



**RKP**

# **Vanadium Electrolyte**

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A Sustainable and Long-Lasting  
Solution for Energy Storage

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## Overview – Reusability and Long-Life Characteristics of Vanadium Electrolyte

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Vanadium electrolyte exhibits exceptional reusability and long-life properties, making it a highly effective solution for energy storage. These advantages stem from its inherent stability and the fundamental electrochemical mechanisms governing its reactions.

As the key energy storage medium in vanadium redox flow batteries (VRFBs), vanadium electrolyte comprises vanadium ions, a supporting electrolyte, and additives. The vanadium ions act as the active material in chemical energy

storage, while hydrogen ions shuttle between the positive and negative electrodes to maintain charge balance. Additives enhance solution stability and promote efficient electrochemical reactions. Because the composition of the electrolyte remains identical in both the positive and negative electrodes, there is no risk of cross-contamination, even during ion migration over prolonged charge-discharge cycles.

Vanadium electrolyte's reusability is demonstrated through its ability to maintain stable chemical properties with minimal side reactions. Furthermore, it can be restored to its original state through recovery operations. With excellent chemical stability, high conductivity, and low resistance, the electrolyte ensures a stable current output, making it ideal for large-scale energy storage. These characteristics enable VRFBs to be repeatedly cycled without significant degradation, effectively reducing long-term operational costs.

Unlike lithium-ion batteries, which suffer from structural degradation due to phase changes, vanadium electrolyte remains in a liquid state throughout the charging and discharging processes. This ensures that deep discharge does not cause damage to the system, contributing to an extended operational lifespan.

The long life and reusability of vanadium electrolyte strongly support its application in the energy storage sector. VRFBs provide notable advantages, including independent scaling of power and energy capacity, fast response times, and high safety standards, making them ideal for applications such as grid energy storage and renewable energy integration.



### Vanadium Electrolyte

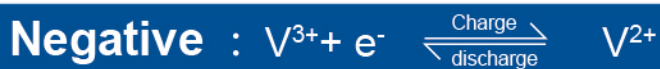


## Introduction to Vanadium Electrolyte and Its Role in Energy Storage

The electrolyte is a critical component of flow batteries, acting as the medium for energy storage. The total storage capacity of a VRFB system is determined by both the concentration and volume of the electrolyte. The physical and chemical properties of the electrolyte, as well as its usage, directly influence the battery's overall performance.

### Role in Energy Storage

A VRFB is an energy storage technology that converts chemical energy to electrical energy through reversible changes in vanadium ion oxidation states. The core reaction principle is as follows:



- During charging, vanadium ions in the positive electrolyte accept electrons and are converted to  $\text{VO}_2^+$  (5+), while vanadium ions in the negative electrolyte release electrons and are converted to  $\text{V}^{3+}$  (3+). This process stores electrical energy as chemical energy in the electrolyte.
- During discharging, the reverse reaction occurs, converting the stored chemical energy back into electrical energy to supply power to the load.

The electrolyte is pumped through the battery stack, where electrochemical reactions take place. Using a proton exchange membrane as a separator, the electrolyte flows past the electrode surfaces, enabling the redox reaction. Current is collected and transmitted via bipolar plates, completing the energy conversion process.

Vanadium electrolyte is also a significant cost component of VRFBs. In a 4-hour energy storage system, the electrolyte and power unit each account for approximately 50% of the initial investment. As charge/discharge durations increase, the proportion of electrolyte costs rises. Therefore, improving electrolyte performance and reducing costs are key areas of focus for VRFB technology development.

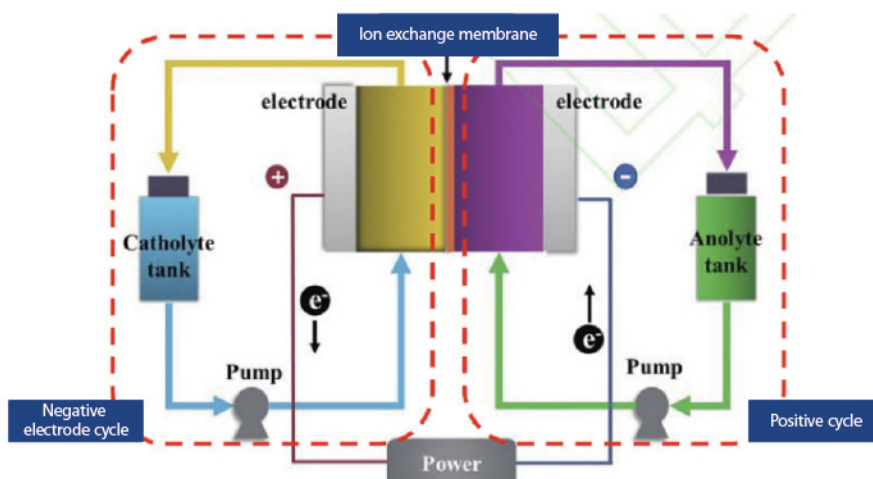
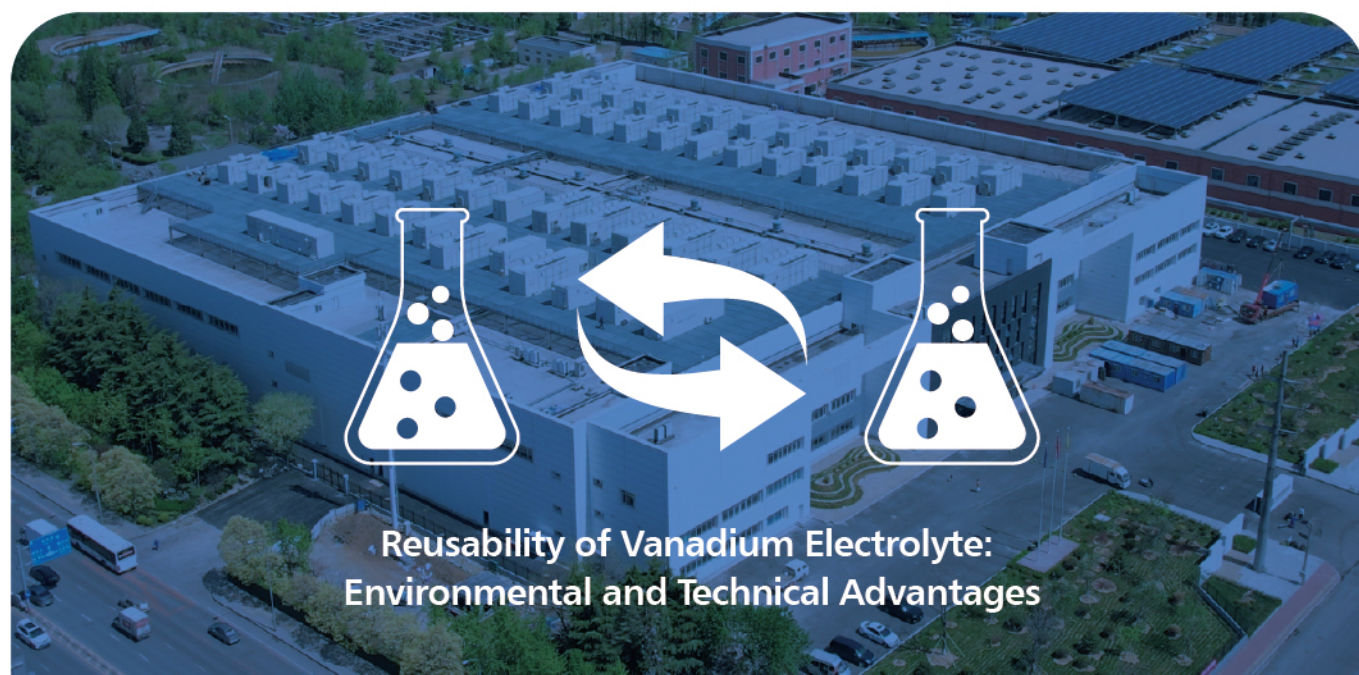


Figure 1. VRFB Principle

## Reusability of Vanadium Electrolyte: Environmental and Technical Advantages

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Throughout the battery's operation, vanadium electrolyte only undergoes changes in oxidation state and does not experience phase changes (e.g., liquid to gas or solid). This ensures that the total amount of active vanadium ions remains constant, preventing material depletion or loss.

From an environmental perspective, vanadium electrolyte significantly reduces resource waste and minimizes environmental pollution. Its ability to be repeatedly recycled presents no risk to human health or the ecosystem. Furthermore, at the end of a battery system's life cycle, the vanadium can be extracted and repurposed for applications in industries such as steelmaking and alloy production, contributing to a circular economy.

From a technical standpoint, the reusability of vanadium electrolyte delivers major advantages. First, it lowers maintenance costs by eliminating the need for frequent electrolyte replacement, thereby extending the battery's lifespan. Second, its high stability ensures consistent performance over long durations, allowing for deep charge/discharge cycles without performance degradation. Additionally, its ability to be regenerated and restored to optimal conditions further enhances its long-term viability, making VRFBs a cost-effective and sustainable energy storage solution.





To enhance the durability of vanadium electrolyte, researchers have continuously explored and innovated various techniques. Key advancements include optimizing electrolyte formulations by incorporating additives that improve electrolyte stability at temperatures above 50°C, thereby increasing the discharge energy density per unit volume of the electrolyte. Adjustments to battery operation modes and parameters have also been introduced to reduce side reactions such as ion migration, which contribute to gradual capacity fade. Furthermore, improvements in system design—such as minimizing leakage currents that lead to self-discharge—allow vanadium electrolyte to maintain stable performance over extended periods, reducing battery replacement frequency and associated costs. As of 2024, vanadium electrolyte has demonstrated a cycle life exceeding 20,000 cycles, with an operational lifespan of more than 20 years—far surpassing the 5 to 8-year lifespan of lithium-ion batteries. This significantly longer lifespan highlights its superior durability compared to many other battery technologies. Several specific methods have been developed to enhance the resistance of vanadium electrolyte to degradation:

- **High-Performance Degradation Inhibitors:** In VRFBs, self-discharge at high states of charge (SOC) in the negative electrode solution can lead to excess accumulation of  $\text{VO}_2^+$  in the positive electrolyte, which is a primary cause of oxidation state imbalance and capacity decay. The introduction of advanced additives can reduce or completely inhibit self-discharge, significantly mitigating capacity fade in vanadium flow batteries.
- **Control Systems to Prevent Capacity Degradation:** Specialized control systems have been developed to slow down electrolyte capacity degradation. These systems include positive and negative electrolyte storage tanks and automated regulation mechanisms that adjust solution concentration and volume in real time. This approach minimizes self-discharge effects at high SOC levels and slows down the rate of oxidation state imbalance, effectively reducing overall battery capacity degradation.

## Technical Analysis: Maintaining Vanadium Electrolyte Performance and Enhancing Resistance to Degradation

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- **Surface-Modified Ion Exchange Membranes:** Recent research has demonstrated that modifying the surface of different types of ion exchange membranes using organic or inorganic materials can significantly enhance their vanadium-blocking capability. This reduces vanadium ion migration between the positive and negative electrodes, thereby minimizing the capacity fade associated with imbalanced active material distribution. Such improvements greatly enhance the long-term performance and efficiency of vanadium flow batteries.
- **Optimized Ion Concentration Ratios and Permeation Rates:** By controlling the concentration ratio of vanadium ions in the positive and negative electrodes and adjusting the dynamic permeation rate of vanadium ions, the issue of capacity degradation can be mitigated while simultaneously improving electrolyte utilization efficiency.
- **Mass Transport Optimization:** The development of mass transfer equations to study the effects of electrolyte temperature and SOC on ion transport across membranes has enabled further optimization of mass transfer coefficients. This reduces unwanted side reactions and simultaneously enhances electrolyte utilization while suppressing VRFB capacity degradation.

Overall, the primary causes of electrolyte degradation can be attributed to two factors: (1) ion migration between the positive and negative electrodes, leading to an imbalance in vanadium concentration and capacity fade, and (2) self-discharge reactions that increase the average valence state of vanadium ions. However, both issues can be effectively restored through simple corrective measures—capacity loss due to ion migration can be recovered by rebalancing the positive and negative electrolyte solutions, while capacity loss caused by self-discharge can be restored through redox reactions or electrolysis. Therefore, strictly speaking, vanadium electrolyte does not experience irreversible degradation, further solidifying its long-term sustainability and operational efficiency in energy storage applications.





From a production capacity perspective, vanadium electrolyte technology has seen significant advancements in recent years. As the core material of VRFBs, its production processes have been optimized for greater efficiency. Rongke Power's upgraded electrolyte production line has incorporated new technologies that simplify impurity removal, significantly improving manufacturing capacity. Upon completion, the new production line is expected to achieve an annual production capacity of 4.5 GWh of electrolyte, making it the world's largest vanadium electrolyte production facility.

From a technological standpoint, improving electrolyte stability—particularly temperature stability—is a primary focus. Enhancing the operational temperature of vanadium electrolyte reduces cooling energy consumption and associated equipment costs while allowing for increased vanadium concentration. This, in turn, boosts the energy density of the electrolyte. Several large-scale additives have already been successfully deployed, and modifications to the supporting electrolyte (such as partially replacing sulfuric acid with other organic or inorganic acids) have demonstrated significant performance enhancements, increasing electrolyte energy density by approximately 50%.

As an electrochemical energy storage technology, VRFBs offer considerable advantages over lithium-ion batteries:

- **Inherent Safety** – Energy is stored in a water-based vanadium electrolyte, eliminating the risk of combustion or explosion.
- **Extended Cycle Life** – VRFBs significantly outperform lithium-ion batteries in terms of cycle life. Unlike lithium-ion batteries, which undergo solid-liquid phase transitions that degrade electrode materials over time, VRFBs operate solely through ionic charge transfer in liquid-phase electrolytes. Commercially deployed VRFBs have already demonstrated more than three times the cycle life of lithium-ion batteries, exceeding 20,000 cycles.
- **Environmental Friendliness and Recyclability** – Vanadium electrolyte is fully reusable and recyclable, making VRFBs a sustainable choice for large-scale, long-duration energy storage applications.
- **Scalability and Flexibility** – The independent scaling of power and capacity in VRFBs allows for flexible system design, making them well-suited for applications such as renewable energy integration and grid storage.

As challenges related to high initial investment costs are addressed—particularly through the adoption of an electrolyte leasing model—along with improvements in operational and maintenance efficiency, the future potential of flow batteries will be limitless.



## Conclusion

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Vanadium redox flow batteries (VRFBs) offer several key advantages that make them a highly promising solution for long-duration energy storage. First, the electrolyte in VRFBs does not experience cross-contamination between the positive and negative sides, as both electrodes contain the same active material. Second, VRFBs provide high safety and reliability. After more than a decade of technological advancements, VRFB technology has gained significant recognition in long-duration energy storage applications and is expected to continue evolving rapidly.

As a core component of VRFB energy storage systems, vanadium electrolyte has demonstrated exceptional long-term stability across numerous operational projects. It has been shown to store and release energy reliably over a span of 15 years or more, maintaining consistent performance and efficiency throughout its lifecycle. Since vanadium ions undergo only oxidation state changes within the electrolyte, without reacting with electrode materials or forming byproducts, the electrolyte retains its chemical integrity even after extended use. Furthermore, at the end of a project's lifecycle, the vanadium can be fully recovered through extraction processes and repurposed for other applications.

In summary, vanadium electrolyte is uniquely positioned as a stable, long-lasting, and recyclable energy storage solution, making VRFBs an ideal choice for large-scale, long-duration applications in the evolving energy landscape.

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