remain a barrier [5]. Continued research aims to reduce costs and improve efficiency and durability, exploring materials like MXene-N inks for scalable solutions [23].

### 5.2 Electric Vehicles and Transportation

Organic redox flow batteries (ORFBs) offer promising advancements in energy storage for electric vehicles (EVs) and transportation sectors. Their scalability and flexibility allow for variable energy and power outputs, meeting diverse transportation system demands [38]. ORFBs provide rapid recharging and extended driving ranges, using organic molecules as active materials, offering a sustainable alternative to lithium-ion batteries and addressing resource scarcity and environmental concerns [38]. Modular designs enhance safety and maintenance, reducing thermal runaway risks and supporting component recycling. This design, alongside innovative materials like negatively charged nanoporous membranes, addresses challenges such as zinc dendrite formation, enhancing efficiency and longevity [15, 48]. Vanadium redox flow batteries (VRFBs) in EVs contribute to reducing greenhouse gas emissions and fossil fuel reliance, providing large-scale energy storage to manage renewable energy intermittency. Their versatility supports services like peak shaving and grid stability, optimizing renewable energy use in EV charging infrastructure [26, 5].

### 5.3 Energy Market Participation

Flow batteries, especially RFBs, are increasingly recognized for energy market participation, offering essential grid services. Their scalability and flexibility support energy arbitrage and ancillary services, crucial for integrating intermittent renewable sources [6]. They deliver services like frequency regulation, voltage support, and load balancing, enhancing market value and operational efficiency [31, 5, 14, 13, 26]. Advanced optimization techniques, such as Bayesian optimization, enhance flow battery performance and economic viability, maximizing revenue streams [6]. Modular designs facilitate scalability and integration into grid infrastructures, supporting various market scenarios.



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Their flexibility and capacity for medium to large-scale storage make them favorable for utilities and power producers, enabling competitive market participation and grid stability [13, 5, 14].

# 6 Challenges and Future Directions

Advancing flow battery technologies necessitates addressing the multifaceted challenges encountered during design and operation, which significantly impact their efficiency and viability. This section examines the specific challenges related to fluid dynamics, mass transport, and electrochemical interactions, which are crucial for improving the performance and scalability of flow batteries for broader energy storage applications.

## 6.1 Design and Operational Challenges

Flow battery systems face critical design and operational challenges that affect their efficiency, scalability, and commercial potential. Accurately simulating complex interactions between fluid dynamics, mass transport, and electrochemical reactions is particularly challenging in high-density systems and under varying conditions [50]. Optimizing flow field designs, like serpentine configurations, is essential to counter issues like non-uniform flow distributions that reduce efficiency [32].

In Vanadium Redox Flow Batteries (VRFBs), managing crossover flux remains problematic, often leading to oversimplified models that inaccurately predict performance [41]. Polarization losses due to ohmic, mass transfer, and charge transfer losses further hinder VRFB performance [32]. For organic redox flow batteries (ORFBs), challenges include the stability and solubility of redox-active compounds and membrane efficiency to prevent crossover [36]. The oxidative instability of charge carriers and high costs of redox materials complicate ORFB development [10, 7].

Zinc-based flow batteries encounter issues like self-discharge, zinc dendrite growth, and the need for improved electrode morphologies [13]. Dendrite formation during plating/stripping processes impacts stability and efficiency [51]. Challenges also include electrolyte crossover, electrode polarization, and separator membrane optimization [43].

In systems with 3D-printed conductive static mixers, clogging risks due to high viscosities and sedimentation disrupt experiments [20]. Measuring through-plane electrical conductivity (tp) is hindered by contact resistance and pressure dependency, affecting reliability [30].

Addressing these challenges involves optimizing electrolytes, membranes, and electrodes, refining flow field designs, and conducting long-term evaluations under practical conditions. This focus is essential for enhancing flow battery competitiveness in stabilizing grids and integrating renewable energy [26, 5, 14, 7].

## 6.2 Material and Component Limitations

Flow battery performance and scalability are limited by material and component challenges, notably in achieving compatibility between membranes and electrolytes to maintain efficiency and prevent capacity loss [19]. Despite advances in high-energy-density systems, synthesis complexity remains a barrier [4]. Assumptions of perfect mixing in tank models often overlook fluid dynamics intricacies, leading to performance prediction inaccuracies [21].

Surfactants, used to stabilize electrolyte suspensions, can weaken gel structures at high concentrations, limiting practical applications [45]. Addressing these limitations is vital for advancing flow battery technologies and ensuring their viability as sustainable energy storage solutions. Enhancements in efficiency, scalability, and reliability can be achieved through better understanding of electrolyte flow, mass transfer dynamics, and flow field designs [12, 5, 14, 13, 3].

## 6.3 Electrochemical Performance and Stability

Electrochemical performance and stability are critical for flow battery efficacy and longevity. Vanadium redox batteries (VRBs) face challenges with non-linear dynamics under variable conditions, leading to inefficiencies [39]. This necessitates advanced control strategies to manage complex operational environments effectively.

Accurately modeling interphases and electrochemical reactions within cells is challenging due to their complexity, complicating predictive model development [28]. Stability is further affected by electrode degradation, membrane fouling, and electrolyte instability, leading to capacity fade and reduced efficiency over time. Addressing these challenges requires advanced materials, optimized cell designs, and improved operational protocols to enhance performance and stability [15, 49, 9, 45, 48].

### 6.4 Modeling and Simulation Challenges

Modeling and simulation of flow batteries are challenged by the complex interplay of electrochemical, fluid dynamic, and thermal processes. Accurately representing transport phenomena, including ion movement, species diffusion, and convective flow, is difficult due to the multi-scale nature of these systems [21]. Balancing computational complexity with predictive accuracy is a significant hurdle, as traditional models often rely on simplifying assumptions that lead to discrepancies [50].

Advanced modeling techniques, such as lattice Boltzmann methods, offer detailed insights into fluid dynamics and mass transport [50]. Accurately representing electrochemical kinetics and thermodynamics is crucial for capturing non-linear redox reaction behaviors [28]. Integrating thermal management models is essential for predicting heat generation and dissipation, impacting efficiency and longevity [15, 1, 14, 48, 46].

### 6.5 Future Research Directions

Future research should focus on developing cost-effective materials and large-scale testing to optimize flow battery commercial viability, including exploring alternative chemistries for innovation [5]. Optimizing micro-emulsion compositions and membrane compatibility is crucial for scalability [19]. Enhancing static mixer design, focusing on particle morphology, could impact charge transfer dynamics [20].

Advancements in organic redox materials and membrane technologies are essential for developing semi-solid and hybrid flow batteries [7]. Exploring additional organic and organometallic materials could enhance neutral pH aqueous organic-organometallic redox flow batteries (NPAO-RFB) performance [22]. Research into cost-effective membranes with improved stability is a priority [8]. Validating models with experimental data and investigating electrolyte property effects on mixing dynamics are essential for improving fluid dynamics simulations [21].

Future research could explore alternative liquid metals for contact materials and conductive colloidal gels for improved stability [30]. Optimizing microfluidic designs and refining nanophotonic engineering are promising areas [25]. Further optimization of polyoxovanadate clusters and ligand modifications could enhance non-aqueous redox flow battery performance [10]. Exploring surfactant effects, container dimensions, and particle volume fractions on carbon black suspension stability is important [45].

Refining optimization algorithms and exploring their application in other energy storage systems could lead to advancements [32]. Future research should focus on novel materials, membrane fabrication optimization, and addressing environmental impacts [26]. These directions highlight the multifaceted approach needed to drive flow battery technology innovation, ensuring their role in sustainable energy storage solutions.

## 7 Conclusion

Flow batteries, particularly redox flow batteries (RFBs), have emerged as a transformative force in the landscape of energy storage solutions, offering unique advantages in scalability, safety, and cost-effectiveness. The integration of bromide ions as complexing agents has significantly enhanced the capacity of iodide ions in RFBs, achieving an impressive energy density of 101 $\mathrm{W\,h\,L_{posolyte+negolyte}}^{-1}$, the highest reported for aqueous flow batteries [44]. This advancement underscores the potential of flow batteries to provide robust and efficient energy storage solutions, particularly in the context of renewable energy integration.

The visualization of intercolloid energy transport and quantification of charge transfer kinetics in redox-active colloids represent significant strides in understanding the energy dynamics within nonconjugated polymers, offering new insights into the optimization of flow battery systems [27].

Additionally, the dynamic response of AC-driven electro-osmotic flow has provided valuable insights into ion diffusion coefficients in charged membranes, which are crucial for optimizing flow battery performance [47].

The development of aqueous redox-flow batteries highlights their potential to deliver low-cost, safe energy storage solutions, emphasizing the importance of creating highly soluble, low-cost redox materials to enhance their viability [7]. These advancements collectively highlight the transformative role of flow batteries in modern energy systems, offering a pathway to more sustainable and resilient energy infrastructures.

As research continues to address the challenges facing flow battery technology, including material limitations, electrochemical performance, and modeling complexities, the future of energy storage looks promising. Flow batteries are poised to play a pivotal role in the transition towards cleaner and more sustainable energy systems, supporting the widespread adoption of renewable energy sources and contributing to a more resilient and efficient energy future.

## References


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