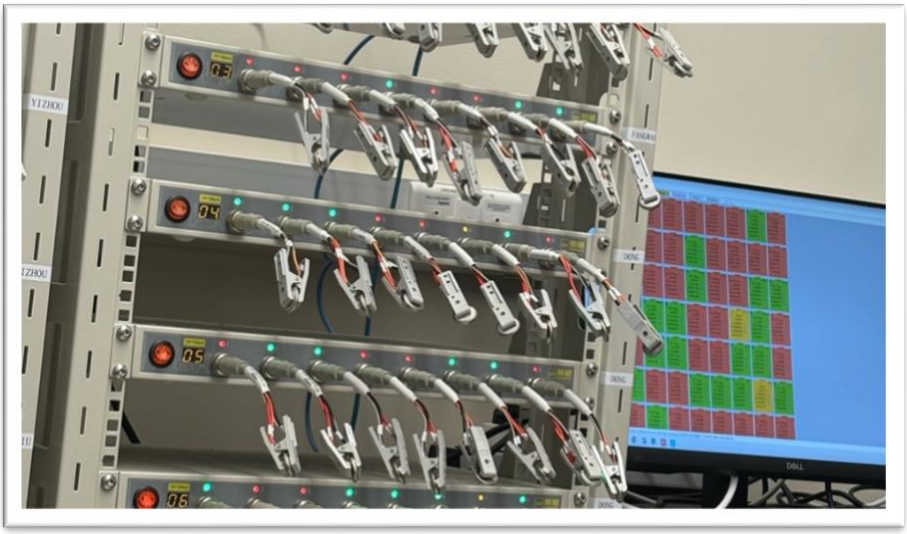
Enhancing Energy Density and Lifespan of V_2O_3-Based Zinc-Ion Batteries



By: Roba Faisal Alnushayri

Supervised by: Dr. Wandi Wahyudi, Prof. Husam N. Alshareef

Energy Transition Specialization, KAUST Academy

Table of Contents

Project objective 3

Progress and Milestones Achieved 3

Abstract 4

Introduction 5

Resources 6

Methodology 6

- **Cell Fabrication** 6
- **Testing Protocols** 7
- **Data Analysis** 7

Results 8

Discussion 11

Conclusion 12

- **Acknowledgments** 13

References 13

Project objective

The project aims to improve the performance of aqueous zinc-ion batteries (ZIBs) by optimizing the electrochemical performance of V_2O_3-based cathodes. The goals include:

- Enhancing energy density and cycle life of ZIBs.
- Investigating the effects of different formation protocols on performance.
- Identifying optimal operating conditions for stability and capacity retention.

Progress and Milestones Achieved

- Fabrication of V_2O_3-based zinc-ion cells.
- Completion of electrochemical testing under various current densities.
- Electrochemical impedance spectroscopy (EIS) and cycling stability experiments conducted.
- Identification of optimal current density (2.5 A/g) with stable impedance response and long-term cycling performance.

Abstract

Zinc-ion batteries (ZIBs) have emerged as a promising alternative to lithium-ion systems due to their safety, low cost, and sustainability. However, their large-scale application remains limited by relatively low energy density and poor cycling stability. In this project, we investigate vanadium oxide (V_2O_3) as a cathode material, leveraging its structural versatility and high theoretical capacity. The study systematically evaluates the effects of different current densities and formation protocols on the electrochemical performance of V_2O_3-based ZIBs. Results demonstrate that a current density of **2.5 A/g provides the optimal balance between capacity and stability**, supported by electrochemical impedance spectroscopy (EIS) and cycling tests. Furthermore, while a high-current formation protocol delivers the highest capacity, the **two-step formation process achieves the best long-term stability**, retaining ~95 mAh/g after 300 cycles. These findings highlight the critical role of operating conditions in enhancing both energy density and cycle life, offering new pathways for the practical deployment of ZIBs in energy storage systems.

Introduction

The global demand for sustainable and safe energy storage technologies has intensified in recent years, driven by the rapid expansion of renewable energy and portable electronics. While lithium-ion batteries (LIBs) dominate the commercial market, they face critical limitations including high cost, resource scarcity, and safety concerns such as thermal runaway. These challenges have fueled interest in alternative aqueous-based energy storage systems, particularly **zinc-ion batteries (ZIBs)**, which offer inherent advantages such as low cost, abundance of zinc, high theoretical capacity, and enhanced safety due to their water-based electrolytes.

Despite these advantages, ZIBs still face two key obstacles hindering their practical deployment: **limited energy density** and **poor long-term cycling stability**. These issues primarily stem from cathode material degradation and sluggish zinc-ion diffusion during repeated intercalation processes. To address these limitations, researchers have turned to vanadium-based materials, which are known for their layered structures, high redox activity, and structural flexibility that can accommodate zinc-ion intercalation. In particular, **vanadium oxide (V_2O_3)** has emerged as a promising cathode material due to its high capacity and structural versatility, which facilitate zinc-ion intercalation [1].

However, the successful implementation of V_2O_3 in ZIBs requires careful optimization of **operating conditions and formation processes**, which directly affect performance metrics such as capacity retention, rate capability, and impedance stability. Previous studies on vanadium-based systems, such as V_2O_5 nanopaper cathodes, have also shown that electrochemical protocol design plays a crucial role in achieving long cycle life [2].

This project seeks to fill that gap by exploring the effects of **different current densities and formation strategies** on the electrochemical behavior of V_2O_3-based ZIBs. By combining galvanostatic charge-discharge cycling with electrochemical impedance spectroscopy (EIS), the study identifies the most favorable conditions for balancing high energy density with long-term stability. The outcomes provide insights into how electrochemical protocols influence battery performance, offering a foundation for future research on the practical integration of ZIBs into large-scale energy storage applications, particularly in renewable energy systems such as solar grids.

Resources

- Materials: V_2O_3 cathode, Zn anode, $ZnSO_4$ electrolyte, fiberglass separator.
- Instruments: Electrochemical workstation, impedance analyzer, cycling test system.
- Prof. Husam N. Alshareef Battries devolopment labartory

Methodology

The project followed a systematic methodology to evaluate the electrochemical performance of V_2O_3-based zinc-ion batteries, with emphasis on cell fabrication, electrochemical testing, and comparative analysis of cycling protocols.

1.Cell Fabrication

The battery cells were fabricated through a **six-step assembly process**, illustrated in **Figure 1**. The fabrication began with the placement of the **V_2O_3 cathode**, followed by the installation of a **fiberglass separator** to prevent short-circuiting. Next, **120 mg of $ZnSO_4$ aqueous electrolyte** was carefully introduced to ensure consistent ionic conductivity. A **zinc anode** was then positioned, after which a **spring and spacer** were inserted to maintain structural stability and uniform pressure during cycling. Finally, the cells were sealed to complete the assembly process, ensuring reproducibility and minimizing electrolyte leakage.

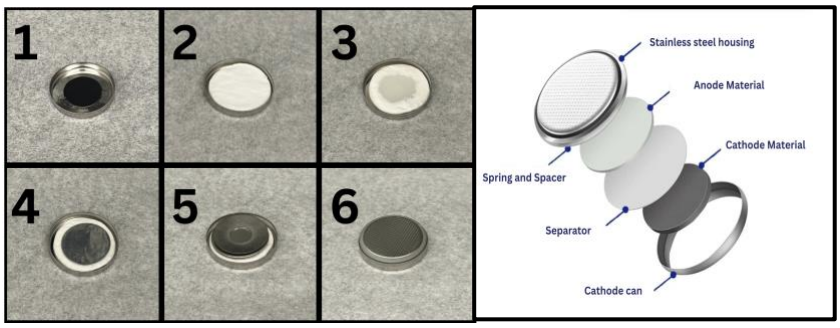


Figure 1- Fabrication process and cell component

2.Testing Protocols

After assembly, the fabricated cells were subjected to a series of electrochemical tests to assess their performance under different conditions:

- **Galvanostatic Charge–Discharge (GCD) Testing:** Cells were cycled at multiple current densities (0.5 A/g, 1 A/g, 2.5 A/g, and 5 A/g) to evaluate rate capability, capacity retention, and cycling stability.
- **Electrochemical Impedance Spectroscopy (EIS):** Impedance measurements were performed at three current densities (1 A/g, 2.5 A/g, and 5 A/g) to investigate charge transfer resistance, ion diffusion characteristics, and overall impedance stability.
- **Formation Process Studies:** To examine the effect of formation strategies, three protocols were tested:
    1. **High Current Protocol** – Single-step formation at high current.
    2. **Two-Step Protocol** – A gradual approach with initial low current followed by higher current cycling.
    3. **Slow Charge–Fast Discharge Protocol** – Asymmetric cycling to mimic potential solar-related use cases.

3.Data Analysis

The results from cycling and impedance testing were compared to determine the **optimal conditions for maximizing both energy density and cycle life**. Discharge capacity trends, Nyquist plots, and long-term cycling stability were used to identify correlations between formation strategy, current density, and battery performance.

Results

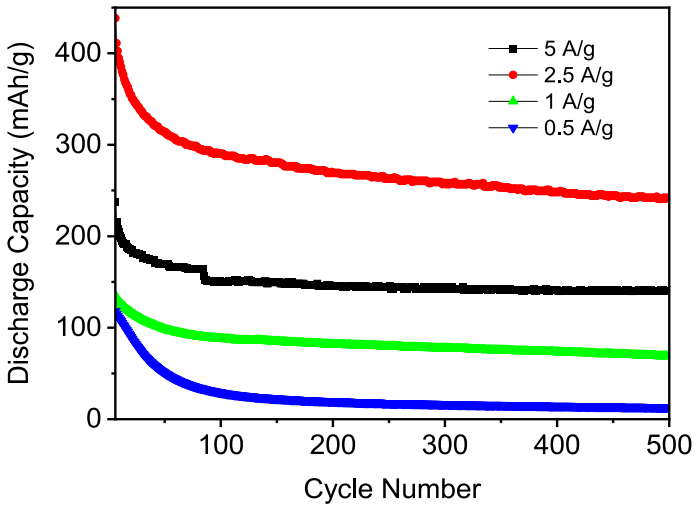


Figure 2 - Discharge capacity under different currents

The graph compares discharge capacity across multiple current densities. Results show that **2.5 A/g delivers the highest stability and capacity retention**, outperforming both lower (0.5 A/g) and higher (5 A/g) current rates. While 0.5 A/g rapidly loses performance, 1 A/g and 5 A/g show moderate results but less optimal balance. This confirms that **2.5 A/g is the most effective operating condition** for V_2O_3 cathodes.

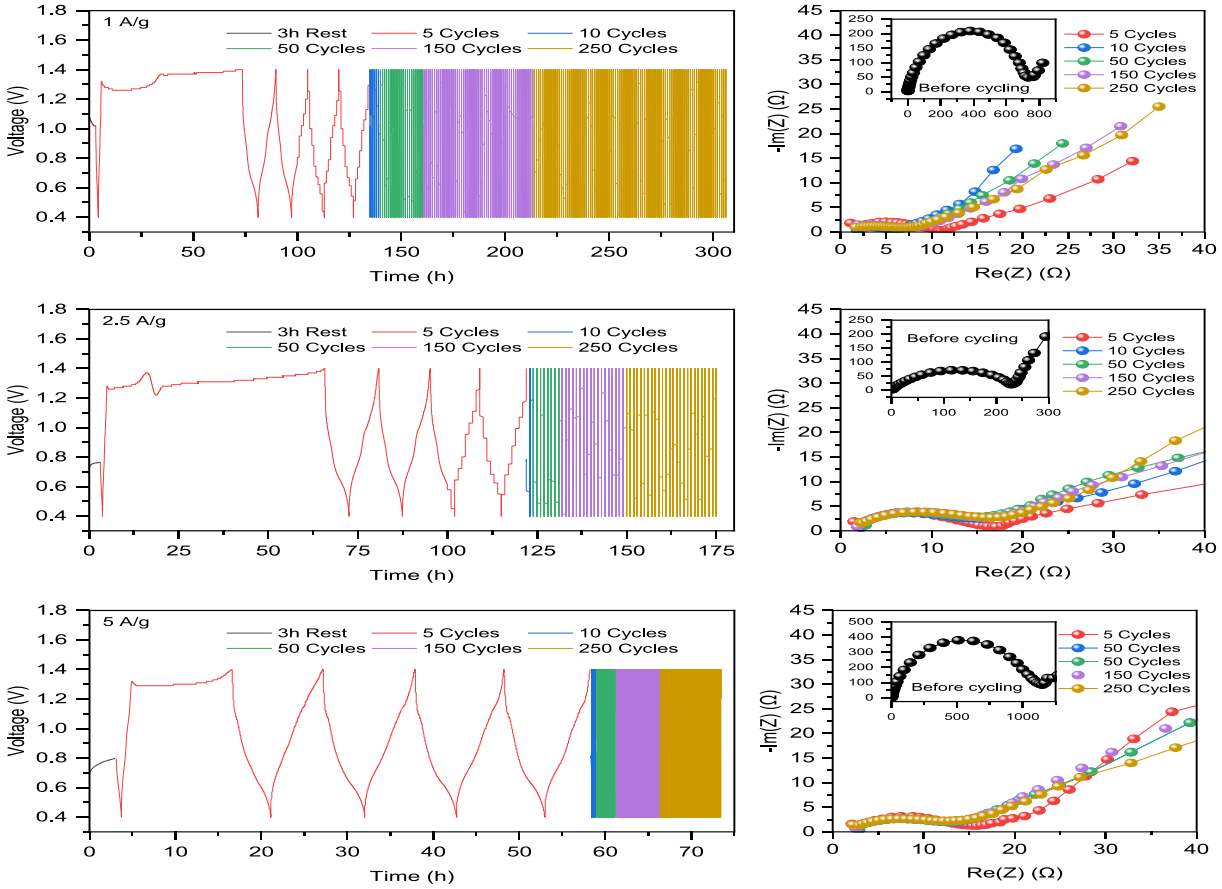


Figure 3 – Electrochemical Impedance Spectroscopy (EIS) at Different Currents

The Nyquist plots reveal that cells cycled at **2.5 A/g exhibit the lowest charge transfer resistance and most stable impedance response**. In contrast, 1 A/g and 5 A/g show higher resistances, indicating less efficient ion transport and poorer long-term stability. These impedance results strongly correlate with the cycling performance, reinforcing the selection of **2.5 A/g as the optimal current density**.

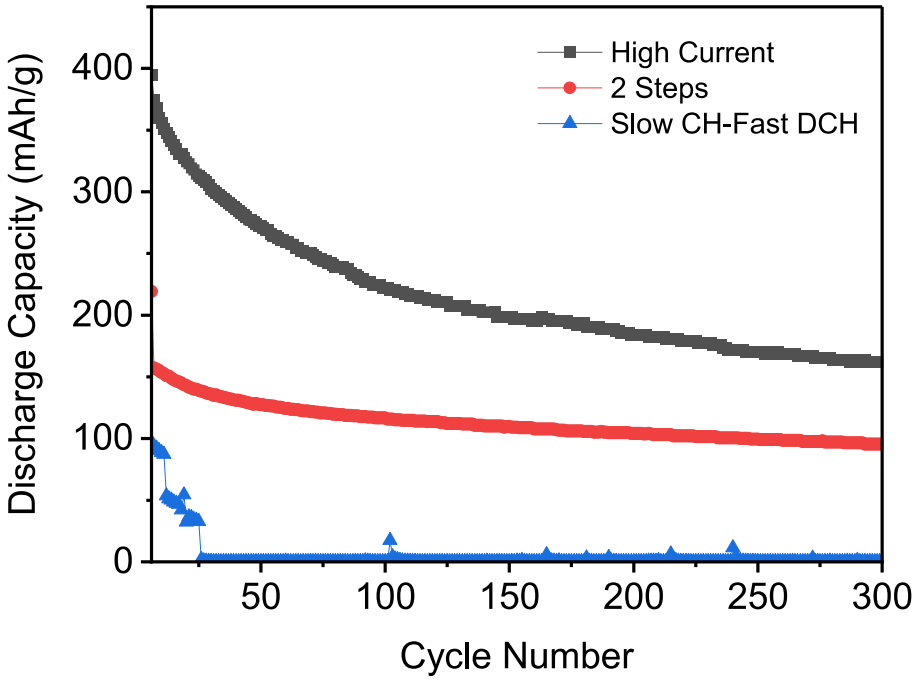


Figure 4 – Discharge Capacity for Different Formation Processes

Three formation protocols were evaluated:

- **High Current:** Retained ~160 mAh/g after 300 cycles, making it ideal for high-energy applications but less stable in the long term.
- **Two-Step Process:** Provided the best cycling stability, with gradual capacity fade to ~95 mAh/g, suggesting suitability for long-lifetime devices.
- **Slow Charge–Fast Discharge:** Showed severe capacity decay, proving unsuitable for this cathode material.

This demonstrates that **formation strategy directly affects electrochemical performance**, with the two-step process emerging as the most stable and reliable approach.

Discussion

The systematic evaluation of V_2O_3-based zinc-ion batteries highlights the importance of both **operating conditions** and **formation protocols** in determining electrochemical performance. Across all experiments, the current density of **2.5 A/g consistently demonstrated superior capacity retention, low resistance, and cycling stability**, making it the most effective operating parameter. This suggests that V_2O_3 cathodes require a moderate current rate that balances ion transport efficiency with structural integrity, avoiding the drawbacks seen at both lower and higher current densities.

Electrochemical impedance spectroscopy (EIS) confirmed this trend, with **2.5 A/g showing the lowest charge transfer resistance**, which aligns with its strong cycling performance. This correlation between impedance characteristics and long-term capacity retention validates EIS as a predictive tool for identifying optimal cycling conditions in zinc-ion batteries.

In addition to current density, the **formation process** played a critical role in long-term performance. The high-current protocol achieved the highest initial capacity but suffered from gradual decline, making it more suitable for high-energy but short-to-medium lifetime applications. The two-step process, in contrast, offered the best balance of capacity and stability, gradually fading to ~95 mAh/g after 300 cycles. This stability highlights the potential of stepwise formation as a strategy for achieving long cycle life in practical applications. Conversely, the slow charge–fast discharge protocol performed poorly, underscoring the incompatibility of this approach with V_2O_3 cathodes.

These findings emphasize that the performance of V_2O_3-based zinc-ion batteries is not determined solely by material properties but also by **operational strategies**. By carefully optimizing current density and formation protocol, it is possible to significantly enhance both the energy density and the lifespan of these batteries. Future work should validate these findings under practical conditions, such as **higher temperature testing and solar-system integration**, to ensure real-world applicability.

Conclusion

This project demonstrated the potential of **V_2O_3-based zinc-ion batteries** as promising candidates for safe, cost-effective, and sustainable energy storage systems. Through systematic testing of different **current densities** and **formation protocols**, the study identified the critical influence of operating conditions on both energy density and cycling stability. Among the tested conditions, a current density of **2.5 A/g consistently delivered the best balance**, offering low resistance, stable impedance response, and superior long-term performance. Likewise, while the **high-current formation protocol** achieved the highest capacity, the **two-step protocol** emerged as the most stable approach, retaining ~95 mAh/g after extended cycling. These findings confirm that **electrochemical strategies play as crucial a role as material selection** in determining battery performance.

Despite these promising outcomes, several **challenges and obstacles were encountered**. Certain formation processes, particularly the **slow charge–fast discharge protocol**, resulted in **rapid capacity decay**, rendering them unsuitable for V_2O_3 cathodes. Additionally, it was difficult to maintain stable performance at **extreme high or low current densities**, which either caused accelerated degradation or insufficient cycling stability. Moreover, testing has thus far been limited to controlled laboratory conditions, and validation under **practical environments**—such as higher operating temperatures or integration with renewable energy systems—remains incomplete.

Looking forward, several **future directions** are essential to strengthen the applicability of this work. First, the slow charge–fast discharge process should be revisited in the context of **solar energy applications**, where asymmetric cycling patterns may be more relevant. Second, testing at **elevated temperatures** must be carried out to confirm the robustness of V_2O_3 cathodes under real-world conditions. Third, **scaling up fabrication** beyond laboratory-scale coin cells will be crucial to evaluate feasibility for larger storage systems. Finally, **defect engineering in V_2O_3** represents a promising pathway to further improve structural stability, cycling lifespan, and overall durability, building upon recent advancements in vanadium-based cathodes.

In conclusion, this work not only highlights the importance of **operational optimization** for V_2O_3-based zinc-ion batteries but also lays the foundation for their potential use in practical large-scale energy storage. With continued refinement and validation, these systems could become viable alternatives for powering renewable energy grids and other applications that demand both **safety and long-term reliability**.

Acknowledgments

Special thanks to **Dr. Wandi Wahyudi** and **Prof. Husam N. Alshareef** for their mentorship and guidance. This work was supported by **King Abdullah University of Science and Technology (KAUST)** with additional support from **KAUST Academy, CREST, WE Spark, and K.A.CARE**.

References

[1] K. Zhu *et al.*, "Defect engineering on V2O3 cathode for long-cycling aqueous zinc metal batteries," *Nature Communications*, vol. 12, no. 1, Nov. 2021

[2] Y. Li *et al.*, "Corrigendum to 'V2O5 nanopaper as a cathode material with high capacity and long cycle life for rechargeable aqueous zinc-ion battery' [Nano Energy 60 (2019) 752–759]," *Nano Energy*, vol. 63, p. 103839, Sep. 2019