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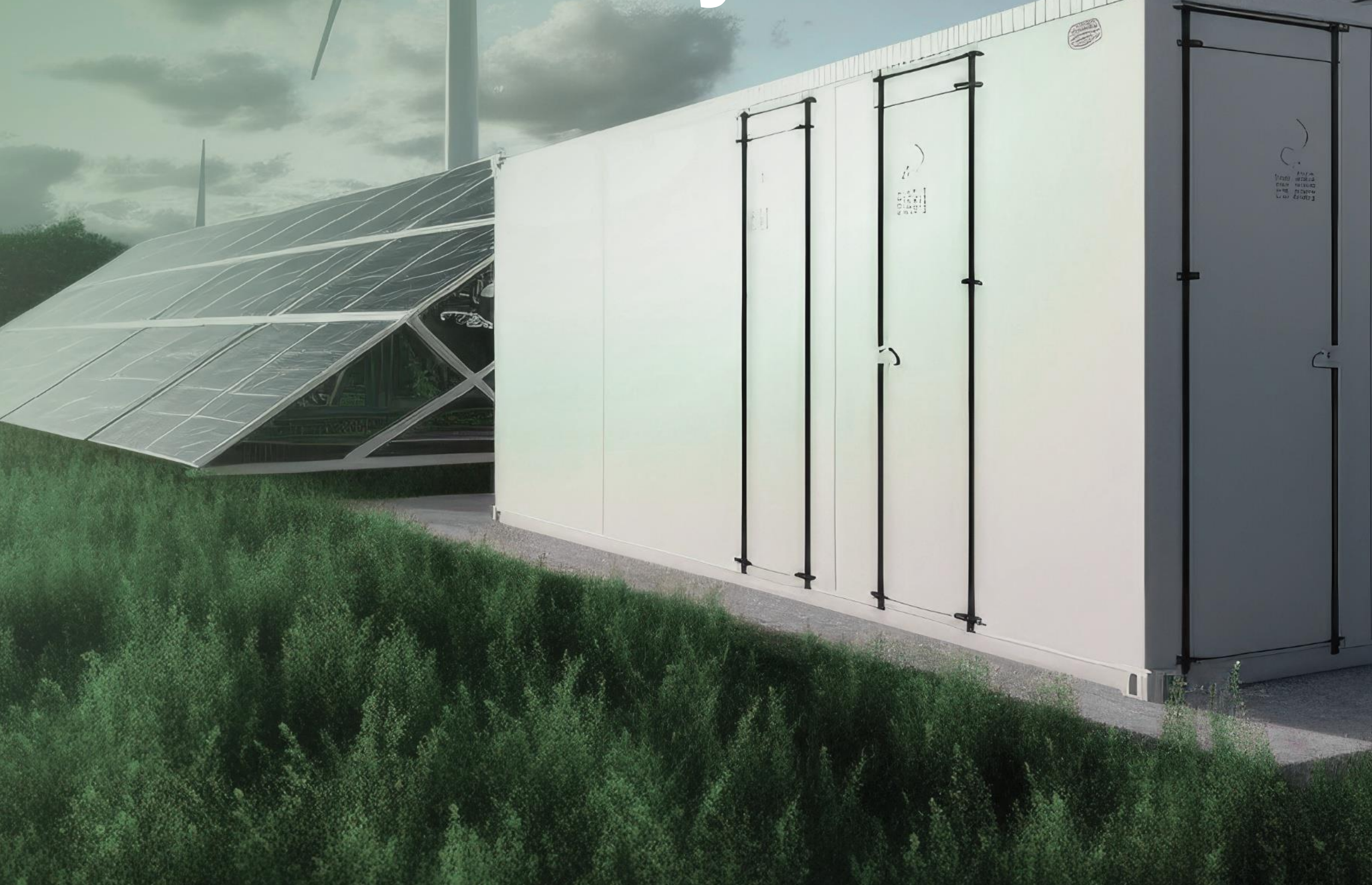
LSF Market Study 2025

South African Vanadium Redox Flow Battery Value Chain Study



Prepared by Customized Energy Solutions India Pvt. Ltd. (CES)

About this study

This study explores the evolving landscape of VRFBs, with a particular focus on opportunities for South Africa within the global market. VRFBs, the most commercially advanced flow battery technology, rely heavily on vanadium, which constitutes approximately ~30-40% of their value. The research assesses market dynamics, supply and demand drivers, technological innovations, and investment prospects over the next five years. It aims to enhance South Africa's competitive edge by identifying pathways for local supply chain optimisation, manufacturing expansion, and strategic investment. Conducted through four structured phases, this collaborative effort - led by CES and global and local experts - seeks to build a robust foundation for South Africa's VRFB sector, supporting its broader goals of industrialization, localization, and participation in the global battery value chain.

About LSF

The Localisation Support Fund NPC ("LSF") is a non-profit company, established in 2021 and funded by private sector contributors committed to localising manufacturing in South Africa. The LSF is a network orchestrator within the localisation ecosystem facilitating the connection between supply and demand participants, enhancing the value of the interactions by funding industry research and the deployment of technical expert resources to accelerate or unblock opportunities for localisation and growth in the manufacturing sector.

About Service Provider

Customized Energy Solutions India Pvt. Ltd. (CES) is supporting LSF for the 'VRFB Market Study'. CES team comprises global thought leaders and experts in energy storage, renewables and e-mobility segments who spearhead diverse projects within the sector, encompassing electric grid simulation; renewable integration; energy audit and demand assessment; energy storage; optimization modelling; load flow analysis; e-mobility transition; and policy/regulatory analysis. CES' experience extends to working with government entities, utilities, and key players in renewables, battery storage, and E-mobility across the US, India, and various nations such as Japan, Canada and South Africa.

Disclaimer

This report has been prepared in fulfilment of a study to assess the global VRFB market, with a focus on identifying strategic opportunities for South Africa's participation and growth in this sector. It aims to evaluate market dynamics, supply and demand trends, technological advancements, and potential investment pathways over the next five years. Through a structured, four-phase methodology, the study examines areas where South Africa can enhance its competitive positioning, strengthen local supply chains, and develop domestic manufacturing capabilities. Supported by a collaborative team of global battery value chain experts and South African policy specialists, the study intends to provide data-driven insights and actionable recommendations to guide stakeholders in advancing the country's industrialization, localization, and economic development through the VRFB industry.

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This research was commissioned by the LSF and was conducted independently by Customized Energy Solutions India Pvt. Ltd. The lead consultant responsible for this report as well as the overall project was Customized Energy Solutions India Pvt. Ltd. The opinions or recommendations contained in this report represent the views of the authors and do not necessarily reflect the views and opinions of the LSF.

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Definitions/ Glossary of Abbreviated Terms

Abbreviation	Full Form
AVL	Australian Vanadium Limited
BoP	Balance of Plant
BTM	Behind-the-Meter
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CES	Customized Energy Solutions
C-rate	Charge/Discharge Rate
DOD	Depth of Discharge
DOE	Department of Energy
EU	European Union
FTM	Front-of-the-Meter
GWh	Gigawatt-hour
ICRFB	Iron-Chromium Redox Flow Battery
IEA	International Energy Agency
IOCL	Indian Oil Corporation Limited
kt	Kilo tonnes (thousand tonnes)
kWh	Kilowatt-hour
LAES	Liquid Air Energy Storage
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
LDES	Long Duration Energy Storage
LFP	Lithium Iron Phosphate
MASEN	Moroccan Agency for Sustainable Energy
MoU	Memorandum of Understanding
Mt	Million Tonnes
MW	Megawatt
MWh	Megawatt-hour
$Na\text{-}NiCl_2$	Sodium-Nickel Chloride Battery
NaS	Sodium-Sulphur Battery
NEDO	New Energy and Industrial Technology Development Organization
NMC	Nickel Manganese Cobalt
NTPC	National Thermal Power Corporation
NZE	Net Zero Emissions
OEM	Original Equipment Manufacturer
ORFB	Organic Redox Flow Battery
PCS	Power Conversion System
PFER	Prospering from the Energy Revolution (PFER) Programme
PHES	Pumped Hydro Energy Storage
PUB	Public Utilities Board (Singapore)
RE	Renewable Energy
REE	Red Eléctrica de España
RTE	Round Trip Efficiency
SOC	State of Charge
STEPS	Stated Policies Scenario
TRL	Technology Readiness Level
V_2O_5	Vanadium Pentoxide
VE	Vanadium Electrolyte
VRFB	Vanadium Redox Flow Battery
ZBRF	Zinc-Bromine Redox Flow Battery

Executive Summary

Why This Study Matters: South Africa at a Strategic Crossroads

This report explores how South Africa can leverage its vanadium resources to capture value in the fast-growing Vanadium Redox Flow Battery (VRFB) market. It combines global market projections, supply chain analysis, risk assessment, and actionable strategies to position the country as a competitive player in the long-duration energy storage (LDES) ecosystem. The recent designation of vanadium as a “moderate-to-high” critical mineral under South Africa’s Critical Minerals and Metals Strategy adds urgency and opportunity to this agenda.

The Global Energy Storage Boom: Where VRFBs Fit In

The stationary storage market is on a steep growth trajectory, projected to reach between 1.0-1.5 terawatts (TW) of cumulative capacity by 2030 as renewable energy penetration accelerates and grids demand long-duration flexibility. Within this context, VRFBs stand out for applications requiring 6-12+ hours of storage, offering inherent safety, long cycle life, and full recyclability of electrolyte. However, their cost competitiveness will depend on achieving economies of scale and optimizing system design. Under the base case scenario LDES is expected to reach about 142 GW, while an accelerated, net-zero-aligned pathway could push this figure to 980 GW by 2030. VRFBs are projected to capture 5-6% of LDES capacity, translating to approximately 7 GW/ 40 GWh in the base case and up to 20 GW/ 120 GWh in the accelerated scenario. Cost reductions are also anticipated, with VRFB capital expenditure declining from around \$380/kWh in 2025 to \$230/kWh by 2030, alongside improvements in round-trip efficiency from 70% to 75%. These trends suggest that VRFBs could achieve Levelized Cost of Storage (LCOS) parity with lithium iron phosphate (LFP) batteries for 8-hour applications by 2030, assuming a 25-year operational life. Notably, electrolyte remains a major cost driver, accounting for roughly 35% of system cost, with vanadium pentoxide (V_2O_5) alone contributing 26–30%.

Vanadium’s Rising Role: Demand Surge Meets Supply Constraints

The adoption of VRFB technology will significantly increase vanadium demand, shifting its role from a primarily metallurgical input to a critical component of the energy transition. VRFB-related demand is expected to rise from about 5% of global vanadium consumption in 2024 to nearly 27% by 2030, with electrolyte requirements growing from 182 kt in 2024 to approximately 1,100 kt by 2030 under the base case scenario, and up to 4,600 kt in an accelerated pathway. However, the supply landscape remains highly concentrated, with China accounting for roughly 67% of global production, followed by Russia at 20%, South Africa at 8%, and Brazil at 5%. Meeting the projected demand of 200 kt of vanadium metal equivalent by 2030 will require a global V_2O_5 output of around 450 kt, representing an increase of more than 200 kt over current levels. While primary producers have announced expansions totalling about 52 kt by 2030, this leaves a significant gap that must be filled through co-production and secondary recovery routes. Price volatility remains a key concern, as vanadium pentoxide prices have stabilized around $10-11/kg since 2024, a level that supports VRFB economics only when combined with cost reductions in non-electrolyte components, innovative business models such as electrolyte leasing, and supportive policy frameworks.

South Africa's Advantage, and Its Challenge

South Africa holds a strategic advantage with its high-grade vanadium reserves, some exceeding 1.5% V_2O_5, and existing primary production infrastructure. However, the country faces structural cost disadvantages compared to Chinese co-production, driven by higher operating costs, logistics challenges, and energy tariffs. Midstream capacity for battery-grade electrolyte production and VRFB component manufacturing remains limited, particularly following the exit of Bushveld Energy from local operations. Despite these challenges, South Africa's recent designation of vanadium as a "moderate-to-high" critical mineral under the national Critical Minerals and Metals Strategy marks a turning point. This recognition opens the door for targeted incentives, streamlined permitting, and public-private partnerships to accelerate beneficiation, midstream manufacturing, and recycling initiatives. It also strengthens South Africa's case for positioning itself as a regional and global hub for VRFB production and export.

What Could Go Wrong: Risks That Must Be Managed

Scaling VRFB deployment faces several interconnected barriers. Supply and price volatility are the most prominent, as vanadium costs remain closely tied to steel demand cycles while South Africa's higher primary production costs add further pressure. Technical challenges include the absence of globally harmonized electrolyte standards (though International Electrotechnical Commission (IEC) specifications are in development), and the limited industrial scale of stack and membrane manufacturing, both of which constrain cost reduction. Market acceptance remains uneven: outside East Asia there are relatively few large, bankable references, and VRFBs face competition from lithium-ion systems, particularly where the value of duration is not explicitly monetized and 6–8-hour LFP solutions prevail. Policy and trade dynamics introduce additional uncertainty, as protectionist measures, export controls, and evolving supply-chain strategies can either open opportunities or restrict market access. These risks underscore the importance of domestic pilots, robust quality standards, pooled offtake, and circular financing mechanisms to stabilize costs and build confidence.

The Circular Advantage: Why VRFBs Are Built for Sustainability

VRFBs possess a distinctive sustainability advantage in their ability to retain electrolyte value over decades of operation. End-of-life electrolyte can be recovered and reused with demonstrated vanadium recovery rates approaching 97%, enabling circular business models, such as leasing and buy-back schemes, that lower lifecycle costs and improve project bankability. Reprocessing options include direct shipment of liquid electrolyte, which is logistically heavy but straightforward, and on-site precipitation into solids, which reduces freight costs but generates liquid waste streams that require careful management. Chemical oxidation methods, such as applying sodium hypochlorite or sodium chlorate at moderate temperatures, can restore electrolyte valence for reuse. In practice, sulfuric-acid-based electrolytes dominate commercial deployments due to their recyclability and process familiarity, whereas mixed-acid formulations, while promising for energy density can complicate effluent management and environmental permitting. Building a national platform for electrolyte recycling and reprocessing will therefore be central to South Africa's competitive position, especially if integrated with standardized quality control and a leasing program that captures the electrolyte's residual value.

From Vision to Action: Strategic Priorities for South Africa

South Africa's pathway to competitiveness involves leveraging critical-mineral status, building midstream capacity, activating domestic demand, and positioning for exports.

I. The priority is to operationalize the critical-mineral designation for vanadium by fast-tracking beneficiation and refining projects under government-backed programs. This may include establishing an Energy Storage Special Economic Zone (SEZ) with fiscal incentives, concessional power tariffs, and expedited permitting for battery-grade V_2O_5 to electrolyte plants and selected VRFB component manufacturing lines.
II. In parallel, South Africa can pursue joint ventures and technology transfer agreements with established electrolyte producers and stack original equipment manufacturers (OEMs), supported by co-funded pilot lines that bridge the gap between lab-scale proof and industrial production. Quality must be institutionalized by adopting forthcoming IEC specifications for vanadium electrolyte, embedding them in a national certification framework, and accrediting local laboratories for batch testing and traceability.
III. On the supply side, secondary recovery from fly ash, spent refinery catalysts, and steel slag may be piloted and incentivized to diversify feedstock and enhance resilience. Demand activation can be driven by anchor deployments in mining microgrids, industrial parks, renewable energy corridors, and telecom clusters, using procurement that mandates 8-hour (or longer) duration and evaluates solutions on duration-based and resilience criteria.
IV. Commercial innovation is equally important: a Vanadium Electrolyte Leasing Special Purpose Vehicle (SPV), potentially capitalized by public finance institutions and private investors, can reduce upfront costs, hedge commodity risk through cap-and-floor indexation, and ensure electrolyte buy-back and reuse.
V. Finally, South Africa can adopt an export-oriented posture by building the Energy Storage SEZ into a manufacturing and logistics hub and pursuing agreements with the EU, UK, and U.S. for mutual recognition of standards and rules of origin, supported by export credit and sustainability-linked finance to scale outbound projects.

The Road Ahead: A Three-Phase Plan

The roadmap proceeds in three phases.

1) In the near term, over the first 12 months, the focus can be on converting policy intent into operational instruments by publishing IEC-aligned electrolyte specifications, accrediting local testing laboratories, and announcing the Energy Storage SEZ with a clear incentive framework. A Vanadium Electrolyte Leasing SPV can be established with transparent

governance and price-stabilization mechanisms. In parallel, two to three anchor projects may be tendered across mining, industrial, and renewable nodes, each requiring at least eight hours of duration so that value accrues to technologies designed for long-duration service.

2) In the medium term, over months 12 to 36, the first electrolyte production line and pilot stack/component facilities can be commissioned within the SEZ, while domestic VRFB deployments scale toward at least 150-250 MWh supported by long-tenor leasing and pooled offtake agreements. Secondary recovery pilots can aim to get operational and feed recycled vanadium into the midstream. Export readiness can be advanced through bilateral standard-recognition and the first shipments of South African-made electrolyte to international markets.

3) In the long term, beyond 36 months, the objective is to achieve a 20-26% reduction in system-level cost versus 2025 baselines through non-electrolyte component innovation and scale, while a fully operational electrolyte reprocessing facility enables recovery rates of 97% or higher. By 2030, cumulative VRFB deployments can target to attain 400-900 MWh across domestic and export markets, underpinned by a credible midstream manufacturing base and a proven operating record in long-duration, high-temperature, and safety-critical environments.

Chapter 1: Market Size and Growth Forecast for VRFB & Vanadium Electrolyte Demand

1.1. Research Methodology for Market Research

This study aims to evaluate the global demand and manufacturing potential of VRFB and their electrolyte components within the stationary energy storage market. The research follows a structured, multi-step methodology combining both primary and secondary data sources to ensure comprehensive and validated findings.

Objectives: The primary objective of the research is to evaluate the global demand and manufacturing potential of VRFB and its electrolyte in the Stationary Energy Storage Market.

Data Collection: A hybrid approach involving both primary and secondary research was used for data collection:

- **Primary Data** was gathered through direct inputs from key industry stakeholders, including battery manufacturers, project developers, and domain experts.
- **Secondary Data** was obtained from credible sources as below:
    - Stationary storage: Annual market reports such as IEA -Battery and Secure Energy Transition (2024)[1] and LDES council's annual report (2024)[2], industry whitepapers, policy documents, proprietary datasets shared by stakeholders, and publicly available databases.
    - Mining & processing: Databases such as US Geological survey, British Geological Survey, mining company reports- Bushveld, Largo Resources etc.
    - Refining: Company websites and investor presentations, industry reports from Roskill, Wood Mackenzie, CRU reports

The report analysis starts from downstream analysing the global demand for VRFB batteries and moves upstream to assess the required quantity of Vanadium compounds to meet the demand of the VRFB industry.

Analytical Approach: The research adopted a top-down analytical framework to estimate VRFB demand. The methodology involved –

1) **Assessing global stationary energy storage demand** by analysing forecasts from international energy agencies and market intelligence reports.
2) **Estimating LDES demand** within the broader stationary storage segment, focusing on systems with discharge durations ≥6 hours.
3) **Deriving VRFB demand** as a subset of total LDES capacity, based on technology adoption scenarios informed by policy trends, cost curves, and expert inputs.
4) **Calculating electrolyte demand**, using established VRFB sizing ratios and electrolyte energy density assumptions, to quantify the corresponding requirement for vanadium-based electrolyte.

Outcome

The methodology has led to refined market projections for both VRFBs and their electrolyte components. It also generated actionable insights for stakeholders regarding future capacity planning, raw material sourcing, and investment strategies in the energy storage value chain.

[1] Batteries and Secure Energy Transitions – Analysis - IEA
[2] Annual Report | LDES Council

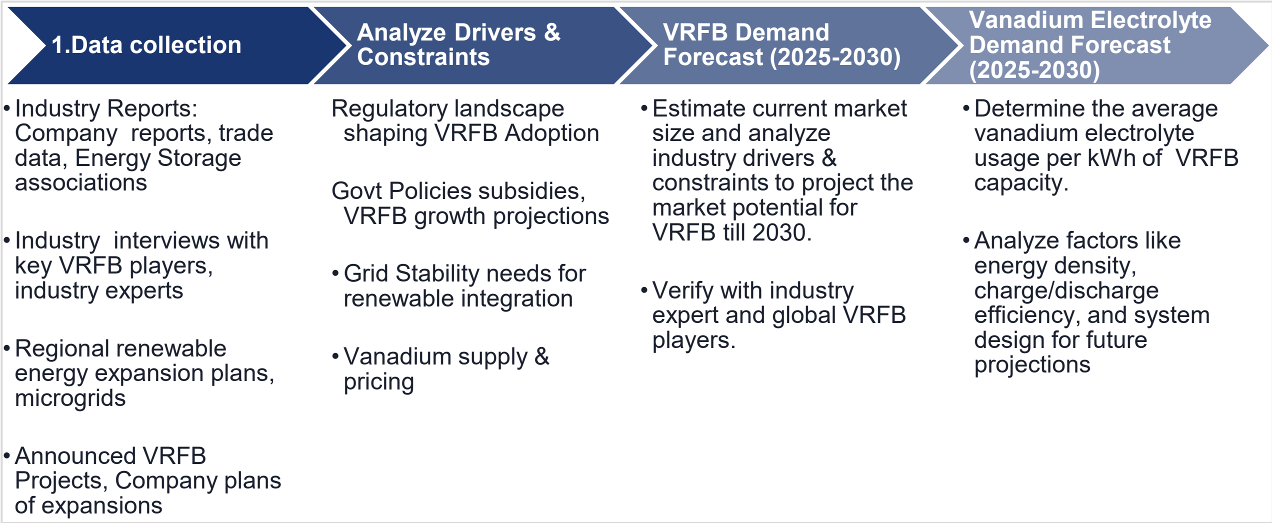

Figure 1: Approach for Global Stationary Storage Market Assessment

1.2. Global Stationary Storage Market Assessment - Scenarios and Assumptions

1.2.1. STATIONARY STORAGE MARKET FORECAST SCENARIOS AND ASSUMPTIONS

Two scenarios are considered for the future projection of the market: a base-case scenario and an accelerated-case scenario, as outlined below. The base year for this study will be 2024.

1.2.1.1. Base Case (STEPS Scenario, means 'Stated Policies Scenario')

The base case scenario is developed using a stepwise approach, grounded in historical data and forward-looking policy-aligned projections. Each market, stationary storage, LDES, VRFBs, and vanadium electrolyte is evaluated as follows:

- **Global Stationary Storage Market (2020–2030)**

For the period 2020 to 2024, actual energy storage deployment data is used based on reported installations. For 2025 to 2030, projections are based on the *Stated Policies Scenario (STEPS)* by the International Energy Agency (IEA), reflecting current government commitments and announced policies. The Global cumulative Stationary Storage market is expected to be ~1000 GW by 2030 in the base case.

- **Global Long-Duration Energy Storage (LDES) Market (2020-2030)**

Actual deployments of LDES (≥6 hours discharge duration) are considered for the period 2020 to 2024. For 2025 to 2030, the analysis incorporates the near-term project pipeline, while medium- to long-term capacity additions are aligned with national targets and projections under the IEA Stated Policies Scenario (STEPS) as referenced by the LDES Council. The Global cumulative LDES market is expected to be ~142 GW by 2030 in the base case.

- **Global Vanadium Redox Flow Battery (VRFB) Market (2024-2030)**

For 2024, actual VRFB project deployments are considered. For 2025 to 2030, project pipeline is considered for the short-term which includes publicly announced and committed projects. By 2030, VRFBs are assumed to represent ~5%[3] of total LDES capacity (base case), as most other electrochemical storage technologies remain at early TRL stages. Li-ion is excluded, and broader LDES is not considered in this share. The global cumulative VRFB market is projected to reach ~7 GW / 40 GWh by 2030 (base case), with annual additions of up to 2 GWh in 2024, rising to around 12 GWh per year by 2030.

- **Global VRFB Electrolyte Market (2024-2030)**

Electrolyte demand is derived from the projected VRFB capacity using established sizing ratios and technical assumptions. Improvements in energy density and electrolyte utilization are factored in to estimate vanadium metal requirements. VRFB electrolyte demand was ~182 kt in 2024 and is expected to rise to ~1,100 kt by 2030 to support an annual VRFB capacity of 12 GWh (base case).

1.2.1.2. Accelerated Case (Net Zero Scenario)

The accelerated-case scenario represents an accelerated growth trajectory, aligned with global net zero ambitions. It assumes strong policy support by different countries (i.e. policies dedicated for introduction of LDES/ VRFB such as LDES shot, UK faraday battery program,

[3] Annual Report | LDES Council

dedicated tenders for LDES), rapid market development, and technology adoption consistent with international climate targets.

- **Global Stationary Storage Market (2020–2030)**

The Accelerated Case is aligned with the Net Zero Emissions (NZE) pathway published by the International Energy Agency (IEA)[4]. This scenario reflects enhanced deployment levels driven by national net zero commitments made at COP28, aiming to decarbonize power systems by 2050 and accelerate energy storage uptake by 2030. The Global cumulative Stationary Storage market is expected to be ~1500 GW by 2030 in the accelerated case.

- **Global Long-Duration Energy Storage (LDES) Market**

Under the accelerated case, LDES growth is based on NZE-aligned targets sourced from IEA projections and the LDES Council's Net Zero scenario[5]. The assumed capacity expansion reflects the critical role of LDES technologies in enabling deep renewable energy integration and achieving 2030 climate milestones. The Global cumulative LDES market is expected to be ~980 GW by 2030 in the accelerated case.

- **Global Vanadium Redox Flow Battery (VRFB) Market**

VRFB deployment is estimated using storage capacity targets specifically set for the power sector in the LDES Council's Net Zero scenario. This includes a more favourable share for VRFBs within LDES technologies, reflecting stronger commercial viability and support in this accelerated pathway. The global cumulative VRFB market is projected to reach ~20 GW/ 120 GWh by 2030 (accelerated case), with annual additions of up to 2 GWh in 2024, rising to around 50 GWh per year by 2030.

- **Global Vanadium Electrolyte Market**

Electrolyte demand under the accelerated case is derived from the expanded VRFB capacity forecast. Calculations incorporate evolving technical parameters, such as improvements in energy density, electrolyte utilization efficiency, and system design optimizations that enhance vanadium consumption per kWh. VRFB electrolyte demand was ~182 kt (kiloton) in 2024 and is expected to rise to ~4,600 kt by 2030 to support an annual VRFB capacity of 50 GWh (accelerated case).

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4 Batteries and Secure Energy Transitions – Analysis - IEA
5 Annual Report | LDES Council

1.3. Vanadium – An Element That Can Be Used in Many Sectors

Vanadium is mainly used in high-strength, low-alloy (HSLA) steels for construction, infrastructure, pipelines, and automotive components, where small additions greatly enhance strength and durability. It also finds use as a catalyst in chemical processes, in titanium alloys for aerospace, and in pigments and ceramics. More recently, vanadium has gained importance in energy storage through VRFBs, valued for scalability, long life, and deep discharge capability.

Only 5% of global vanadium production is utilized in battery applications as of 2024; this share is projected to rise to 27% by 2030, reflecting the accelerating adoption of VRFBs in LDES.

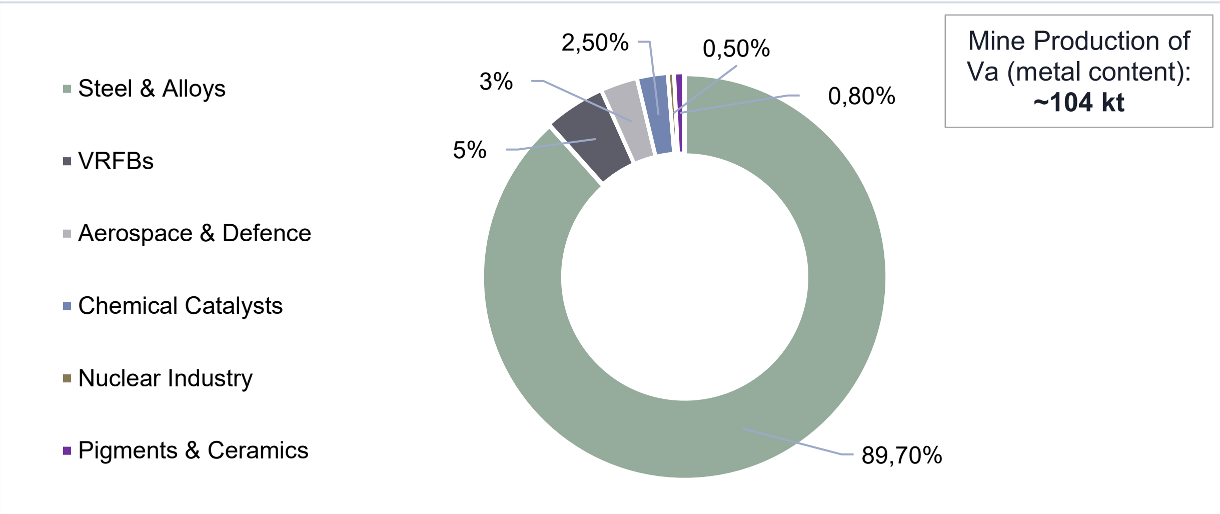

Figure 2: Worldwide Vanadium Production Split by Usage (%) in 2024

Source: USGS Mineral Commodity Summaries 2024 – Vanadium database[6]

[6] USGS Mineral Commodity Summaries 2024

According to CES analysis, VRFB adoption could see a significant growth mainly due to dedicated policy implementation, involvement of more stakeholders within VRFB industry and suitability towards specific applications and environment when compared to other LDES technologies. This could drive a significant increase in vanadium demand by 2030. Under CES 'Base Case' scenario, VRFB build out could result in vanadium metal demand reaching up to 54 kt or 27% by 2030.[7] This represents an incremental increase of nearly 40 kt of vanadium metal compared to few projections of other 3rd party market research groups [8] [9], highlighting the potential for widespread adoption of VRFB technology in the LDES segment.

While few 3rd party market research estimates suggest that VRFBs could account for approximately 8% of total vanadium consumption by the end of the decade, it is aligned with the moderate growth estimates of Vanadium production by 2030. However, CES projects a substantially higher figure after factoring in the additional demand of vanadium metal from global VRFB build out by 2030, steel & alloys will contribute to 67% of the global Vanadium usage.

CES's Projection of VRFB demand worldwide by 2030 is based on a bottom-up estimation that suggests Vanadium requirement (in terms of metal content) will be 54 kt (27%). The Bottom-up approach is covered in Figure 1.

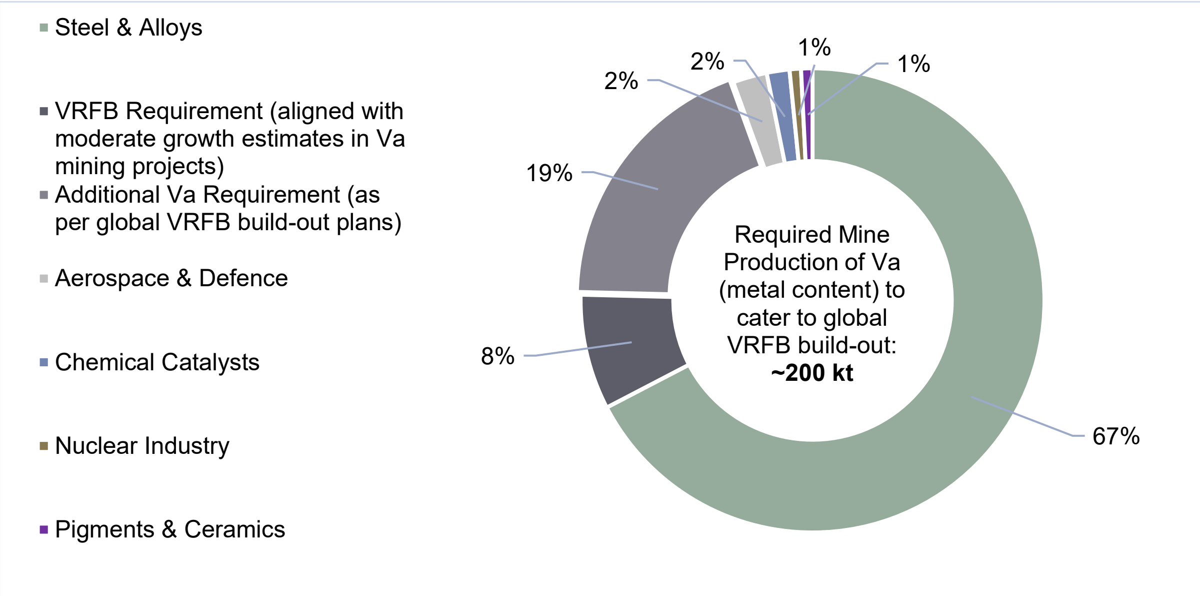

Figure 3: Projected Worldwide Vanadium Usage (%) in 2030

Source: CES analysis, Projections of research groups like GII Research and The Oregon Group

[7] CES estimate of mine production of Va metal in 2030

[8] Ferro Vanadium Market Report: Trends, Forecast and Competitive Analysis to 2031

[9] https://theoregongroup.com/energy-transition/mining/vanadium-double-edged-demand/

Such a sharp rise in demand, however, brings attention to the current limitations on the supply side. Global vanadium supply remains heavily dependent on primary extraction through mining and secondary recovery from steel production processes. With battery-grade vanadium requiring additional purification steps, the supply chain is not yet fully optimized to support large-scale battery applications.

If production capacity does not scale in tandem with demand, the industry could face significant supply bottlenecks by the end of the decade. Addressing this risk will require upstream investment in mining, expansion of refining infrastructure, and exploration of alternative sourcing routes, including recycling of spent electrolytes and by-product recovery.

1.4. Vanadium Battery Value Chain

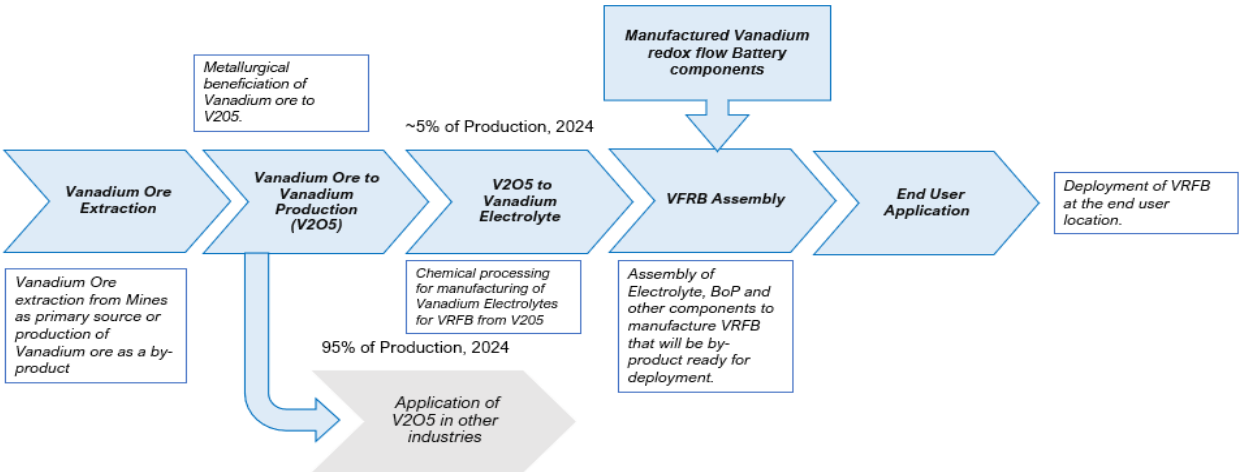

Figure 4: Vanadium Battery Value Chain

Source: CES research[10]

- **Vanadium Ore Extraction:** Vanadium is sourced from dedicated mines or as a by-product of steel production, with China, South Africa, and Russia accounting for ~90% of the 104 kt global output in 2024.
- **V_2O_5 Production:** Extracted ore is processed into vanadium pentoxide (V_2O_5), the key input for battery electrolytes. In 2024, only ~5% of V_2O_5 is used for batteries, while

[10] CES Research and Analysis

~95% goes to steel, catalysts, and pigments. China leads production, followed by South Africa and Brazil, with Australia emerging.

- **Electrolyte Manufacturing:** V_2O_5 is refined to battery-grade vanadium electrolytes, essential for VRFB performance. Manufacturing is led by China, with capacity expanding in Japan, Australia, the US, and Europe.
- **VRFB Assembly:** Electrolytes, stacks, and Balance of Plant (BoP) are integrated into VRFB systems. Leading manufacturers include Rongke Power, Sumitomo Electric, Invinity Energy Systems, and VRB Energy.
- **End-User Applications:** Deployed VRFBs support renewable integration, peak management, load shifting, and grid stability. Key markets are China, Japan, South Korea, Australia, and the US, with pilots in Europe, South America, and India.

1.4.1. GLOBAL STATIONARY STORAGE MARKET ASSESSMENT (2020–2030)

The growth of the stationary storage market is being driven by a combination of factors, including the rapid deployment of variable renewable energy, increased electrification of end-use sectors, and the need for grid flexibility and resilience. Energy storage is increasingly being integrated into capacity expansion plans, both as a peaking resource and to support grid stability.

Policy frameworks such as capacity market participation, time-of-use tariffs, and ancillary service revenues are further incentivizing storage investments. In addition, the emergence of hybrid renewable-plus-storage projects is accelerating installations, particularly in solar-dominated grids. Despite strong momentum, the market remains regionally concentrated, with China, the United States, and Europe leading in terms of installed capacity and project pipelines. However, emerging markets are beginning to show potential, particularly where grid constraints and renewable curtailment issues are becoming more pronounced.

As of 2024, global stationary energy storage installations reached an estimated 356 GW, encompassing both FTM (Front-of-the-Meter) and BTM (Behind-the-Meter) applications. This includes grid-scale systems, industrial users, and distributed residential setups. Projections indicate substantial growth, with total installed capacity expected to rise to approximately 1–1.5 TW by 2030, depending on the policy and technology adoption scenarios.

Among storage technologies, PHES remains the largest contributor, accounting for approximately 195 GW[11], (equivalent to around 1,500 GWh) of storage capacity. These systems typically offer discharge durations exceeding 8 hours, making them well-suited LDES applications. PHES is widely regarded as a mature and cost-effective LDES solution, especially in regions with favourable topography. Despite being mature and cost-effective, future deployment of PHES is constrained by geographical limitations, lengthy construction periods, environmental concerns, and high upfront capital costs when compared to modular

[11] https://www.iea.org/reports/renewables-2024/electricity

BESS. Going forward, a diversified portfolio of LDES technologies will be essential to achieve net-zero targets.

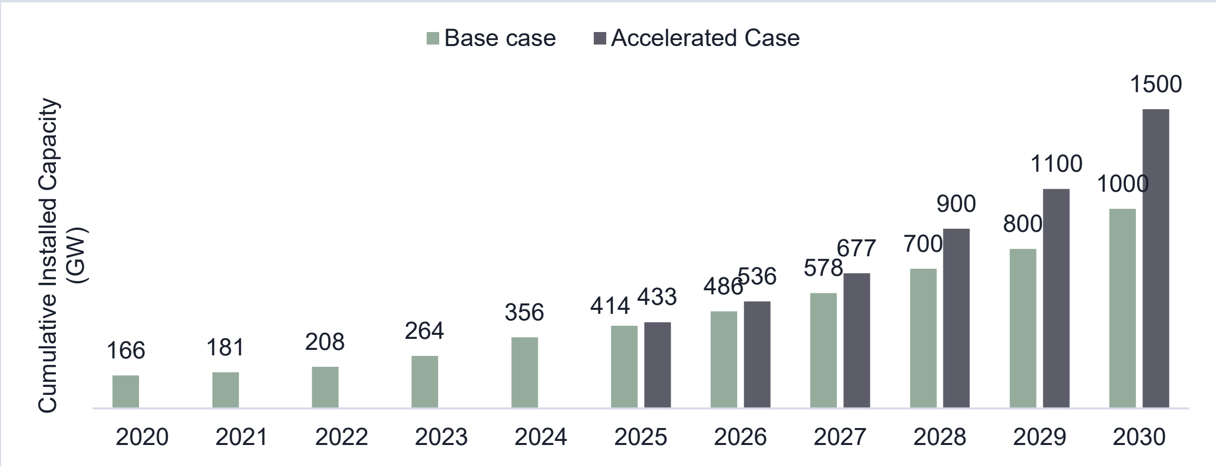

Figure 5: Trajectory of Global Stationary Storage - Cumulative Installations (GW) (2020-30)

Source: CES research and Analysis, Batteries and Secure Energy Transitions – Analysis by IEA, Annual Report 2024 of LDES Council[12]

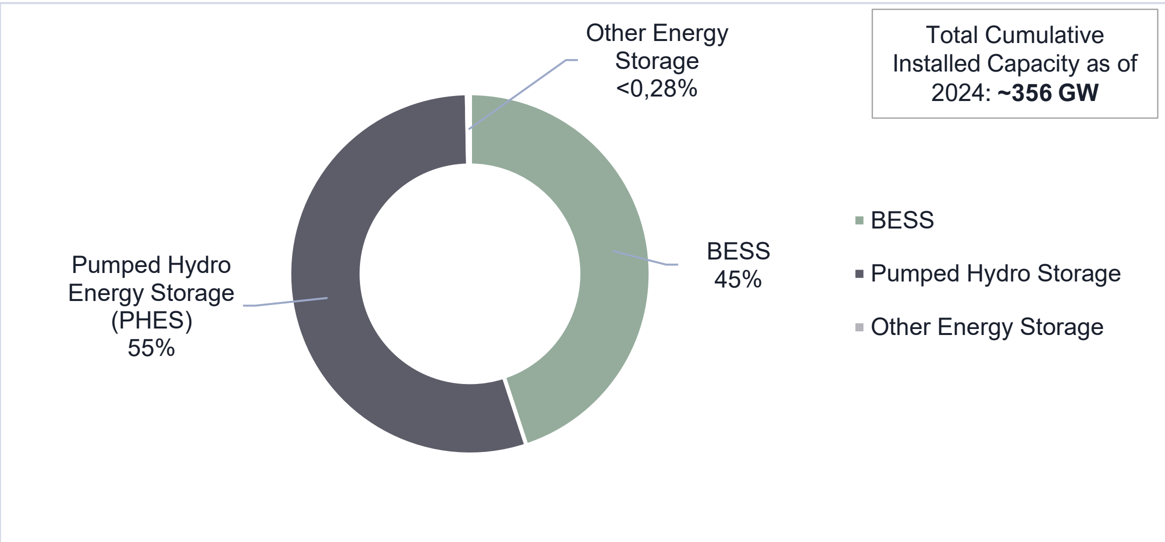

Figure 6: Global Cumulative Stationary Storage Technology Mix (in GW) in 2024

Source: CES research and Analysis, Batteries and Secure Energy Transitions – Analysis by IEA, Annual Report 2024 of LDES Council, IEA Report 2024 on Renewables, Volta Foundation Battery Report of 2024 [13]

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[12] CES research and Analysis; Batteries and Secure Energy Transitions – Analysis - IEA; Annual Report | LDES Council

[13] CES research and Analysis; Batteries and Secure Energy Transitions – Analysis - IEA; Annual Report | LDES Council

Note: Other Energy Storage Include Li-ion BESS, Long duration Electrochemical, Thermal, mechanical and chemical energy storage

BESS follows as the second-largest segment, with an estimated around 160 GW[14] of installed cumulative capacity as of 2024. This market is predominantly driven by Li-ion batteries, which have become the default choice for short-duration storage due to their high energy density, modularity, and declining costs. Li-ion-based BESS are projected to maintain market dominance through 2030.

While BESS has traditionally served short-duration applications (1–4 hours), an increasing number of projects are now deploying Li-ion systems for 6–8-hour durations, blurring the line between short- and long-duration use cases. In contrast, PHES and other alternative technologies - including mechanical, thermal, and electrochemical are primarily focused on the LDES market, where storage durations exceed 6 hours and often extend to daily or multi-day requirements.

1.4.2. LDES MARKET OVERVIEW

"LDES – A Potential Solution to Accelerate Transition to Net Zero Scenarios"

Achieving net zero targets by 2050 hinges on rapid decarbonization of the power sector, which is driving unprecedented growth in renewable energy capacity. In 2024, global RE additions reached approximately 600 – 670 GW, with cumulative renewable capacity projected to scale to nearly 5,500 GW[15] by 2030. China is expected to contribute around 60% of this global growth in RE adoption during 2024-2030, while Europe, North America, and India also play significant roles. This scale of renewable deployment introduces increasing variability into the grid, highlighting the urgent need for planning for LDES solutions.

LDES refers to a class of energy storage technologies capable of delivering continuous power output for six hours or longer. These systems address the limits of short-duration storage like Li-ion batteries, which offer 1–6 hours of fast-response storage but not extended discharge. In contrast, LDES technologies such as VRFB, PHES, and thermal/mechanical systems can deliver multi-hour to multi-day storage, making them critical for high-renewable power systems and system flexibility.

Why LDES Is Needed?

- **Balances Variable Renewable Energy (VRE):** Stores excess solar and wind generation for use during low-output periods.
- **Ensures Grid Stability and Backup:** Supports consistent power supply over extended durations, reducing reliance on fossil-based backup generators.

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14 https://volta.foundation/battery-report-2024
15 https://www.iea.org/reports/renewables-2024/electricity

- **Reduces Curtailment of Renewables:** Increases the utilization of clean energy that would otherwise be wasted.
- **Defers Costly Grid Upgrades:** Offers localized flexibility, avoiding or delaying large-scale transmission infrastructure investments.
- **Supports Hard-to-Abate Sectors:** Enables reliable, clean electricity for industrial and heavy-duty applications.
- **Improves Energy Security and Resilience:** Enhances system robustness during extreme weather, outages, or supply disruptions.

Within the LDES category, VRFBs have emerged as a strong contender, offering 4–12 hours of discharge, scalable beyond 24 hours through flexible tank sizing. Their decoupled energy and power design enables customization for diverse applications, making them well-suited for grid-scale, long-duration needs where safety, lifespan, and cost efficiency are critical. Adoption is driven by growing renewable penetration, supportive policies, and technology advantages over Li-ion and other LDES options. However, barriers such as high upfront costs, limited large-scale track record, and vanadium supply risks persist. A detailed analysis of these drivers and barriers is provided in Chapter 4.

1.4.2.1. LDES Growth Potential and Net Zero Alignment

Several regions are leading LDES adoption, driven by policy, energy transition, and grid modernization goals. China dominates with large-scale PHES and a growing portfolio of VRFB projects, supported by strong state initiatives and manufacturing investments. In the United States, momentum comes from federal programs like the Inflation Reduction Act and DOE-funded pilots advancing flow and thermal storage technologies. Europe prioritizes LDES for energy resilience and climate targets, with major projects in Germany, the UK, and Spain. Australia is actively deploying LDES to stabilize its grid and integrate renewables, with state and federal backing for VRFBs. Meanwhile, India is emerging as a key market, driven by ambitious renewable targets, rising peak demand, and curtailment issues. Recent government tenders and pilots signal a growing role for LDES in India's energy future.

As the share of RE in global electricity mixes rises, LDES will play a pivotal role in ensuring the scalability, reliability, and resilience of future energy systems.

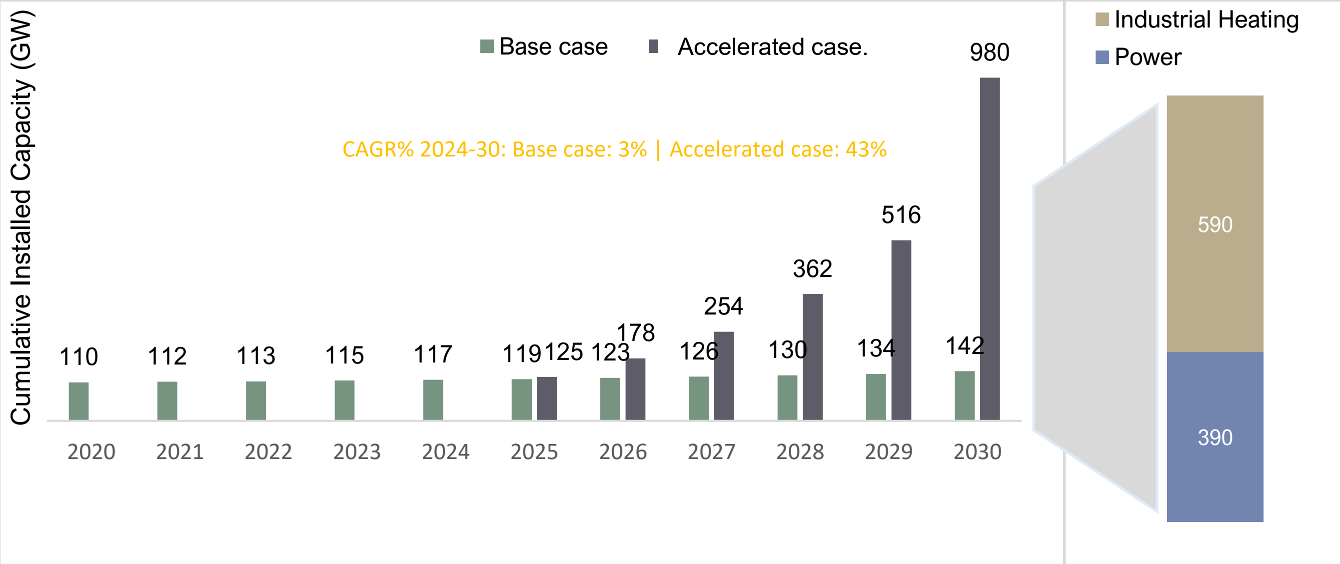

Figure 7: Cumulative LDES Installation Trajectory and Demand Forecast (GW) (2020-2030)

Source: CES Analysis, Batteries and Secure Energy Transitions – Analysis by IEA; Annual Report of 2024 by LDES Council[16]

Between 2020 and 2024, LDES technologies saw limited commercial adoption, with installations growing at an average rate of just 2% annually. This slow uptake is primarily attributed to the relatively low demand for >6-hour storage durations during this period. Most announced energy storage projects globally were sized for up to 4-hour durations, where lithium-ion batteries remain cost-competitive due to their mature supply chains and lower levelized cost of storage (LCOS) compared to alternative LDES technologies. By the end of 2024, the global installed capacity of LDES technologies stood at approximately 117 GW, according to the LDES Council. An incremental addition of around 2 GW is expected in 2025, bringing the total to 119 GW in base - reflecting a slow but steady ramp-up in project deployment.

Looking ahead, LDES adoption is expected to accelerate modestly, with annual growth rates projected to reach around 5% between 2025 and 2030. Lithium-ion systems are anticipated to continue dominating the short- to medium-duration storage segment, but interest in LDES is increasing as decarbonization targets intensify and grid flexibility needs grow.

In its latest outlook, the LDES Council projects two divergent pathways for global LDES capacity by 2030:

- In the base case, installed LDES capacity could reach ~142 GW, reflecting incremental progress under current policy and market conditions.
- In the accelerated case, aligned with net zero targets, LDES capacity could scale up to ~980 GW by 2030. This includes approximately 390 GW for the power sector, where

[16] CES research and Analysis; Batteries and Secure Energy Transitions – Analysis - IEA; Annual Report | LDES Council

storage supports grid flexibility, renewable integration, and peak demand management, and 590 GW for industrial thermal applications, where thermal energy storage enables decarbonization of high-temperature processes in hard-to-abate sectors - demonstrating LDES's potential role beyond electricity.

PHES is expected to dominate with nearly 73% share in dedicated LDES projects, while electrochemical technologies - primarily VRFBs are likely to capture around 5%, while other technologies contribute 22% in both cases by 2030. These projections highlight the critical role LDES could play in enabling system-wide flexibility, accelerating renewable integration, and supporting deep decarbonization - if cost, policy, and market barriers are addressed effectively.

1.4.3. GLOBAL VRFB DEMAND ASSESSMENT

VRFBs are a promising LDES technology which is currently in an early commercial stage. It is well-suited for 4 – 12+ hour storage durations. Their design allows independent scaling of power and energy, making them ideal for applications like renewable energy firming and multi-hour grid support. With long cycle life, non-flammable electrolytes, and stable performance over decades, VRFBs offer a reliable and safe solution to meet the growing need for long-duration storage in net-zero aligned energy.

The performance and economics of VRFBs are expected to improve significantly by 2030. Round-trip efficiency is projected to increase from approximately 70% in 2024 to 75% by 2030, enhancing overall system performance. In parallel, capital expenditure (capex)[17] is anticipated to decline from an average of $380/kWh in 2025 to around $230/kWh by 2030 - representing a cost reduction of nearly 40%. In Chapter 4, the key factors driving capex reduction are further discussed in the South African context.

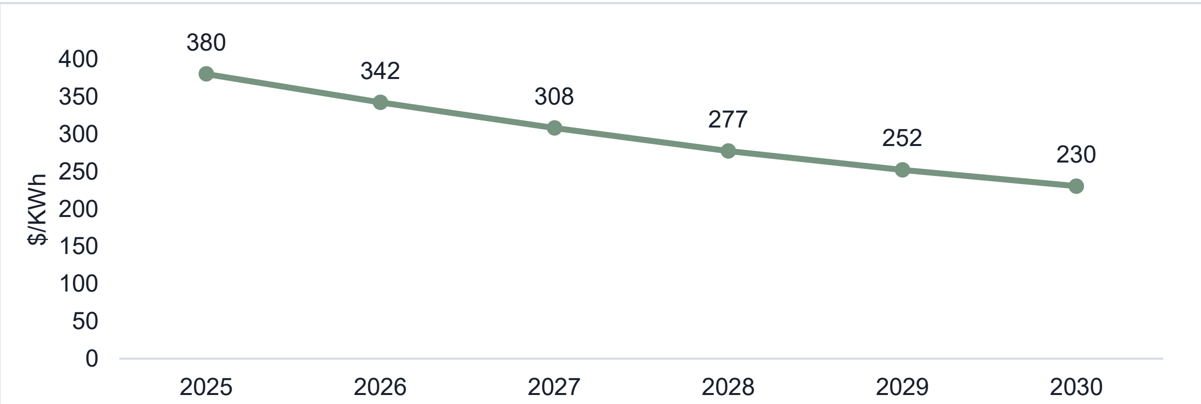

Figure 8: VRFB Capital Expenditure Forecast till 2030, for an 8-hour System ($/kWh)

[17] CES Research and Analysis and Industry Inputs

Source: CES Analysis based on industry inputs

For levelized cost of storage (LCOS) assessments, a daily single-cycle operational profile over 25 years, the LCOS of 8-hour VRFB systems reaches parity with that of lithium iron phosphate (LFP) batteries around 2030, particularly in applications where long-duration, deep cycling is critical. This is due to the capacity replacement requirements of LFP by 15th year, and the slight projected increase in LFP battery prices from 2027-28 onwards.

<u>LCOS Calculation Approach:</u>
Apply year-on-year percentage reductions reflecting (i) electrolyte cost relief from lower V_2O_5/electrolyte pricing and modest energy-density gains, and (ii) non-electrolyte cost declines (stack, PCS, BoP, assembly) from scale and design optimization.
The capex pathway is consistent with:

- *Table 11 (V_2O_5 / electrolyte sensitivity supporting electrolyte-driven declines), and*
- *0 (non-electrolyte cost-down levers in stacks, BoP, PCS, and assembly).*

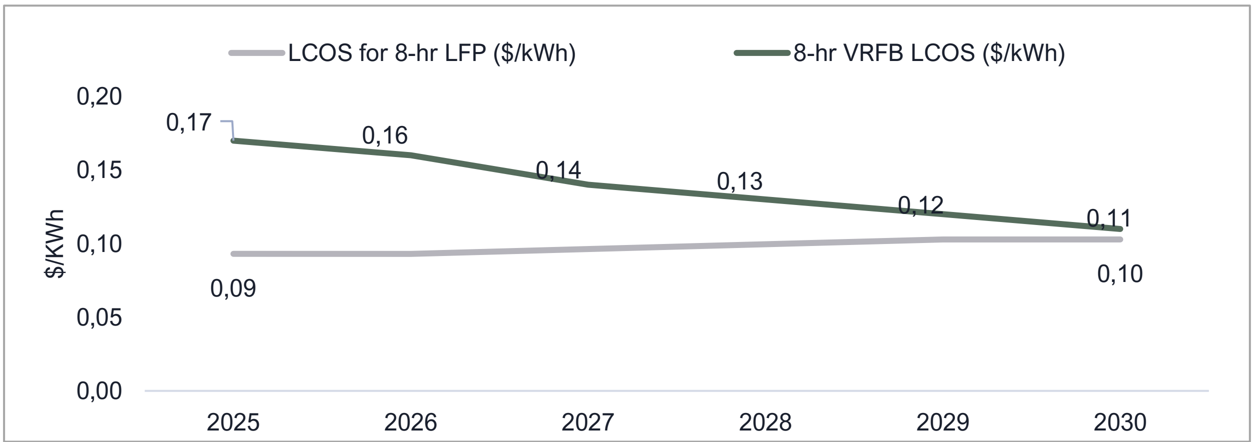

Figure 9: Levelized Cost of Storage (LCOS) for VRFB vs LFP Battery ($/kWh) until 2030

Note: The LCOS comparison has been carried out for an 8-hour VRFB system instead of a 6-hour system, as the unit economics of VRFBs are more favourable at longer durations. At 6 hours, the cost benefits of the technology are not fully realized, whereas at 8 hours the incremental cost of adding energy capacity is relatively low, resulting in significantly better economics and a more meaningful comparison with LFP batteries.

Source: CES Analysis[18]

Between 2020 and 2024, VRFB adoption was limited as most storage projects targeted ≤8-hour durations where LFP batteries offered lower costs and mature supply chains. High upfront investment, shorter project horizon assumptions in LCOS models, and lack of supportive policies further constrained deployment outside regions like China, Japan, South Korea, and Australia. With policy shifts toward duration-based metrics and long-term value, VRFBs are expected to gain greater relevance in the next phase of LDES growth. As policy

[18] CES Research and Analysis

frameworks begin to shift toward duration-based performance metrics and long-term value realization, VRFBs may gain greater relevance in the next phase of LDES market evolution.

Global VRFB Demand Forecast 2024-30

As of 2024, total installed VRFB capacity globally is estimated at ~4 GWh, deployed by key players such as Rongke Power, Sumitomo Electric, VRB Energy, Invinity Energy Systems, and others. Asia leads in global VRFB deployment, with notable installations in China, Japan, and South Korea, followed by emerging interest in Europe and North America.

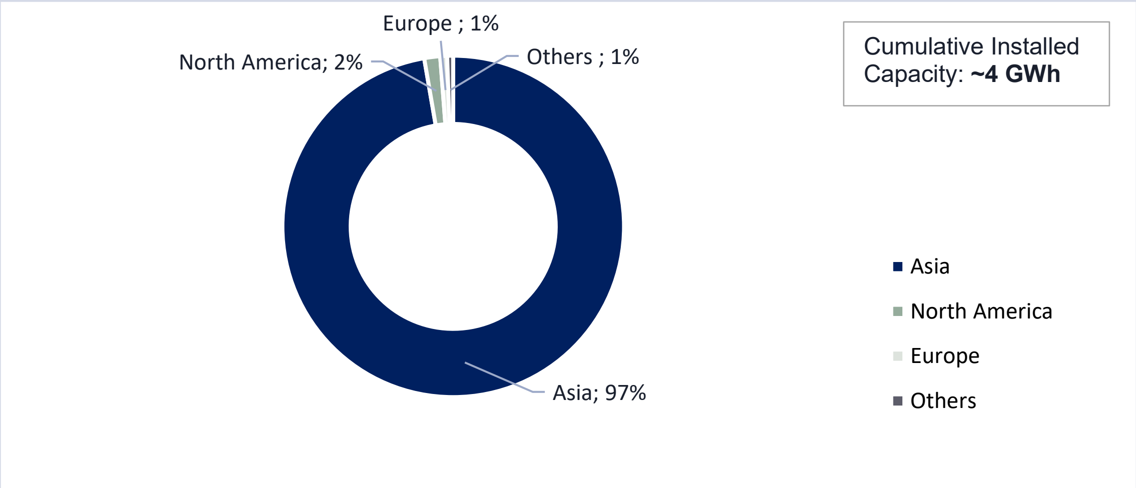

Figure 10: Cumulative Region Wise Deployments of VRFB as of 2024

Source: Industry databases, company announcements, IESA (India energy storage alliance) database

VRFB demand forecast inputs: CES estimates for VRFBs are assumed to account for 3–5% of total LDES deployments through 2030, consistent with estimates from the LDES Council and observed project trends in 2023–24.

Looking ahead, VRFB market growth is expected to remain gradual through 2025–2026, as the ecosystem matures, and project pipelines develop. From 2027 onward, significant acceleration is projected, driven by increasing demand for LDES, supportive policies, and cost optimization.

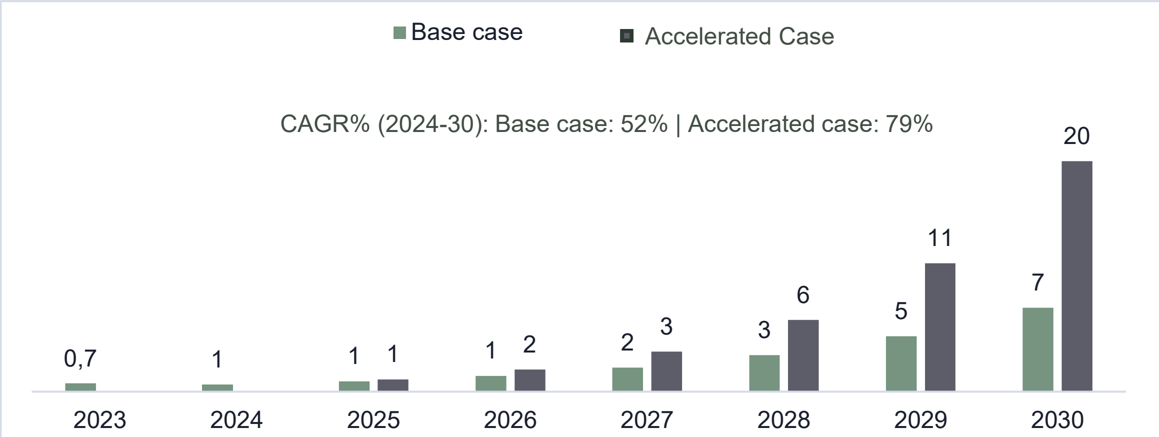

Figure 11: Cumulative VRFB Installed Capacity and Demand Forecast until 2030 (GW)

Source: CES Analysis

VRFB Market forecast Inputs

By 2030, the power sector is expected to deploy 390 GW of LDES capacity globally. Of this, PHES is projected to contribute approximately 73%, VRFB around 5%, and the remaining 22% from other emerging storage technologies. Within this context, VRFB capacity is expected to reach 7GW / 40GWh in CES base case and around 20 GW / 120GWh in CES Accelerated case of cumulative deployment (implying 5-6 hours of storage duration, which is also aligned with the estimates of LDES Council). This corresponds to a market value of ~$3 billion under the CES base case, rising to ~$12 billion in a CES accelerated case, net-zero aligned scenario representing ~4-5% of total global LDES demand by the end of the decade.

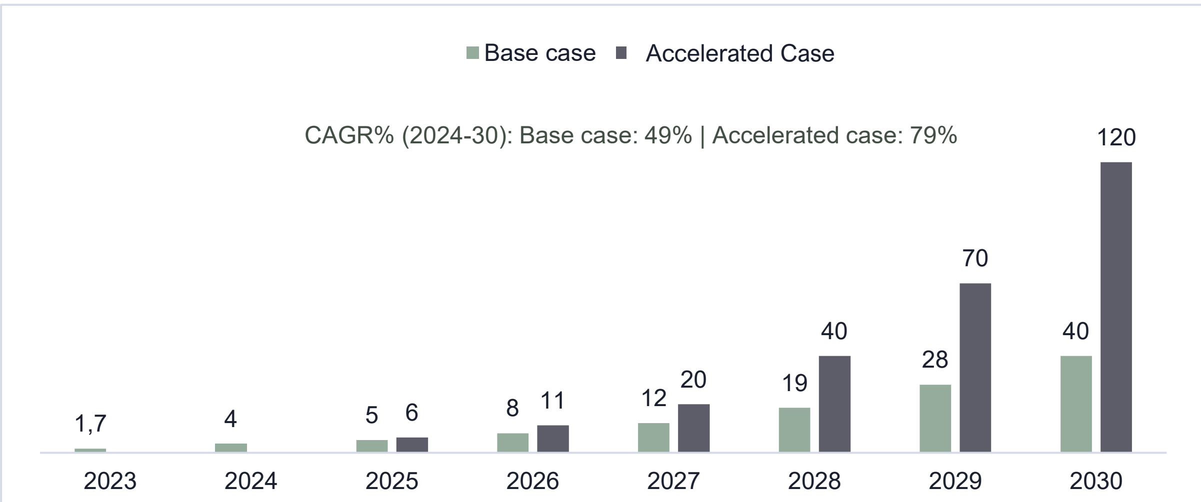

Figure 12: Cumulative VRFB Installed Capacity and Demand Forecast until 2030 (GWh)

Source: CES Analysis

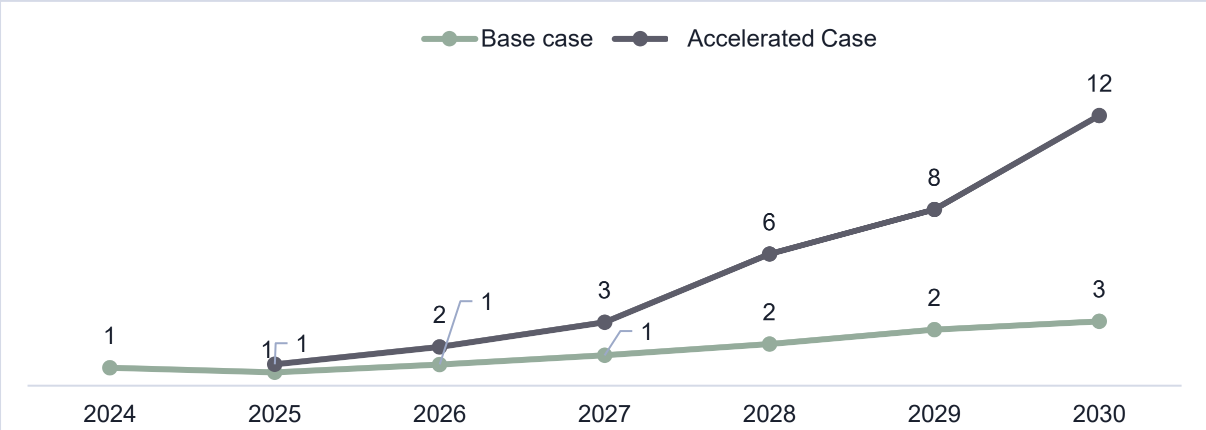

Figure 13: VRFB Cumulative Market Value Forecast until 2030 (in $ Billion)

Source: CES Analysis

Note:
The market value forecast in Figure 13 is derived from capacity projections multiplied by year-specific capex, not the other way around. First, cumulative VRFB capacity (GWh) is estimated under base and accelerated case scenarios. Then, the declining capex trajectory from Figure 8 (e.g., $380/kWh in 2025 to $230/kWh in 2030) is applied to those capacity numbers to calculate annual and cumulative market value.

1.4.4. VANADIUM ELECTROLYTE: THE KEY VANADIUM-BEARING COMPONENT IN VRFB

VRFBs utilize specialized vanadium electrolytes (VE) typically composed of vanadium pentoxide (V_2O_5) dissolved in diluted sulfuric acid (H_2SO_4) solution. A commercially available VE formulated with an equimolar ratio of V^{3+} and VO^{2+}, accounts for approximately 30-50% of the total system cost. Other vanadium-containing compounds used to produce the electrolyte are vanadyl sulphate ($VOSO_4$), and, to a lesser extent, vanadium trioxide (V_2O_3). Among these, V_2O_5 is the most widely used raw material for producing VE, due to low cost, high availability, and the most produced form of vanadium globally. Considering the weight percentage distribution of VRFB components, 85% of the battery component is VE, which is likely to be 100% recyclable. [19,20,21]

Requirement of Vanadium Pentoxide (V_2O_5) per kWh of VRFB Capacity

The amount of V_2O_5 required to deliver 1 kWh of energy in VRFB systems is outlined in table below, based on data from various industry sources. On average, about 8 kg of V_2O_5 is required per kW of storage capacity, as supported by CES Analysis and Australian Vanadium Limited (AVL). Some estimates, such as from the Bushveld Minerals Annual Report, indicate a slightly higher requirement of up to 9.8 kg/kWh depending on system design and efficiency.[22,23,24]

Table 1: Estimated V_2O_5 Requirement per kWh of VRFB Energy Storage Capacity

Kg Requirement per kWh of VRFB Capacity*	Sources
8	CES Analysis
8	AVL Investor Presentation, 2025
9.8	Bushveld Minerals Annual Report 2020

** No global standards for VRFB electrolyte specification are available yet.*

Note: Vanadium electrolyte is typically produced at 95-99% purity, and 1 t of V_2O_5 corresponds to about 0.56 t of vanadium metal equivalent. For VRFB systems, approximately 70 liters of electrolyte are used per 1 kWh of storage capacity, requiring around 8 kg of V_2O_5.

Vanadium solubility depends on its oxidation state and operating conditions

Vanadium concentrations up to 2.0 M (Molarity) are considered chemically stable and suitable for use in VRFB electrolytes. While achieving this concentration is feasible under controlled laboratory conditions using advanced synthesis techniques, it remains challenging in practical applications. This difficulty arises primarily from the slow dissolution rate of V_2O_5 in sulfuric acid, which limits the speed at which vanadium can be incorporated into the electrolyte. When concentrations exceed 2.0 M, the electrolyte becomes supersaturated, leading to the formation of complex compounds and precipitates. These changes compromise the stability of the electrolyte and negatively impact long-term performance. As a result, commercial VRFB

19 Skyllas-Kazacos, M., Vanadium redox battery electrolyte. 2004, US20040241552A1, Unisearch Ltd: United States.

20 J. Martin et al., Preparation of Electrolyte for Vanadium Redox-Flow Batteries Based on Vanadium Pentoxide. Energy Technol. 2020, 8, 2000522.

21 Investor Presentation | February 2025 | ASX:AVL.

22 Bushveld Minerals Annual Report 2020

23 F. Rahman, M. Skyllas-Kazacos, Vanadium redox battery: Positive half-cell electrolyte studies. J. Power Sources 189 (2009) 1212-1219.

24 Investor Presentation | February 2025 | ASX:AVL.

systems typically restrict vanadium concentrations to around 1.6 -1.8 M to avoid supersaturation and maintain reliable operation.

Figure 14 illustrates the relationship between vanadium concentration (mol/L), V_2O_5 requirements (kg/kWh), and electrolyte utilization efficiency (%) in VRFB systems. This analysis highlights the trade-off between maximizing energy density and maintaining electrolyte stability.

For practical calculations, a 70% utilization factor is assumed, meaning only about 70% of the V_2O_5 in the electrolyte contributes to energy storage. The remaining 30% remains electrochemically inactive due to several constraints:

- Thermodynamic limits on cell voltage to prevent hydrogen and oxygen evolution.
- Kinetic restrictions on vanadium redox reaction rates.
- Solubility and thermal stability constraints that cap vanadium concentration.
- Design buffers to prevent overcharge, overdischarge, and membrane degradation.

These factors ensure that a portion of vanadium remains chemically available but electrochemically inactive under normal operating conditions. While higher utilization rates are being explored in research, no validated commercial data currently supports their deployment. These design considerations are essential for ensuring electrolyte stability, operational safety, and long-term reliability of VRFB systems.[25]

	Total Vanadium	V_2O_5	Electrolyte Utilization (kg/kWh)			
	Mole	Mass (Kg)	70%	80%	90%	95%
Saturated	1.60	6	8	7	6	6
Saturated	1.80	6	9	8	7	7
Saturated	2.00	8	11	10	9	8
Supersaturated	2.20	11	15	13	12	11
Supersaturated	2.60	17	25	22	19	18

Utilization factor in % → 70%

Saturated: Balanced & Highly Stable

Supersaturated: Less Stable, Formation of Complex Chemical Compounds & Precipitation

Figure 14: Impact of Vanadium Concentration & Electrolyte Utilization on V_2O_5 Requirement

Source: CES Assessment based on industry reports, industry feedback

Vanadium Concentration Zones in VRFB Electrolytes

Stable Zone (1.6 - 1.8 M): Solubility limits of V ions constrain practical concentrations. Vanadium concentrations up to 2.0 M are chemically stable; however, in practical applications, VRFBs typically operate within the range of 1.6-1.8 mol/L. This range offers an optimal balance between energy density and electrolyte stability. It ensures reliable long-term operation across

[25] M. Skyllas-Kazacos et al., Vanadium Electrolyte Studies for the Vanadium Redox Battery-A Review. ChemSusChem 2016, 9, 1 – 24.

a temperature range of 10-40 °C and minimizes the risk of precipitation and associated performance degradation.

Supersaturation Zone (>2.0 M): Vanadium concentrations exceeding 2.0 M enter a supersaturated state, which significantly increases the risk of precipitation and chemical instability. Figure 14 (red zone) illustrates the onset of supersaturation. Precipitation leads to multiple operational issues:

- Flow path blockage
- Electrode fouling
- Membrane clogging
- Irreversible capacity loss
- Degraded system performance
- Reduced cycle life and reliability
- Increased maintenance requirements

Temperature Sensitivity: Vanadium ion solubility is highly sensitive to temperature, which affects electrolyte stability. At low temperatures (<10 °C), there is an increased precipitation risk for V^{2+}, V^{3+}, and VO^{2+} ions. Whereas, at high temperatures (>40 °C), VO_2^+ (V^{5+}) ions are more prone to forming precipitates. Temperature extremes during idle periods or high/low states of charge (SOC) can trigger precipitation. These sensitivities narrow the safe operating window and may necessitate active temperature control, especially in environments with wide thermal fluctuations.

Commercial Practice:

To ensure consistent performance and minimize maintenance requirements, most commercial VRFB systems operate with vanadium concentrations in the range of 1.6-1.8 mol/L, dissolved in 3-5 mol/L sulfuric acid. This composition has been shown to deliver stable performance within a temperature range of 15 °C to 40 °C. Maintaining this concentration range helps prevent precipitation, supports long-term reliability, and reduces the likelihood of system degradation under varying operational conditions.

1.4.5. VANADIUM ELECTROLYTE DEMAND FORECAST (2025-30)

In 2024, annual VRFB installations reached up to 2 GWh, reflecting modest growth as the technology remained in early commercial stages. However, starting from 2027, annual deployment is expected to accelerate significantly. By 2030, annual installations are projected to reach approximately 12 GWh in the CES base case and up to 50 GWh in the CES accelerated-case scenario. This anticipated scale-up will be accompanied by a corresponding surge in demand for vanadium-based electrolyte, highlighting the need for parallel investments in raw material supply and electrolyte production capacity.

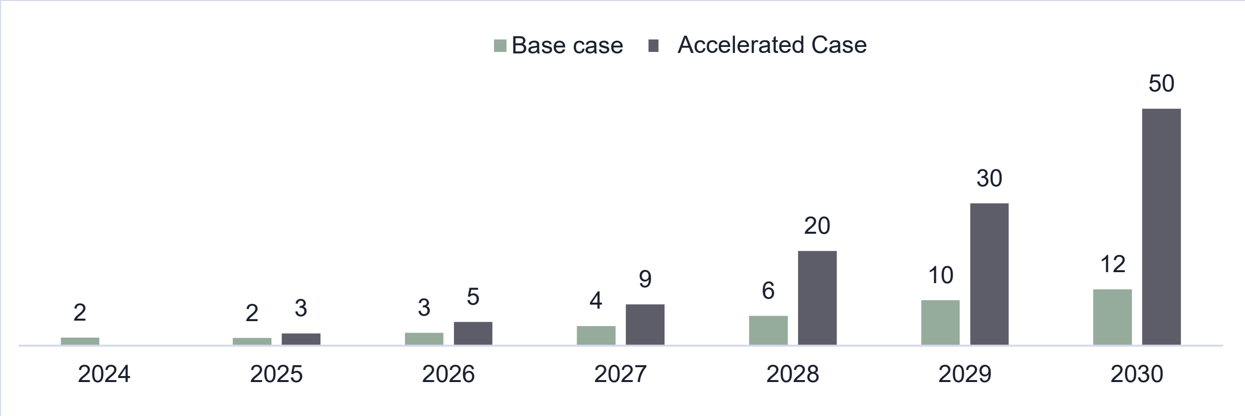

Figure 15: Annual VRFB Installed Capacity and Demand Forecast until 2030 (GWh)

Source: CES Analysis, company announcements, industry inputs

Estimating vanadium electrolyte demand in VRFBs is based on ~70 litres per kWh of capacity, with an assumed density of 1.3 kg/L. The analysis focuses on commercially proven Gen1 electrolyte chemistry to ensure conservative and consistent projections, though newer formulations are under development.

A unique advantage of VRFB technology is that electrolyte is nearly 100% recoverable although reusability has not been considered for 2024-30 forecast since many companies claim that electrolyte can be recycled / reused after 25-30 years. At end of life, it can be reused in new battery systems or processed to extract high-purity vanadium compounds, offering long-term economic and environmental benefits through material circularity. **Between 2024 and 2030, as VRFB deployment scales, new installations will rely on virgin vanadium for electrolyte production. However, existing systems may enable partial electrolyte reuse, helping to reduce the demand for fresh vanadium and improve resource efficiency.** Based on projected VRFB installations, vanadium electrolyte demand in 2024 is estimated at ~182 kt. As VRFB adoption scales, this demand is expected to grow significantly reaching approximately 1,100 kt by 2030 in the base case, and up to 4,600 kt under the accelerated-case scenario, aligned with net-zero storage targets.

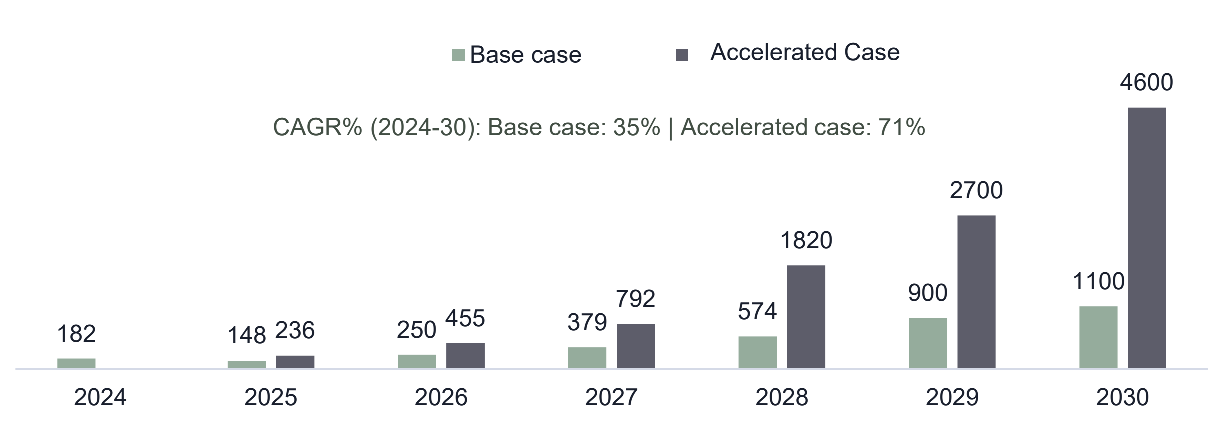

Figure 16: Annual VRFB Electrolyte Demand forecast until 2030 (kt)

Note: 'kt' in this chart refers to the electrolyte solution mass

Source: CES Analysis, company announcements, industry inputs

1.5. Global Supply Landscape of VRFB and Electrolyte

1.5.1. VRFB DEPLOYMENT LANDSCAPE & SUPPLY CAPACITY FORECAST

Table 2: VRFB Projects Deployed Globally (as of December 2024)[26]

Company	Region	Deployed Capacity	Company-Level MoUs, Collaborations & Support
VRB Energy	China	32MWh	• Majority-owned by BID Group, a Beijing-based clean energy investor • Policy and strategic support from China's NDRC • MoU with Chengde Vanadium Titanium for vanadium supply chain integration
	China	100MW/500MWh	
	Europe and Asia	0.32 MWh	

[26] Industry inputs; company websites; public announcements

Company	Region	Deployed Capacity	Company-Level MoUs, Collaborations & Support
			• Collaboration with Yicheng Municipal Government to develop a 3 GWh VRFB plant and 100 MW/500 MWh project
Invinity Energy Solutions	UK	5 MWh	• Formed a 50:50 joint venture with U.S. Vanadium for U.S. battery manufacturing and sales. • Created Vanadium Electrolyte Rental Ltd. with Bushveld Minerals to lease electrolyte for projects. • Signed manufacturing MoU with Everdura (Taiwan); received £2.5M investment from Everbrite
	Australia	8 MWh	
	Canada	8.4 MWh	
Sumitomo Electric	Japan	111 MWh	• Long-term R&D and demo support from Japan's NEDO agency • Collaborated with New York Power Authority (NYPA) for U.S. pilot deployment. • Signed MoU with Morocco's MASEN for North African energy projects. • Worked with Hokkaido Electric Power Co. on large-scale Japanese VRFB
	Usa	12 MWh	
	Morocco	0.5 MWh	
	Japan	8 MWh	
	Japan	0.75 MWh	
	Japan	3 MWh	
	Belgium	1.7 MWh	
	Taiwan	0.75 MWh	
Cell Cube	North America	37 MWh	• Signed MoU with Australian Vanadium Ltd (AVL) to jointly deploy and source electrolyte in Australia. • Partnered with G&W Electric (USA) to distribute VRFB systems for U.S. microgrids. • Tech and deployment collaboration with GmbH (Germany) for distributed energy projects • Part of Austrian community energy pilot integrating long-duration storage
	South America	1.4 MWh	
	Europe	17.28 MWh	
	Middle east and Africa	6 MWh	
	Asia Pacific	3 MWh	
	Australia	6 MWh	
Rongke Power	China	175 MWh/ 700MWh	• Supported by State Grid Corporation of China for multiple utility-scale VRFBs. • Collaborated with Huaneng Power on world's first VRFB-enabled black-start of a thermal plant. • Leading developer of the Dalian 200 MW / 800 MWh project (world's largest VRFB) • Beneficiary of strong national and regional government investment programs
	China	10 MWh	
	China	100 MWh/ 400 MWh	
	China	36 MWh	
	~1900 MWh of more projects deployed by Rongke Power		

Source: CES Research and Analysis; Company Websites; Public announcements

As of December 2024, VRFB technology continues to gain traction globally, with both operational projects and a robust pipeline of upcoming installations. Figure 17 shows the market share of VRFB companies based on their projects deployed and Table 3 elaborates on the completed VRFB deployments across regions such as China, Japan, UK, Australia, Canada, and the EU, led by key players like Rongke Power, Invinity Energy Systems, CellCube, and Sumitomo Electric. China remains the frontrunner in terms of scale, with Rongke Power's 175 MW/ 700 MWh Dalian project being the largest operational VRFB in the world. Europe and the UK have witnessed steady mid-scale adoption, while Canada and Australia are emerging as strong adopters, often backed by public funding and renewable integration initiatives.

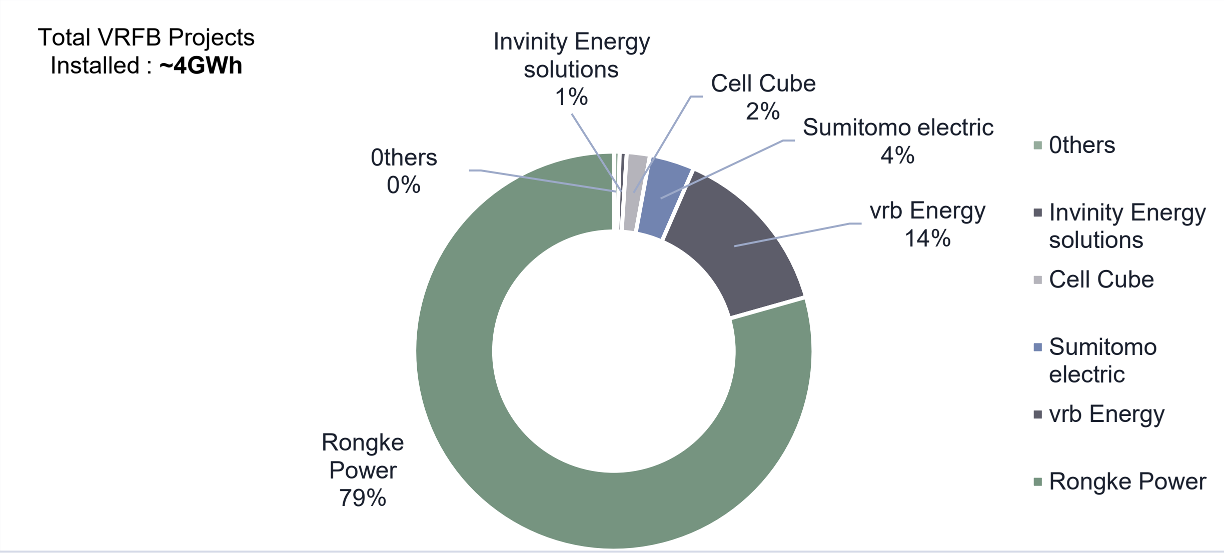

Figure 17: Market Share of VRFB OEMs (based on projects deployed as 2024)

Source: CES Research and Analysis; Company Websites; Public announcements[27]

In upcoming and announced VRFB projects, Asia continues to dominate the pipeline, with Rongke Power planning a 200 MW / 800 MWh Phase II-B project in China and Delectrik progressing with a 1 MW/ 3 MWh system in India. North America and Europe remain a key target market, as seen with Invinity's U.S. and UK projects, H2 inc. Spain project and CellCube's Canada pilot. Smaller but strategic deployments are also underway in Singapore, where VFlowTech is working with Public Utilities Board, Singapore and Shell on grid resilience pilots. These projects are backed by a growing number of partnerships, joint ventures, and public-private MoUs, indicating a globally distributed, policy-supported momentum for vanadium-based LDES solutions.

Table 3: VRFB Projects Announced/ in Pipeline (as of December 2024)[28]

Company	Region	Capacity	Company-Level MoUs, Collaborations & Support
Invinity Energy Solutions	USA	2 MW/ 10 MWh	• Partnership with Elemental Energy • Electrolyte support via JV with Bushveld
	UK	>400MWh	
Rongke Power	China	200 MW/ 800 MWh	• Backed by State Grid Corp. of China • Strategic government investment in LDES
V Flowtech	Singapore	0.25 MW/ 1.05 MWh	• Partnered with NTU Singapore, PUB, and Shell Singapore

27 CES Research and Analysis; Company Websites; Public announcements
28 Company Websites; Public Announcements

Delectrik	India	1 MW/ 3 MWh	• MoU with NTPC Renewable Energy Ltd • Collaboration with IOCL
Cell Cube	Canada	0.25 MW/ 1 MWh	• Partnered with Kibo Energy for Ontario-based pilot projects
H2 Inc	Spain	1.1 MW/ 8.8 MWh	• Project under EU Horizon 2020; collaboration with Red Eléctrica (REE)

Source: CES Research and Analysis; Company Websites; Public announcements

As of 2024, the global manufacturing capacity for VRFBs stands at approximately 4 GWh, with contributions from leading players such as Rongke Power, Invinity Energy Systems, Sumitomo Electric, and VRB Energy. Several emerging companies including VFlowtech, CellCube and Delectrik are also scaling up operations. By 2030, global manufacturing capacity is projected to increase nearly 4 times to ~15 GWh, driven by strong growth plans and emerging demand, particularly from CellCube, Delectrik, and Chinese manufacturers. This anticipated scale-up reflects growing market confidence in VRFBs as a viable LDES solution.

Table 4: Global VRFB Production Capacity (as of Dec 2024)[29]

Company	Manufacturing Capacity (GWh) as of 2024	Manufacturing Capacity (GWh) by 2030	Company Headquarters
Rongke Power	2.5	3.5	China
H2 Inc.	0.33	1.2	South Korea
i-battery Energy technology	0.3	1	China
Sumitomo Electric Industries	0.2	0.5	Japan
Invinity Energy Solutions	0.2	0.5	United Kingdom
CellCube	0.16	5 (8 - Beyond 2030)	Austria
VFlowtech	0.1	1	Singapore
VRB Energy	0.05	0.55	USA
Delectrik	0.02	1	India
Others	0.05	0.5	
Total	**~4**	**~15**	

Source: CES research and analysis of the nameplate capacity addition announcements from various company websites, public announcements

[29] CES research and Analysis; Public announcements; Company Websites

1.5.2. KEY OEMS IN VRFB VALUE CHAIN – ELECTROLYTE PRODUCTION

This section outlines the production capacities of the top eight vanadium electrolyte manufacturers, which collectively account for approximately 93% to 95% of the global production. This concentration indicates a highly consolidated market, with a few key players controlling most of the supply. The total annual production capacity is estimated at 3.7 to 4.0 GWh equivalent, which is critical for meeting the anticipated rise in VRFB deployments.

Table 5: Leading Vanadium Electrolyte Manufacturers in 2024

Company Name	Country	Production Capacity as of 2024 (mn litres/year)	Production Capacity as of 2024 (in GWh eqv. /year)	Production Share
Dalian Borong New Materials Co., Ltd.	China	150	2.14	57%
Sichuan Development Xingneng Vanadium Energy Technology Co., Ltd.	China	60	0.86	23%
Shaanxi Wuzhou Mining	China	10	0.14	4%
Bushveld Energy	South Africa	8	0.11	3%
Hunan Huifeng High Energy Co., Ltd.	China	5	0.07	2%
Le System Co., Ltd.	Japan	5	0.07	2%
US Vanadium	USA	4	0.06	1.5%
Tranvic Group	China	3.5	0.05	1%

Source: CES Research and Analysis, Company Websites, Public announcements

Vertically Integrated (Electrolyte + VRFB Assembly)

Note: The aforesaid table doesn't contain the exhaustive list of global manufacturers, only the major ones

Brief Profile of Major Electrolyte Manufacturers

- **Dalian Rongke Power** has expanded beyond manufacturing into upstream and midstream segments. In February 2025, it began building facilities for electrolyte and bipolar plate production, signalling its intent to internalize the supply chain, reduce third-party reliance, and enhance cost and quality control[30].
- **Sichuan Development Xingneng (China)** – Second-largest player; operates cost-efficient short-process production for scalability.

[30] https://vanitec.org/latest-from-vanitec/article/dalian-rongke-power-launches-rmb-520-million-electrolyte-and-bipolar-plate-project

- **Shaanxi Wuzhou Mining (China)** – Vertically integrated with Zhongcun vanadium mine and key supplier for large VRFB projects like 500 MW Yulin.
- **Bushveld Energy (South Africa)** – Ceased operations in June 2025. Known for high-grade vanadium access, electrolyte leasing model, and partnerships with Invinity & CellCube.
- **Hunan Huifeng High Energy (China)** – Strong upstream access and over 25 vanadium-related patents (vanadium processing and electrolyte manufacturing).
- Le System (Japan) – Sources feedstock from Technology Metals' MTMP project in Australia; specializes in advanced electrolyte formulations for compact VRFBs; strong ties to Japan's renewable sector.
- **US Vanadium (USA)** – Produces ultra-high-purity electrolyte; supports North American VRFB supply chain from Arkansas. Its operations focus on vanadium recovery and purification.
- **Tranvic Group (China)** – Leverages vanadium/titanium resources in China, short-process production lines, and licenses advanced electrolyte patents to other Chinese producers.

Competitive Positioning

This analysis is structured around several critical dimensions that determine a company's strategic strength in the VRFB value chain: technological expertise, production scale, access to raw materials, and strategic partnerships. The presence of a green checkmark (✓) in the following table indicates that a company meets the criteria for that specific category.

Dalian Borong is the most comprehensively positioned player, excelling in technology, scale, raw material access, and partnerships. Its decades-long R&D in vanadium chemistry, role in setting national benchmarks, and validation by global battery manufacturers provide a strong technological edge, reinforced by massive production infrastructure.

Sichuan Development Xingneng Vanadium stands out for its cost-efficient short-process production and economies of scale. While it meets criteria for scale and raw material access, it lacks the technological leadership and strategic partnerships seen with Dalian Borong.

Shaanxi Wuzhou Mining operates at a smaller scale but benefits from vertical integration with upstream vanadium mining, ensuring raw material security - a critical advantage in a supply-constrained market. However, it falls short on technology and scale.

Bushveld Energy was notable for vertical integration, innovative electrolyte leasing, and partnerships with VRFB manufacturers like Invinity and CellCube. Despite these strengths, its closure in June 2025 diminishes its relevance and reduces global supply diversification.

Other players - Hunan Huifeng High Energy, Le System, US Vanadium, and Tranvic Group, have smaller capacities but offer niche strengths. Hunan Huifeng and Tranvic leverage strong raw material access and IP portfolios, Le System specializes in advanced formulations and strategic sourcing from Australia, and US Vanadium plays a key role in North America with ultra-high-purity electrolyte production.

Table 6: Competitive Positioning of Leading Vanadium Electrolyte Manufacturers in 2024

Company Name	Country	Production Capacity as of 2024 (mn litres/year)	Production Capacity as of 2024 (GWh eqv. /year)	Production Share	Techno-logical Forte	Scale Advantage	Access to Raw Materials	Partner-ships
Dalian Borong New Materials Co., Ltd.	China	150	2.14	57%	✓	✓	✓	✓
Sichuan Development Xingneng Vanadium Energy Technology Co., Ltd.	China	60	0.86	23%	✓	✓	✓	✓
Shaanxi Wuzhou Mining	China	10	0.14	4%			✓	✓
Bushveld Energy	South Africa	8	0.11	3%			✓	✓
Hunan Huifeng High Energy Co., Ltd.	China	5	0.07	2%	✓		✓	
Le System Co., Ltd.	Japan	5	0.07	2%	✓		✓	✓
US Vanadium	USA	4	0.06	1.5%				✓
Tranvic Group	China	3.5	0.05	1%	✓		✓	

Source: CES Research and Analysis, Company Websites, Public announcements

In summary, the market is dominated by Chinese firms, particularly Dalian Borong and Sichuan Xingneng, which combine scale, technology, and supply chain integration. Smaller players contribute to regional diversification and innovation in the VRFB ecosystem.

Strategic Implications: Heavy production concentration in China creates both opportunities (scale, maturity) and risks (supply chain vulnerability). Bushveld's exit further reduces diversification, underscoring the need for regional capacity building in the U.S., EU, and Australia to support energy storage independence and localization strategies.

1.5.3. KEY OEMS IN VRFB VALUE CHAIN – COMPONENT MANUFACTURING

In the VRFB sector, stack assembly is the USP as it dictates performance, efficiency, and cost. Unlike the mature electrolyte value chain, stack assembly remains less industrialized due to the complex integration of membranes, electrodes, and bipolar plates, creating opportunities for innovation and competitive differentiation

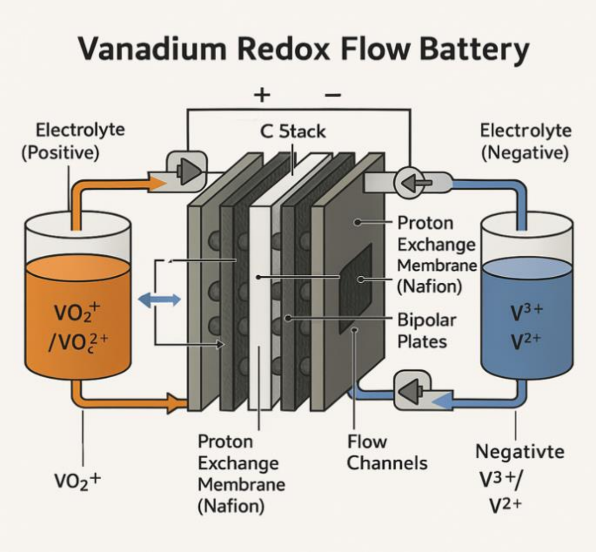

Figure 18: Key Components of VRFB System

Source: CES Research and Analysis, Company Websites, Public announcements

Component manufacturing for VRFBs shows balanced global participation, with growing specialization among firms producing key hardware. Major players in full systems and critical components like stacks and membranes are highlighted below

Brief Profile of Major Component Manufacturers

- **Sumitomo Electric** (Japan) is a pioneer with over 30 years of R&D, known for proprietary membrane and stack technology deployed in 180+ MWh of projects. Its innovation and reliability make it a leader in utility-scale applications.
- **Invinity Energy Systems** (UK/Canada) specializes in modular stack designs for scalable deployment, ideal for commercial and industrial use. It follows a capital-efficient model, outsourcing most manufacturing while retaining in-house stack production in Europe and North America for flexibility and regional responsiveness.
- **V-Flow Tech** (Singapore) offers cost-effective, modular VRFB systems with proprietary designs enabling independent scaling of power and energy post-installation. Its adaptability suits diverse applications, from off-grid solar in Africa to grid stabilization in Europe and Asia, with deployments in 10 countries.
- **H2 Inc.** (South Korea) operates one of the world's largest VRFB plants (330 MWh/year). Fully vertically integrated, it manages R&D, stack design, membrane fabrication, and assembly, optimizing performance and longevity through tailored ion-exchange membranes.
- **Storion Energy** (USA), formed by Stryten Energy and Largo Clean Energy, focuses on building a localized North American supply chain. It uses a proprietary continuous electrolyte manufacturing process and offers a leasing model to reduce upfront costs, appealing to utilities and industrial clients.

- **Dalian Rongke Power** (China) runs gigafactory-scale operations with 1 GW (2.5 GWh) annual capacity and over 3 GWh deployed globally. It also owns UniEnergy Technologies' IP, strengthening its advanced stack technology portfolio.
- **Solibra Energy Storage Technologies** (Germany) is recognized for proprietary membranes that enhance ionic conductivity and reduce vanadium crossover, improving efficiency and lifespan. It manufactures complete stacks in-house for tight integration and high performance in the European market.

Overall, these companies form a globally distributed, technologically diverse VRFB ecosystem.

Case Studies: Supply Chain Integration in VRFB Component Play to Electrolyte Play

Amongst the major OEMs mentioned in the previous sections, the following are highlighted as companies that have achieved vertical integration across key stages – mining, electrolyte production, and battery assembly.

- Dalian Rongke Power has expanded beyond manufacturing into upstream and midstream segments. In February 2025, it began building facilities for electrolyte and bipolar plate production, signalling its intent to internalize the supply chain, reduce third-party reliance, and enhance cost and quality control.
- Sumitomo Electric, a long-standing VRFB leader, has in-house electrolyte production capabilities. Its proprietary technology and robust infrastructure make it a stable, self-reliant player in Asia.
- Storion Energy offers full value chain control—from vanadium mining via Largo to electrolyte production and VRFB assembly. This integration supports cost management, quality assurance, and supply security, aligning with North America's localization priorities.
- Le System Co., Ltd. produces both vanadium electrolyte and compact VRFB systems. Though smaller in scale, its integration and innovation enable it to serve niche markets in Japan's decentralized energy sector effectively.
- Shaanxi Wuzhou Mining combines vanadium mining with downstream battery projects, supplying large-scale initiatives like the 500 MW VRFB project in Yulin, Shaanxi. This reflects China's strategy to secure its domestic energy storage supply chain.
- Lastly, Bushveld Energy, before ceasing operations in June 2025, exemplified vertical integration with vanadium mines, electrolyte production, and strategic VRFB investments (Invinity, CellCube). Its exit marks a major shift in Africa's VRFB landscape, creating opportunities for new entrants.

Strategic Implications: Vertical integration is emerging as a key competitive advantage, enabling firms to mitigate raw material risks, lower costs, and accelerate deployment in a fast-evolving global energy storage market.

Key Takeaways from Chapter 1

Chapter 1 highlights vanadium's rising role in the energy transition, with VRFB demand projected to grow from 5% of total vanadium use in 2024 to 27% by 2030—up to 54 kt under CES's base case, well above many third-party forecasts.

For South Africa, with 2.4% of global reserves (detailed in Chapter 2), this creates an opportunity to strengthen its position in the battery value chain. Vanadium electrolyte, making up 30–40% of VRFB costs, is expected to rise from ~155 kt in 2024 to over 1,100 kt by 2030, necessitating investments in refining and electrolyte production where South Africa can leverage its resource base and attract partnerships.

Chapter 2: Vanadium Supply Chain and Cost Analysis

2.1. Vanadium Market Overview: Global Demand & Supply Drivers

This chapter covers an overview of vanadium metal upstream mining and midstream processing and its usage in vanadium electrolyte production. It explores the current supply demand trends and future production forecasts. Finally, the report also handles vanadium electrolyte cost analysis and V_2O_5 pricing trends globally.

2.1.1. KEY APPLICATIONS AND CONSUMPTION TRENDS

Key Applications of Vanadium in the Global Market:

- **Steel:** The largest use of vanadium is in steel and alloy production. As an alloying element, it improves strength, ductility, and fatigue resistance without adding weight, which is critical for HSLA steels, tool steels, construction rebar, and automotive components.
- **VRFB:** A fast-growing application in large-scale energy storage. VRFBs enable renewable integration with benefits like long cycle life (up to 20,000 cycles), scalability, and non-flammability, making them vital for grid stability in the energy transition.
- **Aerospace & Defence:** Vanadium alloys with titanium and aluminium create lightweight, high-strength, corrosion-resistant materials for jet engines, airframes, and military components. It's also used as a catalyst in chemical processes like sulfuric acid production.
- **Nuclear, Pigments & Ceramics:** In nuclear reactors, vanadium alloys offer low neutron absorption and high thermal stability. Vanadium compounds also serve as pigments and additives in ceramics and glass, enhancing durability and heat resistance.[31] [32] [33]

Consumption Share of Vanadium by Application – Historical

Vanadium consumption is overwhelmingly dominated by the steel and alloys sector, which consistently accounts for around 90% of total usage. Meanwhile, energy storage applications, particularly VRFBs, are steadily gaining traction, reflecting the growing global emphasis on renewable energy integration. In contrast, sectors such as aerospace and defence, chemical, and nuclear industries maintain smaller yet stable shares, indicating a consistent but niche demand for vanadium in specialized applications.

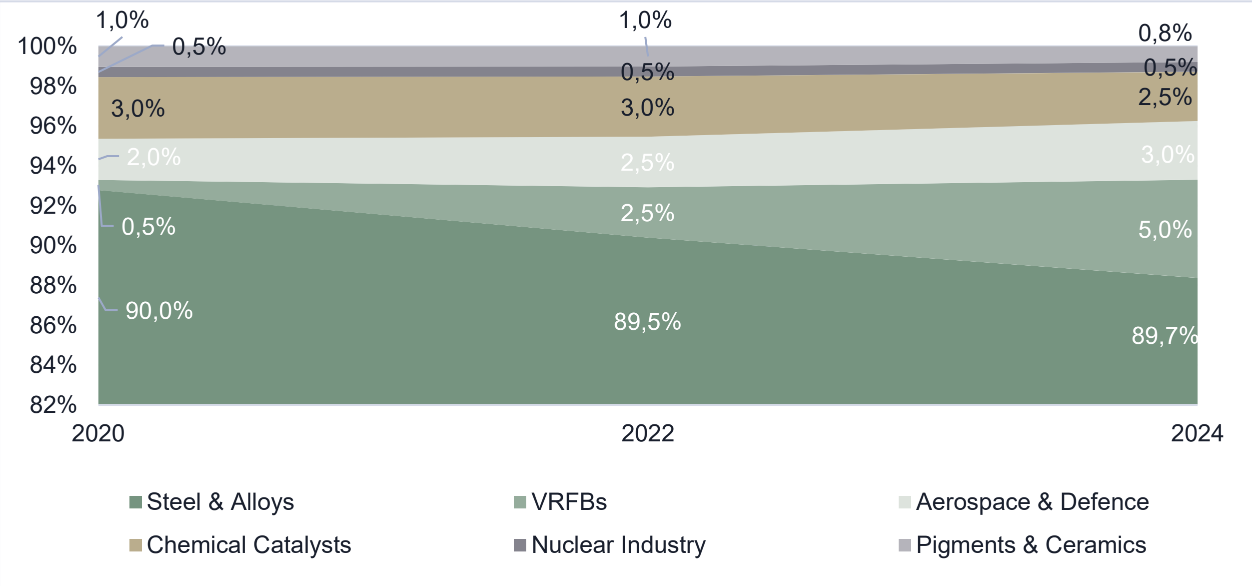

Figure 19: Vanadium Utilization by Application Area - Historical Usage

31 https://www.samaterials.com/blog/vanadium-element-properties-and-uses.html
32 https://www.refractorymetal.org/uses-of-vanadium.html
33 https://vanadiumcorp.com/our-portfolio/critical-metals/vanadium/default.aspx

Sources: CES assessment of industry databases and market reports

Application	CES Perspective [34] [35] [36] [37]

Steel & Alloys	• Dominant Share: Steel has consistently accounted for the largest share of vanadium consumption
	• Trend: This share has remained relatively stable over the past five years due to sustained demand from construction, automotive, and infrastructure sectors.
	• Drivers:
	  • Stable global crude steel production (~1900 million tons in last 4 years).
	  • Increased use of high-strength low-alloy (HSLA) steels in construction and transportation.

VRFBs	• Emerging Growth: While still a small portion of total consumption, VRFBs are the fastest-growing application.
	• Trend: Share has grown from under 1% in 2020 to around 5% in 2024, driven by:
	  • Large-scale renewable energy projects (e.g., China's 100 MW/400 MWh Dalian VRFB installation)
	  • Government incentives for grid-scale energy storage and decarbonization.

Aerospace & Defence	• Stable but Niche: Slight growth due to increased air travel and defence spending worldwide. • Use: Titanium-vanadium alloys in jet engines and airframes.
Chemical Catalysts	• Moderate Share: Stable to slightly declining share as steel and battery applications grow faster. • Use: Catalysts (mainly vanadium pentoxide) in sulfuric acid and maleic anhydride production.
Nuclear Industry	• Minimal Share: Stable but with potential for future growth if fusion reactor technologies scale up.
Pigments & Ceramics	• Small Share: Relatively flat, with limited industrial expansion in ceramic glazes and glass pigments.

2.1.2. MAJOR VANADIUM PRODUCERS AND SUPPLY HUBS

How the World Produces Vanadium: A 2024 Overview

As of 2024, global vanadium production is primarily driven by three key methods: co-product production, primary production, and secondary production (as seen in Figure 20 below).

[34] https://www.grandviewresearch.com/industry-analysis/vanadium-market-report
[35] https://www.polarismarketresearch.com/industry-analysis/vanadium-market
[36] https://www.fortunebusinessinsights.com/vanadium-market-110176
[37] https://www.bushveldminerals.com/vanadium/market/2022-2023/

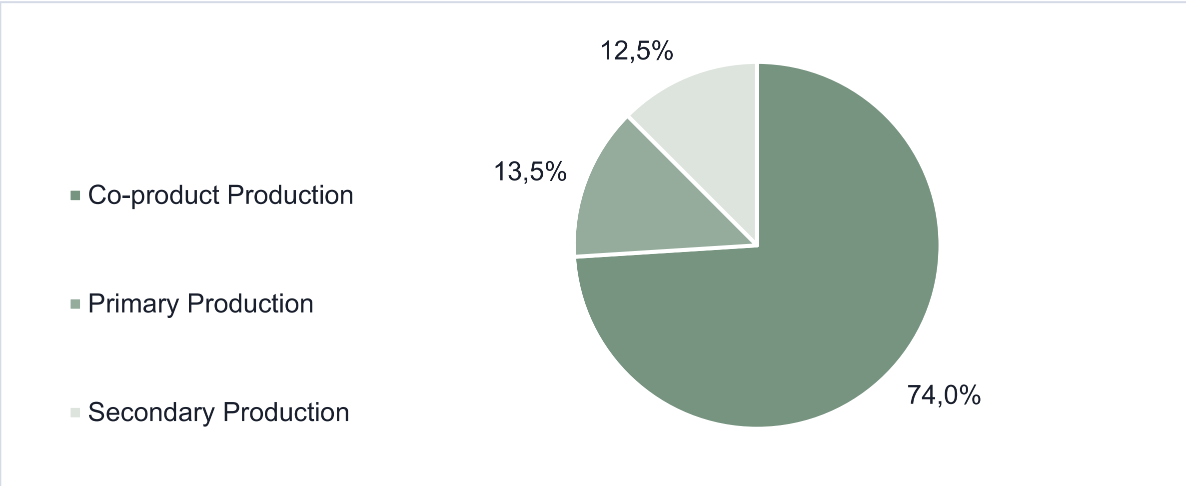

Figure 20: Global Vanadium Production Share as per Different Methods, 2024

a) Co-product production is the dominant method, accounting for approximately 70–75% of global vanadium output. In this process, vanadium is recovered during the extraction and processing of other minerals, particularly iron ore. China and Russia are the leading producers using this method. In China, vanadium is mainly extracted from steel slag generated during the production of steel from vanadium-bearing titaniferous magnetite. Russia follows a similar approach, recovering vanadium during steel manufacturing. This method is economically efficient due to shared processing costs and benefits from high-volume output linked to large-scale steel production. [38 39 40 41]

b) Primary production involves mining vanadium as the main product, typically from ores like Vanadiferous Titanomagnetite (VTM) – *refer Appendix A*. This method contributes about 10–15% of the global supply. Key producers include South Africa, with companies like Bushveld Minerals and Glencore, and Brazil, where Largo Inc. operates the Maracás Menchen Mine - one of the few dedicated primary vanadium mines globally. While this method allows for targeted extraction and lower per unit operating cost, it comes with higher CAPEX requirement. [38 39]

c) Secondary production, or recycling, also accounts for 10–15% of global supply. It involves recovering vanadium from industrial waste materials such as spent catalysts from oil refining, fly ash, and petroleum residues. The United States, particularly in states like Arkansas, Ohio, and Pennsylvania, plays a significant role in this segment, alongside Europe and Japan, which utilize advanced recycling technologies. This method is gaining momentum due to

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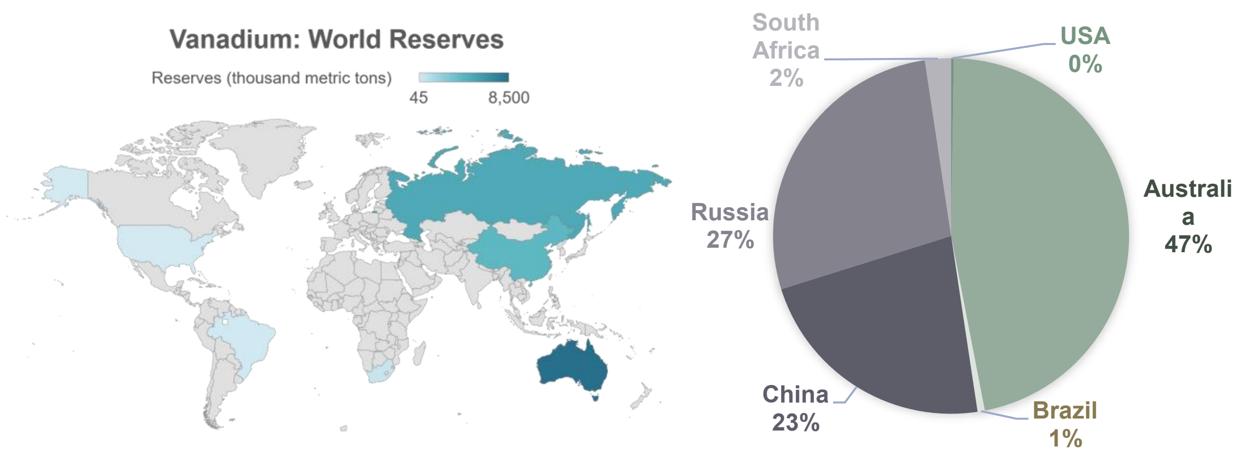
[38] U.S. Geological Survey (USGS) – Professional Paper 926-B
[39] Brigham Young University – Industry Review and Feasibility Study
[40] EPA Technical Background Document
[41] International Vanadium Symposium Proceedings

environmental regulations and the push for a circular economy, although its efficiency depends heavily on the vanadium content in the feedstock, which can vary widely. [42][43]

Major Vanadium Reserves

The global vanadium production landscape in 2024 is highly concentrated and geopolitically sensitive, with a few countries dominating both production and reserves. Global Vanadium reserves were identified to be 18 Mt in 2024 spread across Australia, South Africa, Russia, China and Brazil.



Note: The Vanadium reserves in the map include all those which are exploited through two main methods: co-product production and primary production.

Figure 21: Country-wide Reserves of Vanadium in Terms of Metal Content (2024)

Source: USGS Mineral Commodity Summaries 2024

Australia possesses over 23 Mt of vanadium resources (includes extractable reserves as per Figure 21 and non-extractable mineral), but most of these are low-grade, with concentrations below 1%. This low-grade nature poses economic challenges for large-scale mining unless significant technological advancements occur. In comparison, South Africa has a smaller total vanadium resource base, estimated at over 11 Mt. However, several of its deposits are high-grade, with some exceeding 1.5% V_2O_5. These richer concentrations make South African deposits more economically viable and attractive for further exploration and development.

[42] https://vanitec.org/vanadium/making-vanadium
[43] OneMine – Extractive Metallurgy of Vanadium

A summary of project-wise vanadium resource estimates in Australia and South Africa, based on the most recent reporting standards (JORC, NI 43-101, or SAMREC), highlights the differences in grade.[44] [45] [46] Australia hosts several advanced vanadium projects, most of which report under the JORC Code.

*The difference between **JORC**, **NI 43-101**, and **SAMREC** lies in their origin, scope, and compliance requirements for reporting mineral resources and reserves. **JORC (Australia)** is the Australasian Code that sets minimum standards for public reporting of exploration results, mineral resources, and ore reserves, emphasizing transparency and materiality. **NI 43-101 (Canada)** is a legally binding standard under Canadian securities law, requiring detailed technical reports prepared by qualified persons, with strict disclosure rules to protect investors. **SAMREC (South Africa)** is the South African Code, aligned with CRIRSCO principles like JORC, but tailored to local regulatory and industry conditions, focusing on competence and accountability of reporting professionals. While all three aim for consistency and investor confidence, NI 43-101 is the most prescriptive and legally enforced, whereas JORC and SAMREC are principle-based codes adopted through stock exchange listing rules.*

Table 7: Australia - Vanadium Resources

Project	Company	Resource Estimate (Mt V_2O_5)	Reporting Standard	Notes
Richmond – Julia Creek	Richmond Vanadium Technology	6.7 Mt (1.8 Bt @ 0.36%)	JORC 2012	Largest non-titanomagnetite deposit
Australian Vanadium	Australian Vanadium Ltd	1.54 Mt (208 Mt @ 0.74%)	JORC 2012	One of the most advanced projects in WA
Mount Peake	TNG Limited	0.45 Mt (160 Mt @ 0.28%)	JORC 2012	Multi-metal project (Ti-V-Fe)
Saint Elmo	Multicom Resources	0.75 Mt (267 Mt @ 0.28%)	JORC 2012	Queensland-based
Speewah	King River Resources	14.1 Mt (4.7 Bt @ 0.3%)	JORC 2012	Very large but low-grade

Source: CES Analysis based on Industry Reports

South Africa uses the SAMREC Code, but some companies also report under JORC or NI 43-101 for international investors.[47] [49]

[44] https://k-mine.com/articles/jorc-or-ni-43-101/
[45] https://vbkom.com/Services/Mineral-Resource-Estimation
[46] https://www.sgs.com/en-za/services/resource-and-reserve-estimation

Table 8: South Africa - Vanadium Resources

Project Name	Company	Resource Estimate ($Mt\ V_2O_5$)	Reporting Standard	Notes
Vametco	Bushveld Minerals	3.68 Mt (186 Mt @ 1.98%)	SAMREC / JORC	Operating mine
Brits Project	Bushveld Minerals	1.04 Mt (66 Mt @ 1.58%)	SAMREC / JORC	Adjacent to Vametco
Mokopane Project	Bushveld Minerals	2.03 Mt (298 Mt @ 0.68%)	SAMREC / JORC	Development-stage
Steelpoortdrift	Vanadium Resources Ltd	4.76 Mt (680 Mt @ 0.70%)	JORC 2012	One of the largest undeveloped deposits

Source: CES Analysis based on Industry Reports

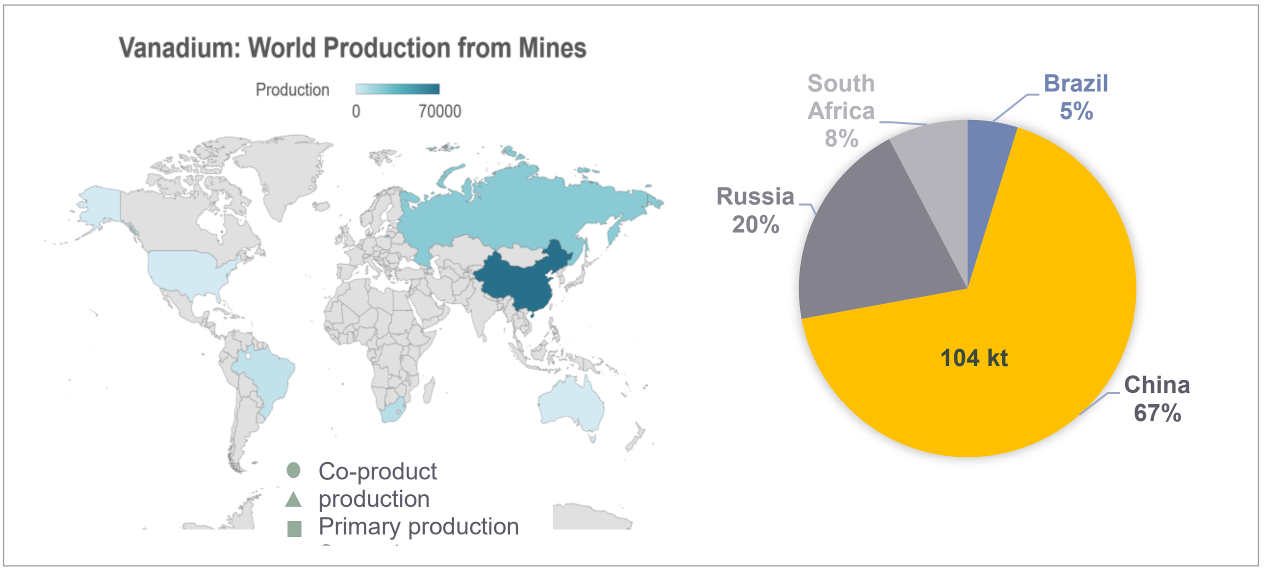


Figure 22: Country-wide Production of Vanadium in Terms of Metal Content (2024)

Note: The Vanadium production indicated in the chart includes the two main methods: co-product production and primary production. Global vanadium production from primary, secondary and co-production stood at 104 kt in 2024, led by China at 67%, Russia 20%, South Africa 8%, and Brazil 5%.

Source: USGS Mineral Commodity Summaries 2024

Major Vanadium Producers

- **China: The Undisputed Leader**

China dominates global vanadium supply, producing about 70 kt of ore in 2024 and holding 4,100 kt in reserves. Most output comes from co-product recovery during steel production, led by companies like Pangang Group and Chengde Steel. This integration with China's vast steel industry makes global vanadium supply highly sensitive to Chinese demand and policy shifts.

- **Russia and South Africa: Strategic Contributors**

Russia produces around 21 kt, mainly through co-product recovery by EVRAZ KGOK. South Africa, with 8 kt of production and 430 kt in reserves, is one of the few countries engaged in primary vanadium mining, led by Bushveld Minerals and Glencore, giving it a unique market position despite smaller volumes.

- **Brazil and USA: Emerging and Niche Roles**

Brazil produces about 5 kt and holds 120 kt in reserves, expanding its role through Largo Inc. The U.S., despite having 45 kt in reserves, relies on secondary production from recycling spent catalysts and ash, making it dependent on imports and strategically vulnerable.

Major Vanadium (V_2O_5) Producer Companies along with Their Capacities

As of May 2025, global co-production capacity for V_2O_5 is estimated at 190–210 kt, primarily from steelmakers producing V_2O_5 as a by-product. However, weak steel prices have stalled expansion plans, leaving co-production capacity largely flat and tied to steel output trends.

In contrast, primary producers, who extract vanadium directly from ores, hold about 36 kt of capacity, representing 96-97% of global primary production (as of May 2025). Unlike co-producers, they can scale independently of steel demand. These producers plan significant growth, targeting 88 kt by 2030, an increase of 52 kt over five years, driven by anticipated demand from emerging applications like VRFBs.

Table 9 Top Vanadium Pentoxide Producers

Company Name	Country	Production Capacity in 2025 (t/year)	Forecast Capacity for 2030 (t/year)	Notes
Major Co-product Producers				
Pangang Group	China	40,000	40,000	▪ Largest global producer, vertically integrated with steel and titanium.[47] ▪ No public expansion plans found; expected to maintain or slightly increase capacity due to domestic demand.
HBIS Group (Chengde Steel)	China	22,000	22,000	▪ One of the largest producers globally, integrated with steel production. ▪ No confirmed expansion, but likely to align with China's infrastructure and steel growth.

[47] Chinacoat Exhibit Information - Pangang Group Vanadium & Titanium Resources

Yuxi Yukun Iron and Steel	China	10,000	10,000	▪ Capacity expected to remain stable, aligned with domestic steel demand.
Total (Major Co-product producers)		**72,000**	**72,000**	▪ In 2022, the global capacity of co-production was at 82 kt.[48]
Major Primary Producers				
EVRAZ	Russia	19,000	19,000	▪ Vanady Tula facility is a key part of EVRAZ's vanadium production.[49] ▪ The facility is expected to be commercialized in summer of 2025, with no further capacity addition plans until 2030.
Largo Inc.	Brazil	11,000	11,000	▪ Operates the Maracás Menchen Mine, one of the highest-grade vanadium deposits.[50] ▪ No declared capacity addition plans yet
Bushveld Minerals	South Africa	3,000	-	▪ Operated the Vametco and Vanchem plants.[51]
U.S. Vanadium	USA	2,000–3,000	4,000-5,000	▪ High-purity V_2O_5 for specialty and battery markets. ▪ Projected to reach a capacity of ~4,000-5,000 t/year by 2030.[52]
Ferro-Alloy Resources Ltd.	Kazakhstan	500	22,400	▪ Balasausqandiq project in development. [53] ▪ Project expected to scale up to 22,400 t/year by 2030.
Vanadium Resources Ltd.	South Africa	-	19,400	▪ Steelpoortdrift project under development.[54] ▪ Expected to reach full capacity by 2027–2028.
Australian Vanadium Ltd.	Australia	-	11,200	▪ Still in development phase (AVL Project), expected to be a major supplier. [55] ▪ AVL Project expected to be operational by 2026; potential expansion to 11,000+ t/year by 2030.
Glencore	South Africa	8,300	8,300	▪ One of the few globally significant primary vanadium operations, enhancing South Africa's upstream value chain position.[56]
Total (Major primary producers)		**36,000**	**87,500**	▪ In 2022, the global capacity of primary production was 15 kt.[48]

Source: CES Analyses, Industry Inputs and Company Reports

48 https://www.lpvanadium.com/dist/assets/docs/Project-Blue-2023-Vanadium-Report.pdf (Project Blue Report)
49 https://resourceworld.com/evraz-invests-260-million-in-acceleration-of-vanadium-mining-and-processing-in-russia/
50 Largo Reports Q4 and Full Year 2024 Operational and Sales Results
51 https://projectblue.com/blue/news-analysis/1077/bushveld-minerals%E2%80%99-shares-suspended-amidst-cashflow-issues-
52 https://usvanadium.com/us-vanadium-high-purity-vanadium/
53 https://www.londonstockexchange.com/news-article/FAR/q4-2023-production-results/16286017
54 https://vr8.global/
55 Chamber of Commerce and Industry - WA.
56 Glencore - Full Year 2024 Production Report

Is the projected 2030 V_2O_5 capacity adequate for 200 kt of vanadium metal production?

In 2024, global vanadium metal production was about 104 kt, while vanadium pentoxide (V_2O_5) output reached 234 kt, reflecting a conversion ratio of 2.25:1.[57] To meet the projected 200 kt vanadium metal demand by 2030 (as estimated in Chapter 1 of this report)., the world would need roughly 450 kt of V_2O_5, an increase of 216 kt over current levels.

Planned expansions by primary producers are expected to add only 52 kt of V_2O_5 capacity by 2030, leaving a 164 kt gap. Filling this gap would require significant growth in co-production from steel slag and vanadium-bearing residues. However, with current co-production capacity at 190–210 kt and a plateauing steel sector, achieving an 80% increase (over next 5-6 years) appears unlikely under current market conditions.

Moreover, environmental regulations, economic feasibility, and technological constraints further complicate the rapid scaling of co-production capacity. Unless there is a major policy push, technological breakthrough, or significant investment in vanadium recovery infrastructure, the supply of V_2O_5 may fall short of the 2030 requirement, potentially leading to market tightness and upward pressure on prices.

2.2. V_2O_5 Price - Historical (2020-2025)

In Figure 23, the 15-year historical price trend of Chinese Vanadium Pentoxide (V_2O_5, >98% purity)[58,59] is illustrated.

57 https://www.argusmedia.com/metals-platform/newsandanalysis/article/2623253-Q-A--China-s-vanadium-oversupply-to-ease-in-2025

58 https://in.investing.com/commodities/vanadium-pentoxide-flake-98-min-cn-futures-historical-data

59 Future Battery Industries CRC report, Development of electrolytes for vanadium redox flow batteries | October 2023

Figure 23: Monthly Average Prices for Chinese Vanadium Pentoxide (V_2O_5>98% purity)

Source: Largo Physical Vanadium's Price Database, Investing.com - Vanadium Database

A breakdown of key events that likely influenced price movements, is discussed below.

- 2010-15 – Stability: Prices stayed between $10,000–$20,000/tonne, driven by steady steel demand and stable supply chains.
- 2015-20 – Volatility: Prices fell below $10,000 in 2016 (oversupply), then spiked above $60,000 in 2018 due to China's rebar standards and speculation, before correcting by early 2020.
- 2020-25 – Disruption to Stabilization: COVID-19 disruptions in 2020 caused early lows, followed by recovery as China's steel demand rebounded. Prices peaked near $20,000 in 2021 on strong construction demand, tight supply, and VRFB interest. From 2022 onward, prices corrected and softened to $12,000–$14,000 in 2023, then stabilized around $10,000–$12,000 by 2024-2025 as supply normalized and new sources emerged. VRFB demand grew but remained secondary to steel.

2.2.1. KEY FACTORS INFLUENCING THE FUTURE PRICING OF VANADIUM PENTOXIDE

Vanadium pentoxide prices are influenced by a complex interplay of macroeconomic, geopolitical, and sector-specific factors:

1. **Steel and Infrastructure Demand (Very High Importance)**

Vanadium's traditional use in high-strength, low-alloy (HSLA) steels remain a major demand pillar. China is the world's largest consumer of vanadium, primarily through its steel industry.

Any uptick in construction activity - especially if driven by government stimulus, can significantly boost vanadium demand. Emerging economies like India, Indonesia, and African nations are also investing in urban infrastructure, boosting demand for vanadium-alloyed steel.[34] Additionally, China's rebar standards continue to influence domestic vanadium consumption, i.e. stricter rebar standards in 2018, requiring higher vanadium content in construction steel.[60]

2. **Supply Chain Constraints and Strategic Stockpiling (High Importance)**

Vanadium is now classified as a critical mineral in the U.S. and EU, prompting efforts to diversify supply chains and reduce dependence on China and Russia. Domestic mining initiatives in the U.S., Kazakhstan, and Australia are underway. Geopolitical tensions (e.g., Russia-Ukraine war) and export restrictions could disrupt supply.

3. **Energy Storage Demand (Moderate Importance)**

The energy storage sector, particularly VRFBs, represents a fast-growing but volatile source of vanadium demand. Large-scale battery projects can create sudden spikes in consumption, tightening supply and driving prices higher. On the other hand, it can have a stabilizing effect against falling prices, even if overall steel output plateaus.

4. **Raw Material and Production Costs (Low to Moderate Importance)**

Vanadium pentoxide production depends on vanadium-bearing ores or steel slag, both of which are subject to cost fluctuations. Rising energy prices, labour costs, and environmental regulations can increase production costs. Environmental concerns may limit expansion in some regions, tightening supply. The U.S. Geological Survey in 2022 noted that despite increased vanadium production, environmental controls may continue to constrain output, particularly from steel plants that produce vanadium as a byproduct.[61]

Table 10: Summary - Relative Importance of Key Drivers of Vanadium Pentoxide Price

Factor	Relative Importance
Steel & Infrastructure Demand	High
Supply Chain & Strategic Stockpiling	Moderate–High
Energy Storage (VRFBs)	Moderate
Raw Material & Production Costs	Low

Source: CES Analysis

According to the World Steel Association, global crude steel production has shown a generally upward trend over the past decade, with some fluctuations due to macroeconomic and

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60 https://vanadiumprice.com/2018/11/02/chinas-new-vanadium-steel-rebar-standards-take-effect-whats-next-for-vanadium-market-2/

61 Mineral Commodity Summaries 2022 (USGS) - Vanadium

pandemic-related disruptions.[62] Despite a slight dip in 2022–2024 due to global economic uncertainties and energy constraints, the overall trend remains stable and resilient.

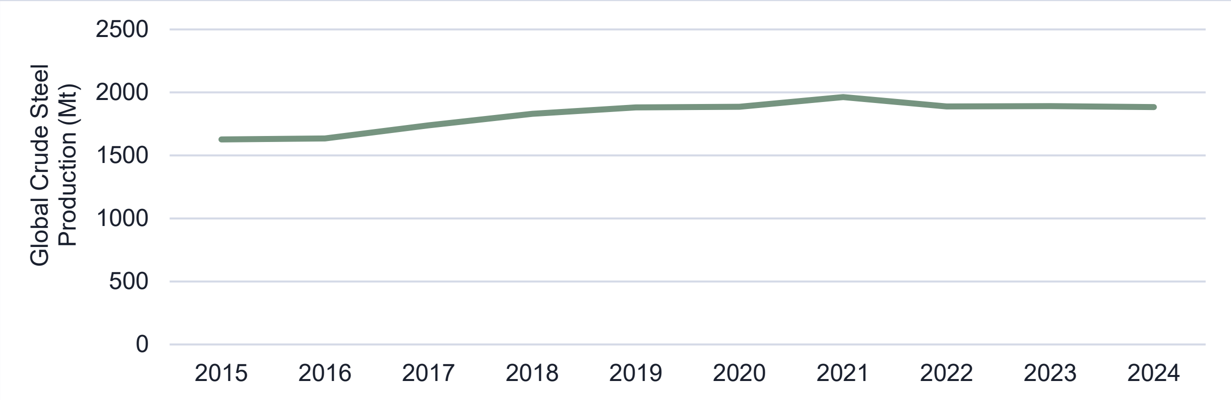


Figure 24: Global Crude Steel Historical Production (2015–2024)

Source: World Steel Association 2024 Report

- **Vanadium Pentoxide Price Outlook for 2030 is Strongly Linked to Steel Production Forecast**

Global steel demand is forecast to grow from 1.9 billion tonnes in 2024 to approximately 2.0 billion tonnes by 2030, reflecting a modest CAGR of 1%.[63] [64] Given the strong correlation between steel production and vanadium demand, this underpins a stable price outlook for V_2O_5, likely remaining in the current range barring major supply shocks. The current price range of $10,000–$12,000/tonne is likely to persist, supported by stable and growing steel demand, government support in key markets like China, infrastructure expansion in emerging economies and gradual diversification of vanadium demand into energy storage.

2.2.2. COST STRUCTURES ASSOCIATED WITH VANADIUM EXTRACTION AND PROCESSING

In vanadium production, particularly through the co-production method, it is difficult to isolate costs specific to vanadium. This is because co-production is closely tied to iron and steel manufacturing, where multiple outputs share the same processes, infrastructure, and operating expenses. To address this challenge, the analysis focuses on primary production, which extracts vanadium directly from vanadium-rich ores through mining and processing.

[62] World-Steel-in-Figures-2024.pdf
[63] Green Transformation needs clear orientation – Forecasting the steel demand in 2030 - Bronk & Company
[64] Pedal to the Metal 2025

This method provides a clearer and more traceable cost structure, free from the complexities of cost-sharing in co-production. For this purpose, the cost structure of a leading global supplier of high-purity vanadium, operating fully integrated mines and processing facilities, was examined. Their vertically integrated model offers a realistic view of standalone vanadium production economics.

The cost breakdown reveals that cash operating costs (excluding royalties) account for the largest share at 68%, followed by depreciation and amortization (14%), and conversion costs (7%). Other components include consumables for conversion (6%), distribution costs (4%), and royalties (3%).

As per the analyses of research groups like Project Blue, the vanadium cost curve in Figure 26 provides an indicative visualization of the relative cost positions of various vanadium pentoxide producers, segmented by processing route. The bottom quartile of the cost curve is dominated by a small number of primary producers (light blue), who benefit from vertically integrated operations with processing facilities typically located near mine sites. These producers enjoy the lowest production costs between $9-$13/kg (inflation adjusted costs for 2025), making them the most competitive in the market. But these primary producers offer 15% of the global production output, thereby having very limited impact on the global market pricing. It's worth noting that while their operating costs are low, primary producers face significantly higher capital expenditure (capex) to establish production facilities, which can be a barrier to scaling.

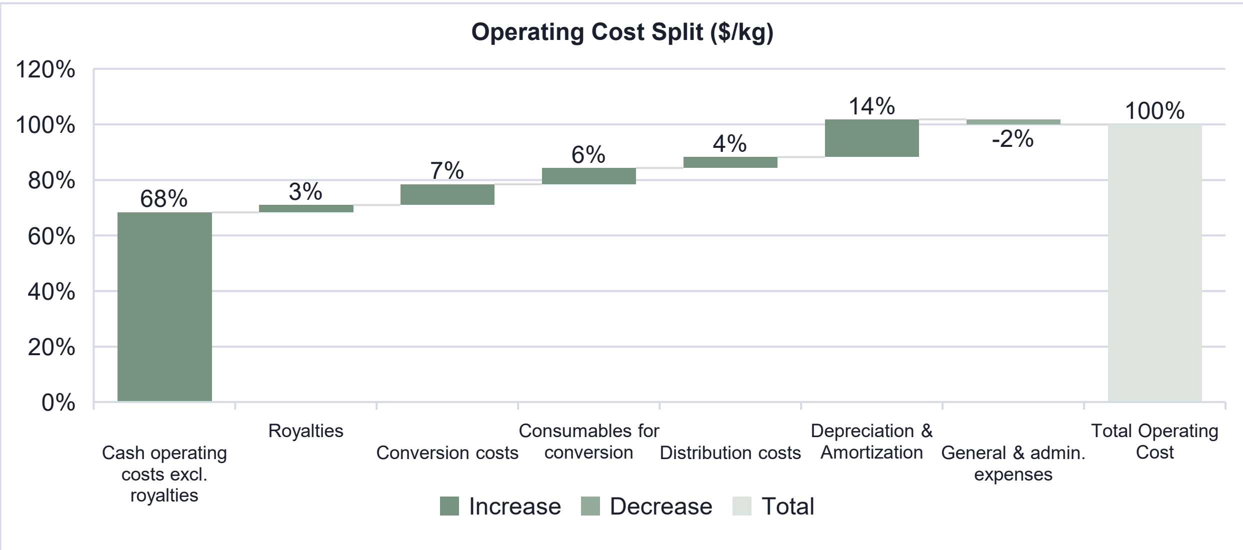


Figure 25: Operating Cost of Vanadium Extraction & Processing into V_2O_5

Source: CES Analyses based on Largo Inc. Quarterly Report of Jan-Mar 2025

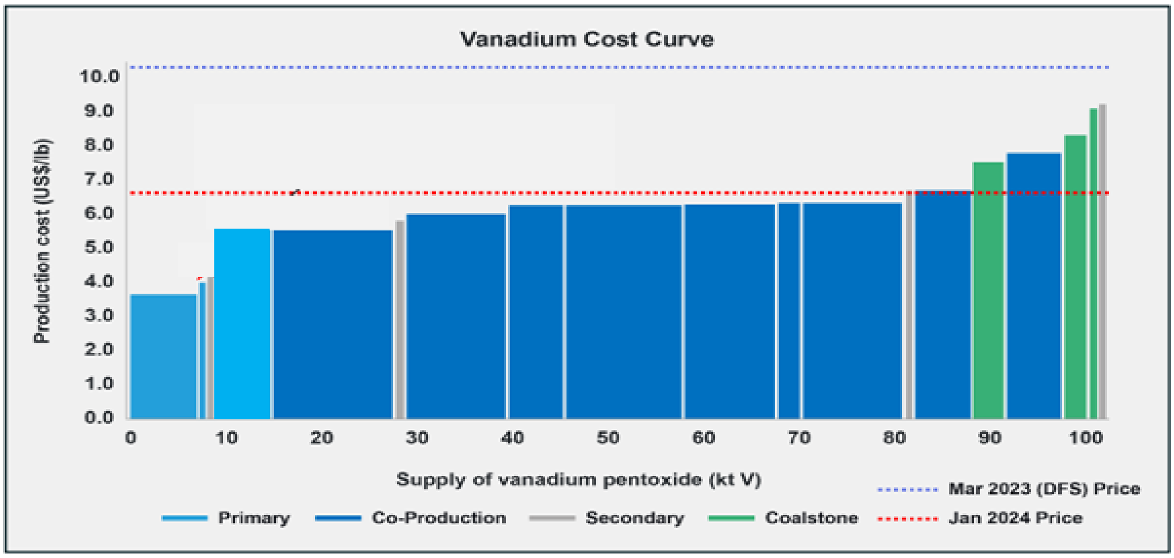


Figure 26: Vanadium Pentoxide Production Cost Curve (as of 2024)

Source: CES Analyses of Company Announcements (Neometals)

Co-producers (dark blue) occupy the middle quartiles, starting from around US$13/kg (inflation adjusted costs for 2025). Pangang and HBIS Chengde are thought to be amongst the lowest cost co-production operations. These operations typically extract vanadium as a by-product, often from steel production, which helps offset some costs. Secondary producers (grey), which rely on a diverse range of feedstock and recycling routes, are generally positioned in the upper quartiles due to higher and more volatile costs. Coalstone-based production (green) also appears in the higher cost range.

Although the production cost of primary vanadium is generally lower than that of co-production sources, the latter, primarily from China and Russia, which together account for approximately 70-80% of global vanadium capacity, significantly influences market pricing. This is because a substantial portion of their capacity remains underutilized and is sold at lower prices, thereby undermining the economic viability of primary vanadium producers.

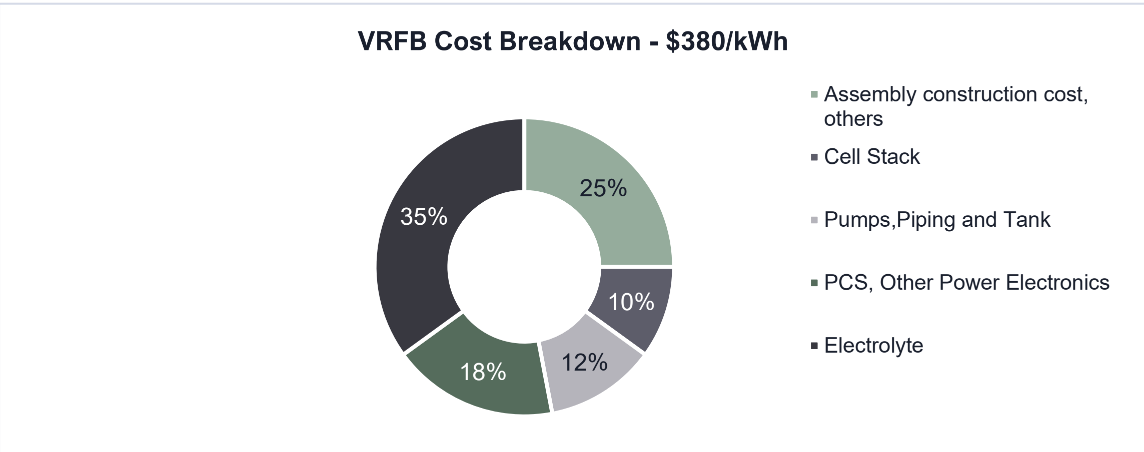
As indicated in Figure 25, cash operating expenses - comprising around 68% of total costs, can push the breakeven price up to approximately $14.3/kg of V_2O_5. In contrast, current market prices are notably lower: around $12.5/kg in Europe and $10.5–$11/kg in China. This 15–20% price gap between primary and co-producers reflects a lack of transparency in the pricing mechanisms, which continues to challenge the sustainability of primary vanadium production.

2.3. Assessment of Vanadium Electrolyte Cost for VRFB Feasibility (2025-2030)

2.3.1. A BREAKDOWN OF VRFB COST

In 2024, within a VRFB system, the electrolyte is the largest cost driver, contributing about 35% of the total cost per kWh. Assembly, construction, and other system costs follow at 25%. Power conversion systems (PCS) and related electronics account for 18%, while pumps, piping, and tanks make up 12%. The cell stack, despite being the core electrochemical component, represents only 10% of the cost. This indicates that cost reductions in electrolyte formulation and system integration could have a greater impact on overall VRFB economics than stack improvements alone.

The average VRFB price for a 6–8-hour duration system in 2024 was estimated at $380/kWh, based on inputs from multiple OEMs. Of this, the vanadium electrolyte alone contributes roughly $130/kWh. (Note - Typically, a 1 kWh VRFB requires about 70 litres of electrolyte and 8-10 kg of V_2O_5, underscoring the material intensity and its influence on system cost.)



Source: CES Analysis, Industry Inputs and Company Reports

Figure 27: Cost Breakdown of VRFB in $/kWh for a 6-8 hr System (2024)

2.3.1.1. A Cost Breakdown of Vanadium Electrolyte and Impact of Vanadium Pentoxide

Within the electrolyte, V_2O_5 dominates, contributing about 82% of electrolyte cost, making vanadium pricing a key factor in VRFB scalability. Other chemicals, such as sulfuric acid (2%), hydrogen peroxide (1%), and phosphoric acid (0.4%), play a minor role, while processing costs add roughly 2.5%.

The cost impact of V_2O_5 is significant, estimated at $110/ kWh, which translates to 82% of electrolyte cost and 26-30% of total VRFB system cost. This contrasts sharply with lithium-ion batteries, where lithium compounds typically account for only 8-12% of overall cost. Consequently, vanadium price volatility remains a major determinant of VRFB economics.

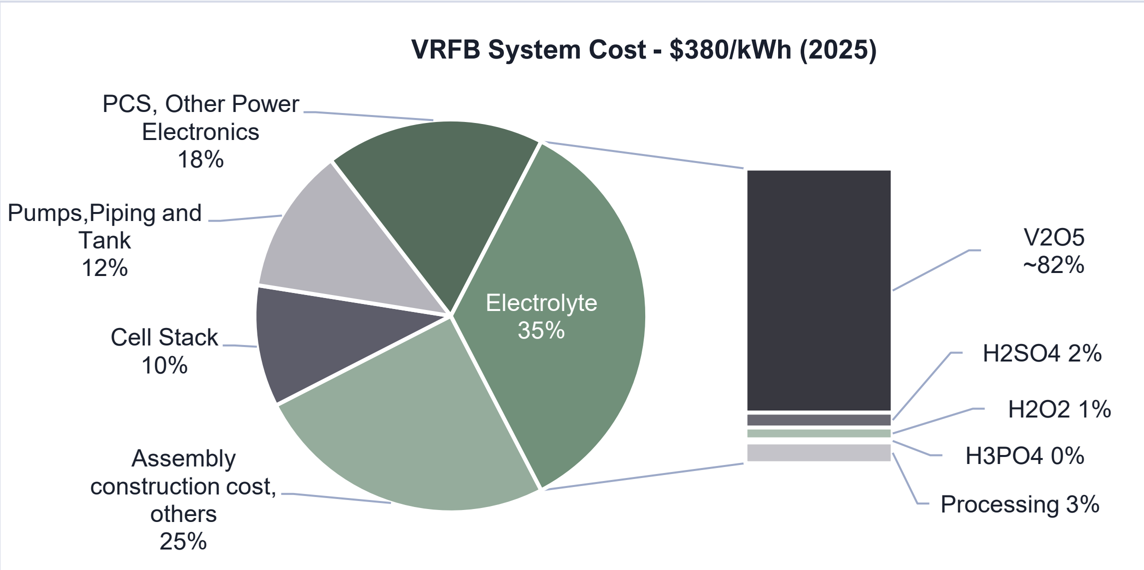


Figure 28: A Cost Breakdown of Electrolyte in VRFB System (Cost Share in $/kWh), 2025

Source: CES Analyses, Industry Inputs

2.3.1.2. Breakdown of VRFB Stack Cost and Its Impact on Overall System Cost

In a VRFB system, stacks account for about 10% of total cost (~$38–40/kWh). Developers are working to reduce costs and improve efficiency, with particular attention on the stack, which is the core component where electrochemical reactions occur. Within the stack, the membrane plays a critical role in ion exchange and performance. Some developers report innovations that could cut membrane costs by up to 50%. However, since the membrane represents only

3% of total system cost, even major reductions here would have a limited impact on overall VRFB economics.

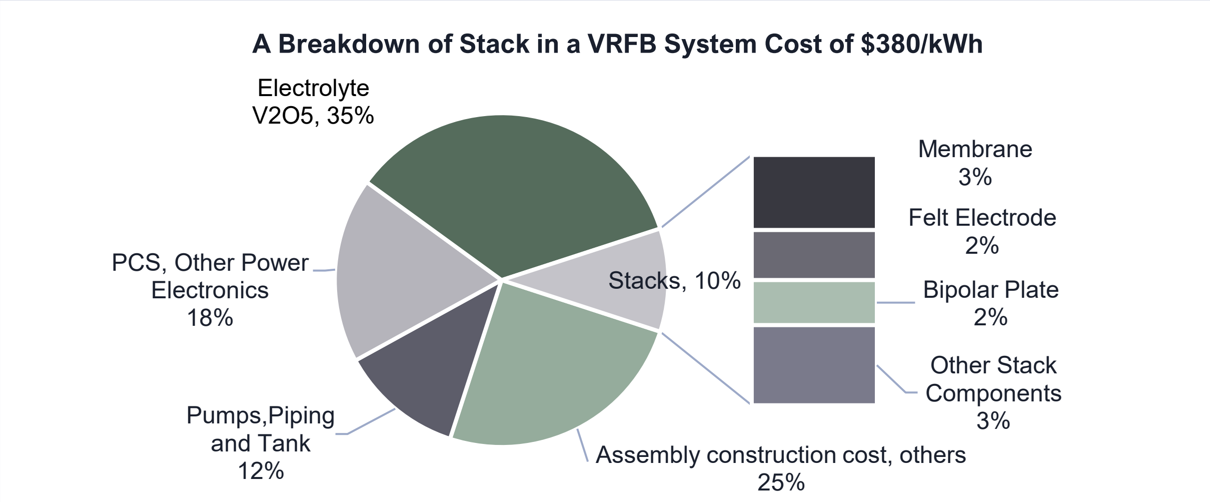


Figure 29: A Cost Breakdown of Stack in VRFB System (Cost Share in $/kWh)

Source: CES Analyses, Industry Inputs

2.3.2. ENVISAGED PRICE OF ELECTROLYTE & VANADIUM PENTOXIDE FOR LCOE FEASIBILITY IN VRFB

V_2O_5 is extracted from VTM ore, which contains 1.0% to 1.5% V_2O_5 by weight. The following representative flow diagram further reveals the utilization and cost dynamics of V_2O_5 in the VRFB.

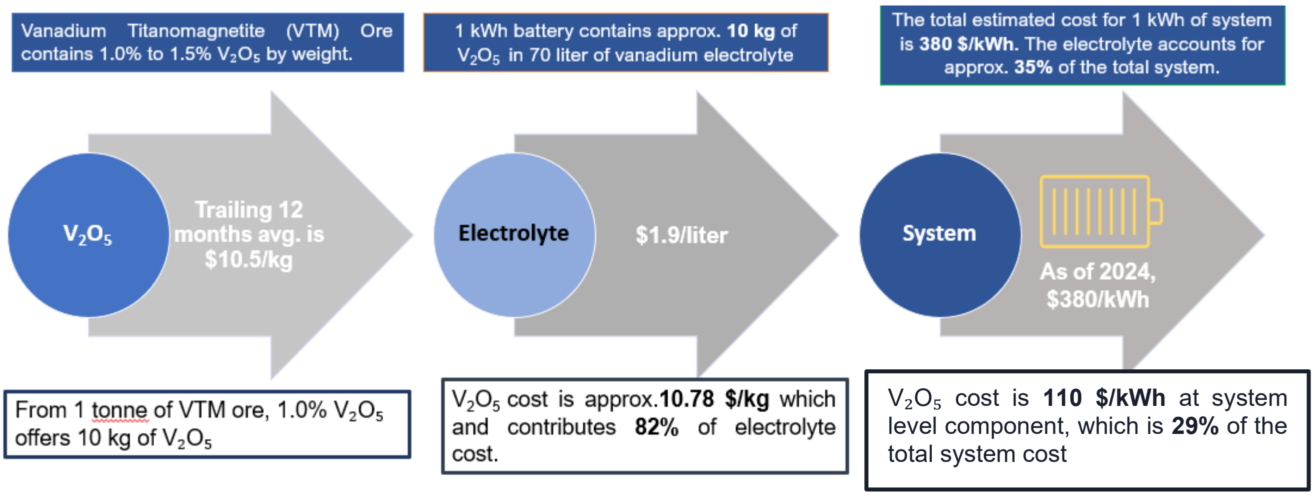


Figure 30: End-to-End Integration of V_2O_5: From Procurement to System Development

Source: CES Analyses, Industry Inputs

To assess VRFB cost reduction potential, various scenarios were analysed, focusing on the link between system cost and V_2O_5 pricing.

I. Stack Components (Membrane, Electrodes, Bipolar Plates)

Membranes, essential for ion exchange, are among the most expensive stack elements. Recent innovations in polybenzimidazole (PBI) and non-fluorinated ion-exchange membranes have demonstrated potential cost reductions of up to 50%, without compromising performance.[65] [66] Electrodes and bipolar plates can also be optimized using materials like carbon felt and graphite composites, which may reduce stack costs by 20–30%.[67]

II. Balance of Plant (BoP)

Modular system designs and the adoption of composite or polymer tanks in place of steel alternatives can lead to BoP cost reductions of 15-25%.[68] Additionally, improved flow field designs and low-friction pumps contribute to both operational efficiency and lower long-term costs.

III. Power Electronics (PCS)

Standardizing PCS components and integrating them with renewable energy inverters can reduce projects costs by ~15%. Ongoing R&D in bidirectional converters and digital control systems is further enhancing efficiency and driving down costs.[69]

IV. Assembly & Construction

Prefabricated, containerized systems and automated assembly lines are enabling cost reductions of 20–30% in construction and deployment.

Considering the ongoing R&D efforts aimed at reducing the costs of other VRFB components, a sensitivity analysis has been conducted with a focus on V_2O_5 prices, while assuming all other component costs remain constant (refer to Table 11).

If the price of V_2O_5 moves by $1/Kg, a corresponding $25-40 price movement can be seen in overall system cost assuming others component cost in the overall system remains constant. This underscores the critical role of vanadium pricing in making VRFB systems competitive with lower-cost lithium-ion technologies. However, the data also shows diminishing returns beyond a certain point. Once V_2O_5 prices fall below $7/kg, further system cost reductions become increasingly difficult through vanadium price cuts alone. This highlights the need for broader innovations in system design, manufacturing efficiency, and integration to achieve deeper cost reductions.

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[65] https://pubs.rsc.org/en/content/articlehtml/2024/qi/d4qi00520a
[66] https://www.mdpi.com/2077-0375/11/3/214
[67] https://www.sae.org/publications/technical-papers/content/2024-32-0085/
[68] https://www.z-henergy.com/en/article/a157.html
[69] https://www.miningreview.com/battery-metals/research-underway-to-cut-cost-boost-energy-density-of-vrfb/

Table 11: Sensitivity Analysis: Cost of V_2O_5 affecting VRFB System Cost

VRFB System Cost \$/kWh	Electrolyte Cost (35% Cost Share) in \$/kWh	V_2O_5 Cost in Electrolyte (82% Cost Share) in \$/kWh	Equivalent V_2O_5 Cost in \$/Kg	V_2O_5 Cost in \$/lbs	Remarks
630	221	181	18	8	Assuming SA V_2O_5 pricing between \$30-40 Vanadium content/kg, reflecting around \$16/kg to \$18/kg, which is around \$630/kWh to \$555/kWh
605	212	174	17	8	
580	203	166	17	8	
555	194	159	16	7	
530	186	152	15	7	
505	177	145	14	7	
480	168	138	14	6	
455	159	131	13	6	
430	151	123	12	6	
405	142	116	12	5	
380	133	109	11	5	The VRFB capex reduction from \$380/kWh to \$230/kWh is difficult for Primary Vanadium producers under a healthy demand market, but under a bearish market, the price of \$11/kg-\$8/kg of V_2O_5, VRFB serves as an alternative Market.
355	124	102	10	5	
330	116	95	9	4	
305	107	88	9	4	
280	98	80	8	4	
255	89	73	7	3	VRFB capex reduction <\$200/kWh is unlikely solely due to V_2O_5 price reduction
230	81	66	7	3	
205	72	59	6	3	
180	63	52	5	2	

Source: CES Analysis based on industry inputs,

Note: The higher end of price is covered from \$630/kWh to capture the higher system cost market outside China

If V_2O_5 prices remain around \$10/kg through 2030, VRFB systems will face economic challenges. While this aligns with the current market average and supports a system cost of about \$370–\$380/kWh, forecasts suggest prices will stay flat at \$10–\$11/kg, driven by weak steel demand and macroeconomic headwinds. This price range limits VRFB competitiveness against lower-cost LFP batteries for short hour duration (< 6 hr).

To accelerate VRFB adoption in 8 hr systems, system costs must drop to roughly $200/kWh, which would require either price reduction in non-electrolyte components through R&D and government incentives or more competitive vanadium sourcing. Without such measures, global vanadium producers may face pressure, especially in a bearish steel market, prompting co-producers to offload material at lower prices, potentially disrupting market dynamics.

Although V_2O_5 supply is projected to rise from ~200 kt in 2023 to 250 kt by 2030, demand particularly from VRFBs, is expected to surge after 2026 (Figure 31). Achieving sustainable pricing near $9–$11/kg will likely favour vertically integrated players with direct mine access, such as Largo Resources and Australian Vanadium Limited, positioning them to maintain competitiveness as demand grows.

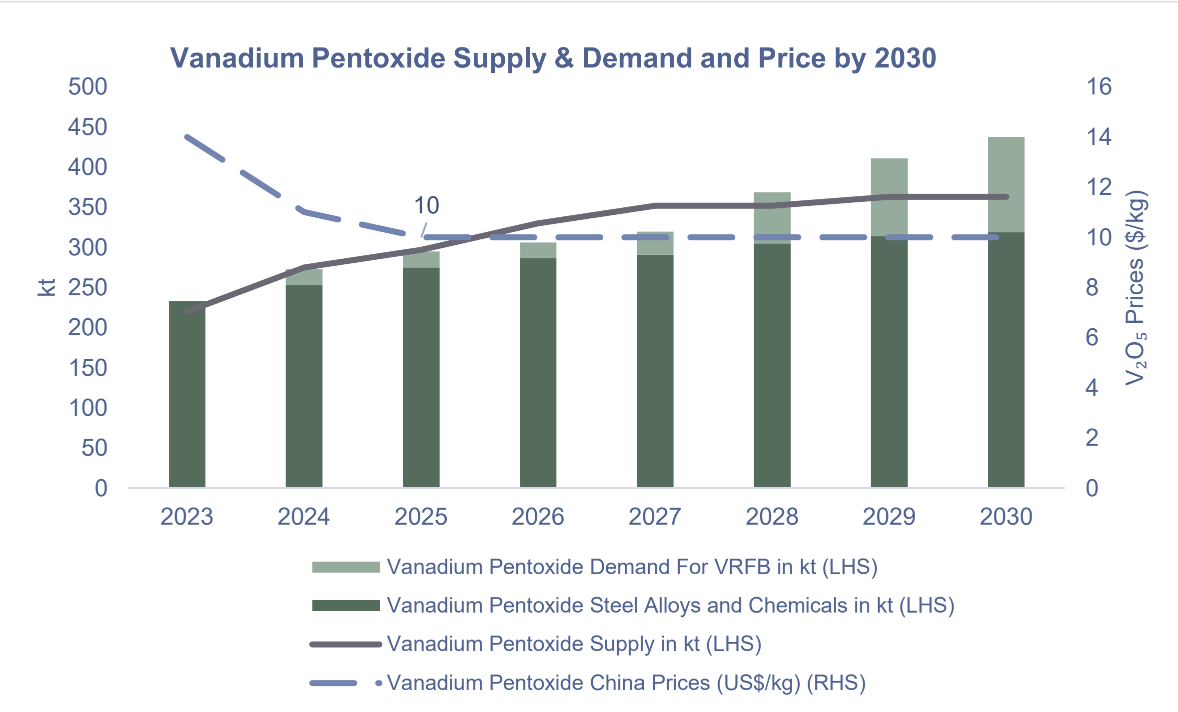

Figure 31: A Snapshot of Vanadium Pentoxide Supply- Demand & Price Dynamics (2023-2030)

Source: CES Analyses based on pricing agencies, various industry research group reports like Project Blue, Investing.com databases etc. For the steel demand forecast, the 2024 Chinese govt. announcement on the steel rebar is considered.

Note: For V_2O_5 China price trends, please refer sub section 2.2.2

Key take aways from chapter 2

China holds the highest vanadium production globally with over 67% share. V_2O_5 is sourced from both primary ores and secondary materials like spent catalysts, petroleum residues, and utility ash. Primary producers include South Africa, Brazil, and emerging projects in Australia, while secondary supply is growing in the U.S., Canada, and Saudi Arabia. In 2024, global vanadium metal output was 104 kt, with V_2O_5 production at 234 kt. To meet the projected 200 kt vanadium demand by 2030, about 450 kt of V_2O_5 will be needed - 216 kt more than current levels. Planned expansions from known sources add up to 52 kt, leaving a 164 kt shortfall. Countries such as China have plans of expansion through co-production. Major policy, technological, or investment shifts are required to raise the supply to meet the demand.

The projected supply shortfall is primarily driven by demand from the (VRFB) sector, rather than the traditional steel and pigment markets, which together account for over 95% of current consumption. This limits the potential for sharp price spikes, supporting a conservative price estimate of around $10/kg. Chinese V_2O_5 prices are forecasted to remain near $10/kg through 2030, due to weaker demand from the steel and infrastructure sectors.

The overall cost optimization of VRFB systems is largely driven by the electrolyte component, with V_2O_5 alone contributing around 35% to the total system cost. A modest 2-3% reduction in V_2O_5 pricing could result in a $25-$50 decrease in overall system cost, assuming other component costs remain constant. On the other hand, a 15-20% cost reduction in non-electrolyte components - such as the stack, BoP, PCS, and assembly could lead to a $40-$50 drop in system cost, provided the electrolyte cost remains unchanged.

Chapter 3: Technological Benchmarking and Competitive Positioning

3.1. Approach to Technological Benchmarking & Competitive Positioning

This chapter begins by classifying major energy storage technologies based on their discharge duration capabilities – short, medium, and long-duration. This classification provides a foundational understanding of where each technology fits in terms of operational use cases, from frequency regulation and spinning reserves to renewable energy firming and seasonal storage. Technologies such as lithium-ion and flywheel are categorized as short-duration, while VRFBs, iron-air batteries, and PHES considered as long-duration. This segmentation sets the stage for a more granular mapping of technologies.

Following this, a detailed technology mapping exercise is conducted, plotting each major energy storage technology by its discharge duration (ranging from seconds to weeks) and power rating. This visual and analytical mapping helps identify overlaps, gaps, and niche applications across the storage spectrum. It also highlights the unique positioning of VRFBs, which offer multi-hour to multi-day discharge capabilities with scalable power ratings, making them particularly suitable for grid-scale and industrial applications.

The next section delves into a focused discussion on key LDES technologies, grouped by their underlying chemistries. Technologies such as iron-air, liquid metal, and gravity-based storage are briefly profiled, highlighting their working principles, development status, and potential advantages. This overview provides context for understanding the diversity and innovation within the LDES space, and how these technologies compare to VRFBs in terms of performance, cost, and scalability.

A comparative analysis of LDES performance parameters is then presented, covering metrics such as round-trip efficiency, cycle life, LCOS, energy density, and system lifetime. This analysis offers a takeaway on how VRFBs stack up against other long-duration technologies, both in technical and economic terms. The goal is to identify where VRFBs hold competitive advantages and where they may face challenges, especially considering emerging alternatives.

Subsequently, the chapter evaluates the techno-commercial readiness of various LDES technologies. Technologies are assessed based on their current deployment status, technology readiness levels (TRLs), and scalability potential. Then, an LCOS assessment helps determine the technologies which are likely to compete with or complement VRFBs in the coming decade.

The chapter then presents a comprehensive SWOT analysis and technology risk assessment for VRFBs. This will include an evaluation of strengths such as safety and long cycle life, weaknesses like vanadium cost volatility, opportunities in renewable integration, and threats from disruptive chemistries. Key risks – such as electrolyte degradation, system efficiency bottlenecks, and manufacturing scale-up challenges, are analysed to inform mitigation strategies and investment decisions.

Then, the chapter explores whether any emerging LDES technologies could significantly impact the future of VRFBs. This includes assessing the disruptive potential of technologies like iron-air and organic flow batteries, based on their cost trajectories, scalability, and innovation pace. The analysis helps stakeholders understand whether VRFBs can maintain their relevance or need to evolve in response to technological shifts in the LDES landscape.

Finally, the chapter explores innovative business models that can accelerate VRFB adoption. Traditional direct sales models have struggled due to high upfront costs, prompting the need for alternative financing mechanisms. Hence, the closing section also explores multiple leasing models where sellers and buyers share investment and operational responsibilities. Case studies of successful vanadium deployments are also analysed to extract best practices and inform recommendations for future commercialization strategies.

3.2. Comparative Analysis of VRFB vis-à-vis Other Energy Storage Technologies

3.2.1. CLASSIFICATION OF ENERGY STORAGE TECHNOLOGIES

Energy storage systems are broadly categorized into electrochemical, mechanical, and chemical technologies, each designed to store energy and later supply to the grid. The classification of these systems is primarily based on discharge duration, short-, medium- and long-duration storage depending on the application requirement and grid requirement.

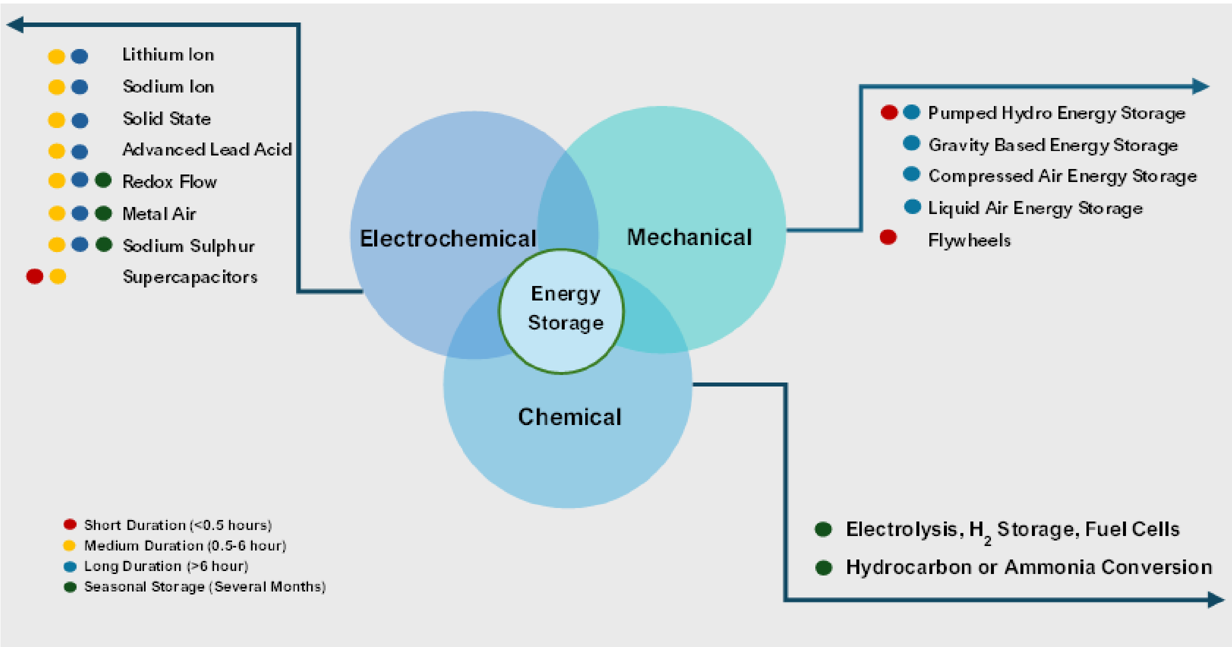

Figure 32: Technologies for Short Medium-and Long Duration Energy Storage

Source: CES Analysis

Short-duration (< 0.5 hours) technologies are essential for frequency regulation, peak shaving, and maintaining power quality. Medium-duration (0.5 - 6 hours) storage is typically used to shift energy from lower demand to peak hours, ensuring grid reliability and optimizing energy dispatch. Long- duration (>6 hour) energy storage plays a crucial role in grid balancing, RE integration, and providing backup power during extended outages. These systems are essential for achieving high renewable energy penetration and decarbonization goals. The energy storage technologies described in this section span three storage technology families:

I. **Electrochemical Energy Storage** - These systems store energy through electrochemical reactions-converting chemical energy to electricity during discharge and reversing the process during charging. They are crucial for portable devices, electric vehicles, and grid storage. All the following battery types operate on this fundamental principle:

- **Lithium-ion (Li-ion**): Most common; uses lithium ions moving between electrodes.
- **Sodium-ion (Na-ion)**: Similar to Li-ion but uses sodium; cost-effective for large-scale use.
- **Solid State Battery (SSB)**: Use solid electrolyte to transport ions between electrodes for safer and more stable performance.
- **Advanced Lead-Acid (PbA)**: Traditional type using lead and sulfuric acid; reliable and low-cost.
- **Redox Flow Batteries (RFB)**: Stores energy in liquid electrolytes via redox reactions.
- **Metal-air**: Involves the electrochemical oxidation of a metal (e.g., zinc, iron) with oxygen from the air.
- **Sodium-Sulphur (NaS):** High-temperature molten salt battery; ideal for long-duration grid storage.
- **Supercapacitors:** Deliver rapid charge and discharge, ideal for short bursts of power.

II. **Mechanical Energy Storage** – These systems store energy by converting electrical energy into mechanical energy, holding it in that form, and then converting it back to electrical energy when needed. They are often characterized by their large scale, long operational life, and suitability for grid services.

- **Pumped Hydro Energy Storage (PHES)**: Stores energy by moving water between two reservoirs at different heights.
- **Gravity based Energy Storage (GBES):** Lifts heavy masses to store energy, often called "gravity batteries."
- **Compressed Air Energy Storage (CAES):** Stores energy by compressing air and holding it in large underground caverns or tanks.
- **Liquid Air Energy Storage (LAES):** Stores energy by liquefying ambient air and storing it in insulated cryogenic tanks.

- **Flywheels:** Store energy as rotational kinetic energy in a rapidly spinning rotor (flywheel).

III. **Chemical Energy Storage** – This refers to the process of converting electrical energy into chemical bonds, storing it in the form of chemical fuels or compounds, and then releasing that energy as electricity or other useful forms (like heat or fuel for transportation) through chemical reactions. This approach is particularly attractive for long-duration and seasonal energy storage due to the high energy density of chemical bonds.

Among these, electrochemical storage technologies (lithium-ion, redox flow and sodium sulphur batteries) are most versatile and flexible forms of energy storage. They can serve a wide range of discharge duration from short, medium- to long -duration applications.

3.2.2. APPROACH TO TECHNOLOGY PRIORITIZATION FOR DIVERSE USE CASES

This section outlines a strategic framework for prioritizing energy storage technologies, aligning each solution's capabilities with specific application needs. This approach supports informed decision-making by evaluating technologies across key criteria - technical feasibility, commercial viability, environmental impact, and maturity (detailed discussion is in Section 0).

Figure 33 provides a more detailed overview of electrochemical storage technologies mapped across varying discharge durations-broadly categorized as short, medium, and long-duration storage. The vertical axis represents the discharge duration, indicating the period a system can supply power once charged. This categorization is critical for aligning technological solutions with specific grid applications and end-user requirements.

Energy storage technologies are prioritized based on power output and discharge duration, forming a performance spectrum - from supercapacitors and electrochemical batteries to CAES, PHES, and hydrogen systems. This mapping helps match technologies to specific use cases, from short bursts of high power to long-duration, large-scale storage. Within this framework, electrochemical batteries offer versatile solutions, especially for medium to long-duration needs. Their scalability and adaptability make them central to both grid-scale and behind-the-meter applications in current and future energy strategies.

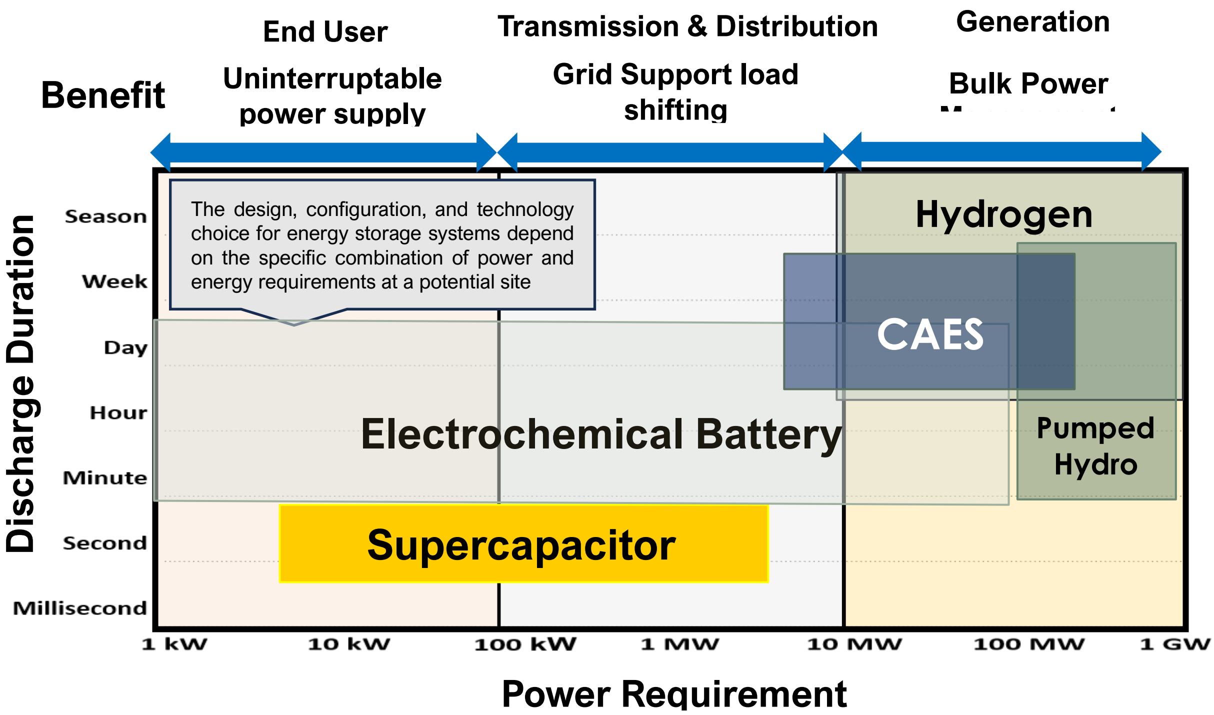

Figure 33: Technology Mapping of Energy Storage Systems by Discharge Duration and Power

Source: CES Analysis

3.2.3. EMERGING NON-LITHIUM ELECTROCHEMICAL ENERGY STORAGE

The increasing need for grid modernization and renewable energy integration is accelerating a shift beyond lithium-ion batteries toward diverse non-lithium electrochemical technologies. Alternatives such as redox flow batteries, sodium-based systems, metal-air chemistries, and advanced lead-acid are gaining momentum.

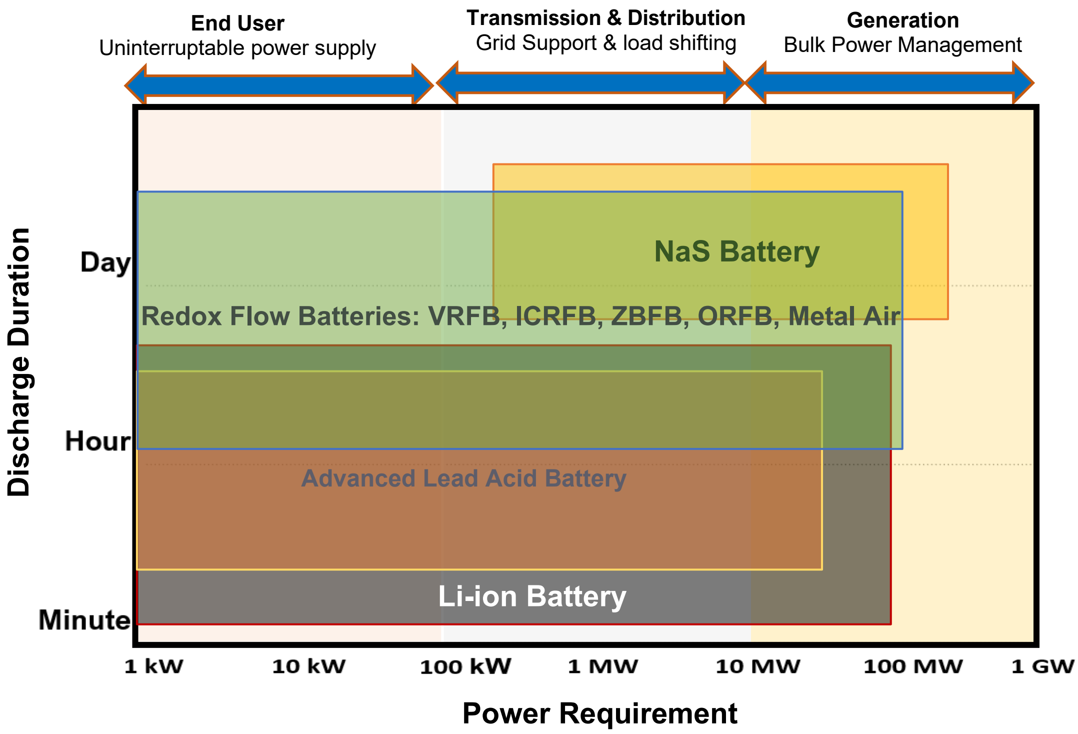

Figure 34: Technology Mapping of Electrochemical Energy Storage Systems by Discharge Duration & Power Rating

Source: CES Analysis

Among emerging non-lithium technologies, redox flow batteries (RFBs) and metal-air systems are particularly promising for medium-to-long duration energy storage. Their modular architecture enables independent scaling of power and energy, offering flexibility across a range of grid applications. Various RFB chemistries - such as vanadium (VRFB), zinc-bromine (ZBFB), iron-chromium (ICRFB), and organic (ORFB) - bring distinct advantages, including cost-effectiveness, material diversity, and lower environmental impact, positioning them as strong candidates for grid-scale and sustainable storage solutions.

3.2.4. REDOX FLOW BATTERY CONFIGURATION AND COMPONENTS

Redox Flow Batteries (RFBs) store energy through redox reactions involving electroactive species in liquid electrolytes. These electrolytes are stored in two separate external tanks and are circulated through an electrochemical cell stack using pumps during charge and discharge cycles. Energy is stored chemically in the electrolyte and converted to electrical energy through redox reactions at the electrodes. A membrane between the half-cells enables selective ion transfer (typically protons) to maintain charge balance, while a cooling system regulates heat during operation.

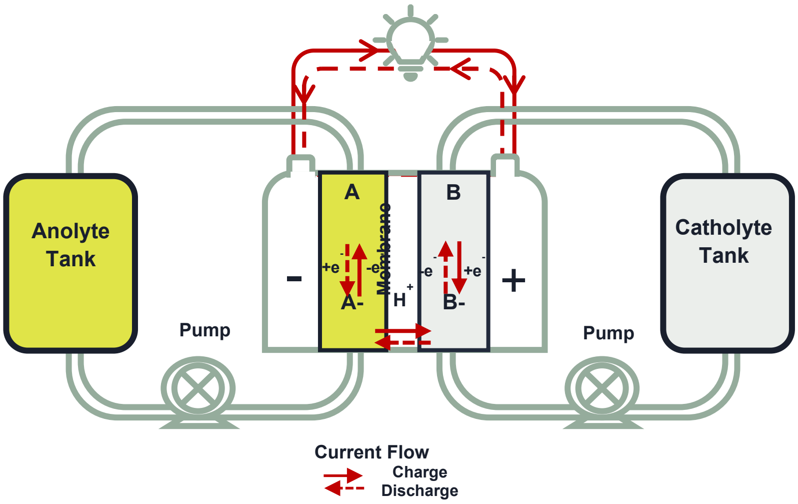

Figure 35: General Schematic of a Redox Flow Battery

Source: CES Analysis

A typical RFB system comprises the following key components:

- **Electrolyte Tanks & Pumps:** Two external tanks store the liquid electrolytes containing active redox species, circulated by pumps through the battery stack.
- **Liquid Electrolytes**: Solutions containing redox-active ions (e.g., vanadium, iron, zinc, or organics) that undergo reversible oxidation states to store energy.
- **Electrochemical Stack**: Composed of multiple cells with porous electrodes where the redox reactions occur.
- **Ion-Exchange Membrane:** A selective membrane separating the electrolytes, allowing ion passage for charge balance while preventing active species mixing.
- **Thermal Management System**: A cooling system to regulate temperature and maintain efficiency during operation.

Their modular architecture, decoupled power and energy scaling, and long operational life (25+ years) position them as a cornerstone of next-generation, non-lithium energy storage solutions.

3.2.4.1. Zinc-Bromine Flow Battery (ZBRF)

In a ZBRF system, an aqueous electrolyte containing zinc and bromide ions circulates through the system. During charging, zinc is electroplated onto the negative electrode while bromine is generated at the positive electrode. During discharge, these reactions reverse - zinc dissolves back into the electrolyte and bromine is reduced, enabling efficient and reversible energy conversion.

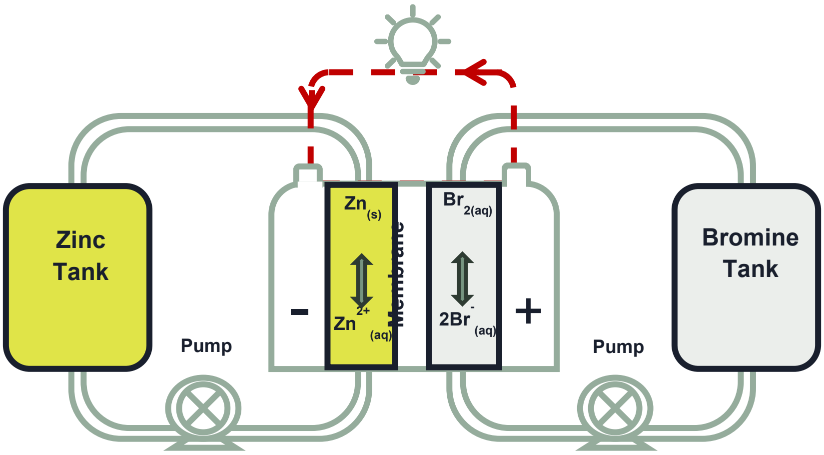

Figure 36: Schematic of Zinc-bromine Redox Flow Battery

Source: CES Analysis

ZBRF offer moderate energy density, inherent safety, and utilizes abundant, cost-effective materials. These characteristics make them well-suited for stationary storage applications, including off-grid systems, renewable energy integration, and commercial backup.

However, several technical challenges currently hinder their broader adoption. These include issues with zinc dendrite formation and high self-discharge rates (partially attributable to bromine crossover). Furthermore, maintenance complexity, alongside bromine toxicity, and the electrolyte's sensitivity to high temperatures (above 50°C), can significantly impact both performance and operational safety.

3.2.4.2. Iron -Chromium Redox Flow Battery (ICRFB)

ICRFBs are an emerging energy storage technology that harnesses iron and chromium ions in liquid electrolytes. Their appeal lies in the use of abundant, cost-effective metals, making them a promising alternative for regions aiming to diversify energy storage solutions and reduce dependence on critical raw materials.

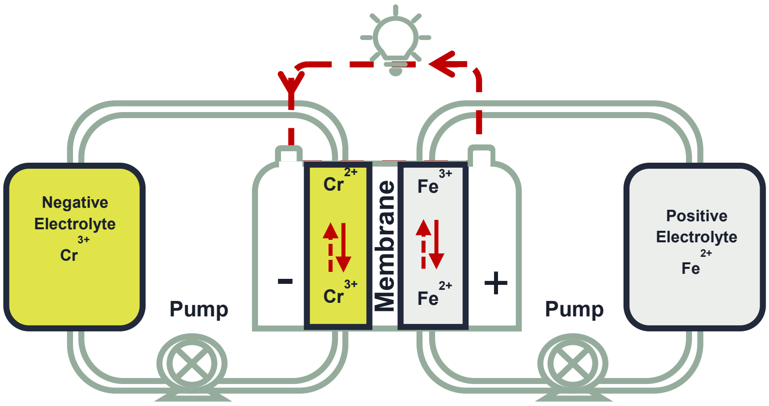

Figure 37 Schematic of Iron-Chromium Redox Flow Battery

Source: CES Analysis

South Africa stands at the forefront of global ICRFB development, leveraging its position as the world's leading chromium producer. This strategic edge is amplified by China's dependence on South African supply and the West's push to diversify away from Chinese-controlled value chains—making ICRFBs both a technological breakthrough and a geopolitical asset.

The country's abundant resources, growing technical expertise, and access to high-growth markets across Africa, MENA, India, and Southeast Asia reinforce its dual role as a resource base and innovation hub. Progress is evident: South Africa has developed a multi-kilowatt energy storage system and proprietary methods to convert locally sourced ferrochrome into low-cost electrolytes. With the technology now at TRL 5-6, it has proven its viability in relevant environments and is advancing toward pilot-scale deployment.

As global momentum builds, the focus is shifting to the scalability of electrolytes - the cornerstone of ICRFB systems. Companies like Redox One are leading commercial-scale production, supported by an indigenous crystallization process that transforms liquid electrolytes into solid salt form. This innovation simplifies transportation, reduces costs, and enables easy reconstitution at high-demand destinations like China, enhancing commercial readiness and paving the way for global deployment.[70]

3.2.4.3. Metal-Air Battery

Metal-air batteries are a unique category of electrochemical energy storage systems that generate electricity through the chemical reaction between a metallic anode and oxygen drawn from the surrounding air. Their key advantage lies in their exceptionally high theoretical energy density, attributed to drawing oxygen directly from the atmosphere, eliminating the need to

[70] https://redoxone.com/redox-one-a-mine-to-megawatt-solution/

store a cathodic reactant internally. Common chemistries include iron-air, zinc-air, and aluminium-air, each leveraging abundant materials.

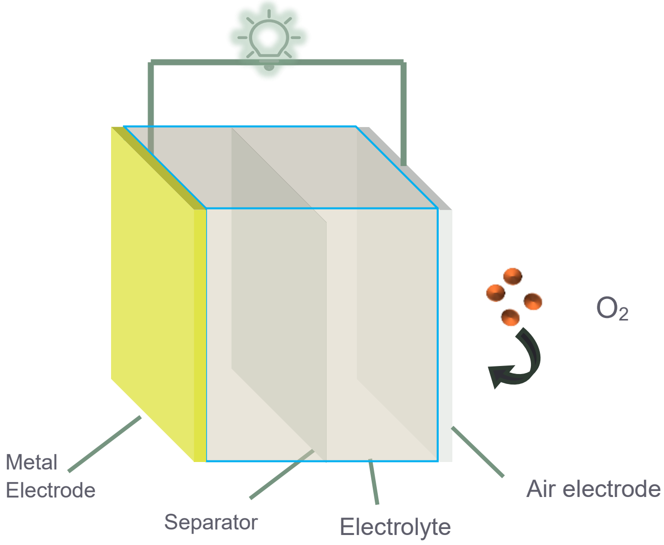

Figure 38: Schematic of Metal- air Battery

Source: CES Analysis

A typical metal-air battery consists of four key components:

i. Metal Anode: Active material (e.g., zinc, aluminium, lithium, iron) that oxidizes during discharge to release electrons.

ii. Air Cathode: Porous electrode that enables oxygen diffusion and acts as the positive terminal.

iii. Electrolyte: Ionic conductor (aqueous or non-aqueous) facilitating ion flow between electrodes.

iv. Separator: Porous membrane preventing short-circuiting while allowing ion transfer.

Despite their high energy potential, challenges like limited rechargeability (especially in aluminium-air), dendrite formation (in zinc systems), and low cycle life persist. However, ongoing R&D is unlocking their promise for scalable, stationary grid-support applications.

In conclusion, this section outlines a framework for selecting energy storage technologies based on discharge duration (across a minutes-to-days discharge spectrum, as in Figure 33 and Figure 34) and application needs. Among non-lithium options, redox chemistries-especially VRFBs-stand out for their maturity and reliability in medium to long-duration storage. While other redox systems show promise, they currently face technical hurdles and lower readiness levels. Complementary technologies like sodium-sulphur, advanced lead-acid, and metal-air also play a critical role. Continued innovation across these chemistries is essential to enable scalable, sustainable, and application-aligned energy solutions.

3.3. Assessment of Diverse Storage Technologies as per Techno-commercial Attributes

To support strategic evaluation, energy storage technologies are assessed across two key dimensions: Technological Parameters and Commercial Parameters (Table 12).

The "**Technological Parameters**" category forms the foundational technical assessment criteria for evaluating various energy storage. It encompasses critical aspects such as performance metrics (e.g., round-trip efficiency, power density, energy density), operational capabilities (e.g., response time, cycle life, operational temperature range), and any inherent technical limitations or specific infrastructure requirements.

Commercial Parameters assess the market viability of energy storage technologies by evaluating material costs, supply chain scalability, environmental impact, and overall cost-effectiveness through LCOS. Technology Readiness Level (TRL) adds insight into maturity and commercialization potential, ensuring selected solutions are scalable, sustainable, and aligned with long-term deployment goals.

Table 12: Example Technical and Commercial Parameters for Storage Technology Assessment

Example Technical Parameters	Example Commercial Parameters
Power Density: Rate at which energy can be delivered per unit mass or volume	**Bill of Material:** Extent of critical raw material needed for manufacturers of different energy storage solutions, and any constraints in mining and processing
Discharge Duration: The time it takes for different energy storage technologies to fully discharge itself	**Technology Readiness Level (TRL):** A scale used to evaluate the maturity of technology from early research and concept stages to fully developed
Round Trip Efficiency: Ration of energy charged to storage system to the energy discharged from the system and takes into consideration energy losses from power conversions and parasitic loads	**Global Capacity:** The overall manufacturing capacity that is live for different energy storage technologies globally and deployed globally in the form of actual project
Response Time: Measures how quickly the system can respond to a demand for energy and the time it takes for a system to provide energy at its full rated power	**Impact on Environment:** Evaluated negative and irreversible impact that a system has on the environment
Deployments: The constraints as higher gestation period geographical constraints for deployment etc.	**LCOS:** The per unit cost of storage system, considering all associated capital, operational and manufacturing costs

Source: CES Analysis

Low Medium High

Table 13: Comparison of Storage Technologies as per Key Techno-commercial Parameters

Parameters	Advanced Lead Acid	Lithium-ion (NMC)	Lithium-ion (LFP)	Sodium-ion	Metal -Air	VRFB	ICRFB	[a]ZBRF	[$]NaS	*Na-NiCl₂	PHES	CAES	[&]LAES
TRL	9	9	9	6-7	5-6	9	6-7	9	9	9	9	7-9	7-8
Efficiency (RTE%)	75-85	85 – 95	85 – 95	85 – 90	40-60%	60-78%	60-65%	68-72 %	80%	85-95%	70-85%	40%-60%	40%-60%
DOD	80%	90%	90%	90%	90%	100%	100%	100%	100%	80%	85%	80%	80%
Energy Density (Wh/kg)**	30 - 60	240-260	160 - 180	90-140	150-800	35-60	10-15	65-80	222	100-120	0.5-1.5	2-10	30-80
Energy Density (Wh/L)**	80 -120	500-700	300-500	150-200	150-700	25 -35	12-20	20-25	376	150-180	0.3-1.5	0.4-20	150-200
Cycle life	1,500 – 2,000	2,000 – 7,000	2,000 – 10,000[a]	2,000 – 3,500	500-2,000	10,000-20,000	>10,000	3,000-5,000	7,300	4,500	10,000-20,000+	10,000-25,000+	15,000-30,000+
Safety (Thermal Stability)***	Medium	Low	Medium	Low	High	High	High	Medium	Medium	Medium	High	High	High

Parameters	Advanced Lead Acid	Lithium-ion (NMC)	Lithium-ion (LFP)	Sodium-ion	Metal -Air	VRFB	ICRFB	[a]ZBRF	[$]NaS	*Na-$NiCl_2$	PHES	CAES	[&]LAES
Toxicity of Chemicals	High	High	High	High	High	Medium	Medium	Medium	Low	Low	Low	Low	Low
Self Discharge[$$]	~3-5%/Month	~0.5%/ Month	~0.5%/ Month	~1-2%/Month	~5%/Month	~0.05%/day	~1%/day	~3%/day	~20%/day	~15%/day	~0	~0	~0.05%/Day
Life (Years)	3-6	5-10	5-10	5-10	3-8	25-30	25	10-15	20	20	25-40	25-30+	25-30+
Discharge Duration	2 - 6	2 - 6	2 - 6	2 - 6	4- 10	4 – 12	4 – 12	4- 10	6-10	6-10	6 - 20+	2 – 24+	4 – 20+
Operating Temperature	-20ºC to +50ºC	+10ºC to +35ºC	-20ºC to +55ºC	-10ºC to +50ºC	-20ºC to +40ºC	+10ºC to +50ºC	+40ºC to +60ºC	0ºC to 50ºC	-40°C to +70°C	-20°C to +60°C	0°C to +40°C	+20°C to +40°C	+15°C to +70°C
Recyclability	Limited Metal	Limited Metal	Limited Metal	Limited Metal	Moderate	High	Moderate	Moderate	Limited Metal	Limited Metal	NA	NA	NA
System Cost ($/kWh)	220-250	140-160	100-120	150-350	350+	280-400	350-450	300-650	200-320	300+	180-260	260-450	240-400
Available C-rates	C/5-C/10	C/2 – 10C	C/4 – 10C	C/2 – 2C	C/2-C/6	C/5-C/8	C/5-C/10	C/3-C/6	C/6-C/8	C/5-C/10	C/4-C/10	C/4-C/10	C/2-C/10

Parameters	Advanced Lead Acid	Lithium-ion (NMC)	Lithium-ion (LFP)	Sodium-ion	Metal -Air	VRFB	ICRFB	[a]ZBRF	$NaS	*Na-NiCl$_2$	PHES	CAES	&LAES
Battery Chemistry	Lead, Carbon Electrodes	Lithium, Manganese, Nickel, Cobalt, Graphite	Lithium, Iron, Phosphate Graphite	Prussian Blue Analogues, Hard Carbon	Metal anode (alkaline electrolyte)	Vanadium (Acidic electrolyte)	Iron, chromium, Bismuth, Indium, Hydrochloric acid	Zinc, Bromine	Sodium, sulphur, Alumina	Sodium, Nickel Chloride	Strict geographical conditions	Underground and salt domes	Caverns

Notes: **VRFB**: Vanadium Redox Flow Battery, **ZBRF**: Zinc Redox Flow Battery, **ICRFB**: Iron-Chromium Redox Flow Battery **NaS**: Sodium Sulphur $BASF (Inside module :300-350°C), **Na-NiCl$_2$**: Sodium Nickel Chloride Battery & Sumitomo (Inside module < -195°C). **PHES**: Pumped Hydro Energy Storage, **CAES**: Compressed Air Energy Storage, **LAES**: Liquid Air Energy Storage, **GES**: Gravity Based Energy Storage, [a]mature but still evolving technology, **system level numbers for NaS, Na-NiCl$_2$, $$considering no idling time between charge and discharge, ***Only thermal stability is considered here. There can be other consideration such as toxicity, corrosivity. etc. # lower Depth of Discharge (DOD) cycle. Toxicity here refers to the use of potentially harmful substances in raw materials. System Cost include battery energy storage system (BESS) and power conversion system (PCS) together.

Takeaway: Mature systems like lithium-ion, VRFB, and PHES offer high efficiency and scalability, while emerging technologies such as sodium-ion, metal-air, and CAES are steadily advancing toward maturity, with ongoing innovations enhancing their potential for cost-effective and LDES. The above table highlights that each technology exhibits unique performance characteristics - such as efficiency, cycle life, response time, and storage duration. The choice of technology depends on specific application requirements, grid support functions, and overall cost-effectiveness. The parameter-wise evaluation is discussed below.

VRFBs offer a balanced profile for long-duration storage, combining high cycle life (10,000–20,000), 100% DoD, strong thermal stability, and excellent recyclability through reusable vanadium electrolytes. While their energy density and efficiency are moderate compared to lithium-based systems, they provide a reliable and safe solution for grid-scale applications with a service life of 25-30 years. South Africa has emerged as a key player in VRFB deployment, leveraging its vanadium reserves to support domestic manufacturing and energy resilience.

- **Technology Readiness Level (TRL):** Most technologies are commercially mature (TRL 9), except sodium-ion, metal-air, and ICRFB, which are still developing. Mechanical systems like LAES are emerging, while CAES is mature but varies by configuration.
- **RTE & DoD:** Mechanical systems like CAES and LAES have lower round-trip efficiency (40-60%), while redox flow batteries (RFBs) offer better performance. Most technologies achieve 80-90% depth of discharge, whereas redox flow systems, including VRFBs, can reach 100%.
- **Energy Density**: Varies by chemistry and system design. Compact, cell-based technologies like Li-ion offer higher energy density, while modular systems - such as RFBs and mechanical storage -tend to have lower energy density due to reliance on ancillary components like tanks, turbines, or pumps.
- **Cycle Life & Lifespan**: RFBs typically offer operational lifespans of 25-30 years, NaS falls in the mid-range, while most other electrochemical batteries have significantly shorter lifespans of around 5 -10 years.
- **Safety, Stability and Recyclability**: ICRFBs are considered safer and less toxic than other RFBs, as well as Li-ion and lead-acid systems, due to their use of low-toxicity materials. High-temperature technologies and Metal-Air exhibit higher self-discharge rates, while mechanical systems show no significant toxicity or thermal risks. In terms of recyclability, VRFBs excel with reusable vanadium electrolytes. ICRFB and ZBRF offer moderate recyclability, though handling of chromium and bromine requires care. Lithium and sodium-based chemistries face recycling challenges due to complex materials, while mechanical systems like PHES, CAES, and LAES are not conventionally recyclable but benefit from long operational lifespans (25-40 years).
- **Cost:** LFP offers the lowest cost for short-duration use. ICRFB and Metal-Air are costlier due to lower maturity and efficiency.

In South Africa, the deployment of VRFBs is particularly well-suited to regions with high ambient temperatures and fire-prone environments, where the inherent thermal and chemical stability of VRFBs offers a distinct safety advantage over other battery chemistries. Additionally, the availability of high-grade vanadium resources within the country supports the production of quality electrolytes, which can enhance system performance and deliver efficiency benefits. Favourable environmental conditions and access to high-grade vanadium make South Africa well-suited for large-scale VRFB deployment in grid and industrial storage.

Conclusion

No single energy storage technology fits all needs; selection depends on specific application requirements-discharge duration, energy and power density, lifespan, safety, environmental impact, and cost. Li-ion (LFP) remains dominant for short-duration due to its low cost and scalability. Mechanical systems promising for long-duration storage, involve significant geotechnical and civil engineering risks. Most LDES technologies remain early-stage and capital-intensive, with cost and feasibility varying by location and scale.

3.4. Techno-commercial Readiness of Emerging LDES with Respect to VRFB

The projected technological readiness viability trajectory for each energy storage technology reflects its anticipated progression towards widespread market adoption across specific timeframes (e.g., 2024, 2027, 2030). This trajectory, typically categorized as **Low**, **Medium**, or **High**, signifies the increasing maturity and adoption potential of technology, contingent upon the successful resolution of identified technical and system-level challenges over time.

- **Low**: Technology faces significant technical, economic, or market barriers to widespread commercial adoption; limited current market presence.
- **Medium**: Technology demonstrates increasing maturity and market penetration, with ongoing efforts to overcome remaining challenges and scale up.
- **High**: Technology is commercially viable, widely adopted, proven in repeated use, and actively being sold in the market.

Table 14: Technological Readiness Roadmap for Energy Storage Technologies

Low Medium High

Energy Storage	Technology	2024	2027	2030	Technical and System-Level Bottlenecks to Commercial Adoption
Electrochemical Batteries	Advanced-PbA	Medium	Medium	Medium	Short cycle life (< 2000 cycle), lower ED (~40 Wh/kg) & chemical toxicity
	Li-ion (LFP)	High	High	High	Streamline supply chain, short cycle life compared to RFBs & need TMS
	NaS	Low	Medium	Medium	High operating temperature (270-350°C) & require TMS
Redox Flow Batteries (RFBs)	ICRFB	Low	Low	Medium	Early-stage; scaling & supply chain still evolving
	ORFB	Low	Low	Low	Early stage; stability & degradation
	VRFB	Medium	High	High	Vanadium price volatility, lower ED, & streamline supply chain
	ZRFB	Low	Low	Low	Material toxicity, crossover reactions & electrolyte sensitive @50 °C
Mechanical	CAES	Low	Medium	Medium	Require TMS, specific geology condition & lower RTE
	PHES	High	High	High	Substantial upfront costs & specific geology condition

Note - ED: energy density, PbA: lead Acid, TMS: Thermal Management System

Source: CES Analysis

Advanced lead-acid batteries are a mature and cost-effective solution for short to medium-duration energy storage. However, they suffer from limited cycle life, performance degradation influenced by Depth of Discharge (DoD), and the use of toxic materials. As safer and more efficient technologies emerge, their relevance in future energy systems is expected to decline.

Lithium-ion (LFP) batteries supported by mature supply chains and high energy density, are gaining momentum in 8-hour configurations for LDES. While they face challenges such as thermal management, shorter cycle life compared to RFBs, and sustainability concerns, LFP systems are expected to play a key role by 2030. However, competition from emerging chemistries like RFBs may intensify as the market evolves.

NaS batteries are attracting commercial interest for LDES due to their high energy density. However, their requirement for high operating temperatures introduces technical and safety challenges, demanding specialized thermal management systems (TMS). These limitations may slow widespread adoption, though moderate market uptake is expected by 2030.

ICRFBs is emerging as viable options for LDES, with stable aqueous electrolytes and excellent scalability, and are better suited for grid-scale applications. However, adoption is limited by slow chromium kinetics, hydrogen evolution, and electrolyte complexity. Recent advances-such as bismuth additives to reduce cycle fade and rebalancing units to manage hydrogen buildup and maintain electrolyte quality-are improving system reliability. With continued progress in efficiency, durability, and cost, broader ICRFB deployment is expected by 2030.

VRFBs are gaining commercial traction for their long cycle life, safety, and scalable architecture that decouples power and energy. However, adoption is slowed by high upfront costs, low energy density, and a fragile supply chain. V_2O_5 prices remain volatile, affecting overall system economics. Decades of research have led to continuous electrolyte improvements, including the innovative use of single mixed inorganic acids, resulting in distinct generations (discussed in Chapter 1). Importantly, the recyclability of VE offers a compelling sustainability edge. Risks such as leakage and cross-contamination are mitigated through robust system design. Crucially, vanadium is infinitely recyclable, enabling circular economy models that reduce lifecycle costs and environmental impact. With progress in scaling, reuse, supply chain development, broader adoption is expected by 2030.

ORFBs utilize carbon-based molecules like quinones, viologens, and TEMPO as active materials, offering a sustainable, metal-free alternative for LDES. Their tuneable chemistry avoids reliance on critical metals such as vanadium, making them attractive for future scalability. However, commercial adoption is limited by chemical instability, electrolyte degradation, and short cycle life. Ongoing research is focused on enhancing molecular durability, membrane compatibility, and electrolyte stability, with broader viability expected in the coming years.

ZRFBs is leveraging low-cost, abundant materials and strong safety profiles. ZRFBs offer higher energy density and simpler stack designs but face issues like zinc dendrites, bromine crossover, and toxicity.

CAES is advancing slowly due to site dependency, low efficiency, and high capital costs. Still, its long-duration capability makes it a viable medium-scale solution by 2030, especially in areas with suitable geology.

Conclusion

From the framework developed to assess the technology readiness for commercial deployment of various energy storage technologies, VRFB and LFP batteries stand out as the most suitable candidates. This assessment is based on several critical factors, including the maturity of their supply chains, superior cycle life, and effective thermal management capabilities.

3.5. Commercial Promise of Non-Vanadium Chemistries & the Impact of VRFB Electrolyte Advancements on Vanadium Utilization

3.5.1. EVOLVING FLOW BATTERY TECHNOLOGIES AND THEIR COMMERCIALIZATION POTENTIAL

VRFBs represent the most commercially mature RFB technology, with a proven track record in MW-scale deployments. In contrast, other flow batteries remain in earlier stages, mostly limited to pilot and demonstration projects (as seen in Table 15

Table 14). This assessment compares next-generation RFB chemistries to VRFBs, focusing on cost-effectiveness, performance, and market potential.

While other variant of RFBs may broaden the technology landscape and introduce competition, VRFBs retain a distinct advantage through the long-term stability, recyclability, and retained value of vanadium electrolyte. The pace of RFBs adoption will influence electrolyte cost reduction efforts and shape the market expansion strategy for VRFBs.

Traditional (All-Liquid) RFBs: These systems involve only fluid-phase redox active species during charge and discharge. Notable examples include the VRFB and ICRFB system.

Hybrid RFBs: These systems involve a phase change at one of the electrodes during the electrochemical reaction, typically featuring the deposition or dissolution of a solid material. A prominent example is the ZBRF system, where zinc metal plates onto the anode during charging and dissolves back into the electrolyte during discharge.

While a few specific models are highlighted, the table reflects the diverse landscape of RFB development, spanning from commercially available VRFB systems to emerging organic chemistries. It emphasizes core strengths like long cycle life and enhanced safety from non-flammable, water-based electrolytes-key attributes for LDES. At the same time, it identifies common bottlenecks across chemistries, including cost, system complexity, and the need for further validation of long-term stability and scalability, especially for newer technologies.

A critical overarching challenge hindering the commercialization of RFBs, is the difficulty in securing consistent and substantial investment. Numerous companies, even those with relatively mature technologies (e.g., Redflow [71]), have ceased operations or undergone mergers. This can be attributed to a confluence of factors, including technological defects that impede performance or reliability, and critically, insufficient capital from investors or early adopters to sustain research, development, and commercial scaling. This disparity risks widening the cost and deployment gap between RFBs and LFP. Despite some emerging interest from larger institutions and limited public equity raising, the RFB sector requires more robust financial backing to fully realize its potential and compete effectively in the market.

[71] Redflow Halts Delivery of Residential Flow Batteries Due to 'Unexpected Product Failure Modes' | Greentech Media

Table 15: Developments in Non-Vanadium Flow Battery Compared with Vanadium Battery

Electrochemical Flow battery type	Chemistry	Company	Model	Discharge Duration (Hours)	Average RTE (%)	Cycle Life	CAPEX ($/kWh)	Recyclability	Strength	Challenges	Technological Maturity
Traditional	Vanadium	Ronke Power	U Power	4-24	80	20,000+	280-400	High	Non-flammable, Long lifespan, Scalable	Volatile V_2O_5 cost	Commercial
	Iron-chromium	ESS Inc. (USA)	Energy Warehouse	4 - 12	70-75	20,000+	340-410	High	Low-cost, abundant material, safe	System complexity, rebalancing	Pilot-Commercial
Hybrid	Zinc-Bromine (Non-flow)	Gelion	Endure	4-12	85-90	5,000	300-500	High	Modular, non-flammable	Scalability, structures supply chain	Pilot-Commercial
	Zinc-Bromine	Redflow (Australia)	ZBM3	2-12	80	3,600	370-1470	Moderate	Modular, non-flammable	Zinc dendrite, complex control	Commercial
	Organic	XL Batteries	--	6-10	40-75	--	--	Moderate	Potential low cost, tuneable chemistry	Stability and Degradation of Organic Molecules	Emerging

Notes:

- Vanadium is listed in the table as a benchmark chemistry to assess the performance parameters of other non-vanadium chemistries. Redflow has shut down after administrators failed to secure a buyer.[71]
- Aqueous inorganic VRFBs were a technical success, particularly as the system is “symmetric,” where the same species can be used as a catholyte (positive charge storer) and an anolyte (negative charge storer). The symmetric design is especially useful because crossover of species is not a major issue anymore and electrolyte rebalancing (needed due to water osmosis over time) effectively allows decades of reliability. However, this chemistry suffers from the volatile cost of vanadium (insufficient global supply), which impedes market growth.

3.5.2. IMPACT OF VRFB ELECTROLYTE ADVANCEMENTS ON VANADIUM UTILIZATION

Gen 1 and Improved Gen 1: Gen 1 and its improved variants represent the most mature and widely deployed form of VRFB technology (refer to Appendix B). These systems have a strong commercial track record, with installations across multiple regions including China, Europe, and the United States. Improved Gen 1 designs incorporate additives that enhance vanadium solubility and energy density while improving stability and operational temperature range. Performance is expected to improve further by 2030 as additive chemistries continue to advance.

Gen 2: Gen 2 systems were developed to achieve higher capacity compared to Gen 1; however, they introduced significant safety and operational challenges due to the use of bromine-based chemistries. These issues limited adoption, and as a result, Gen 2 did not progress into widespread commercial deployment.

Gen 3: Gen 3 represents the latest stage of VRFB development and is currently at the pilot and early commercial deployment stage. It employs a mixed-acid electrolyte formulation that allows higher vanadium concentrations (>2.0 M) compared to Gen 1 (1.6-1.8 M), enabling reduced electrolyte volumes, smaller system footprints, and lower costs. Gen 3 also improves temperature range and stability but requires careful management of chlorine-related risks. The technology for recycling Gen 3 Electrolyte is yet to be developed which is presently seen as a challenge (covered in section 4.4). With greater maturity and scaling, Gen 3 VRFBs are expected to play a significant role in LDES markets by 2030.

Table 16: Comparison of VRFB Electrolyte Generations and Their Market Adoption

Parameter	Gen 1 is the first formulation to be developed and industrially accepted	A modified Gen 1 is the mostly accepted at this point	It is highly chemically reactive and causes formation of bromine gas and corrosion: also, it is more costly to produce	Gen 3 gaining momentum toward pilot-scale commercialization projects
	GEN 1 All-Vanadium	**Improved GEN 1**	**GEN 2 (Vanadium-Polyhalide)**	**GEN 3 (Mixed Acid)**
Electrolyte composition (both side)	V/sulphate	V/sulfate	V/HBr/HCl solution	V/H_2SO_4 /HCl
Negative Couple	V(III)/V(II)	V(III)/V(II)	V(III)/V(II)	V(III)/V(II)
Positive Couple	V(IV)/V(V)	V(IV)/V(V)	$Cl^-/ClBr^{2-}$	V(IV)/V(V)
Vanadium Concentration (M)	1.5 – 2	1.6 – 2.5	2.0 – 3.5	2.0 – 2.7
Supporting Electrolyte	H_2SO_4	H_2SO_4	HBr, HCl, NaCl, KCl, NaBr, KBr	H_2SO_4 and HCl

Temperature Range (°C)	15 - 40	10 – 40	0 - 50	-5 - 50
Specific Energy (Wh/kg)	20 – 25	25 - 40	25 - 50	35 - 55
Energy density (Wh/L)	20 - 33	30- 50	35 - 70	30 - 40
Positive overcharge reaction	Oxygen	Oxygen	Bromine	Chlorine
Advancement	First Electrolyte	Additives to stabilize the V ions into the solution	Increase the operational temperature range and reduce the volume	Use an acidic mixture to increase the V solubility over broader range of temperature. No cooling or heat exchanger needed
Charge/Discharge Efficiency (%)	86%	>85%	80 - 83%	80 - 85%
Innovator	Skyllas-Kazacos & co-workers	Improved GEN 1	Skyllas-Kazacos	Pacific Northwest National Laboratory

As of 2025, Gen 1 and Improved Gen 1 VRFBs dominate the commercial market, with multiple suppliers achieving large-scale deployments. Gen 2 systems are considered obsolete and are no longer actively pursued. Gen 3 systems are in early deployment stages, with strong potential to scale by 2030 as technology maturity improves and demand for higher energy density, lower-cost flow batteries accelerate. To summarise, by 2030, improved Gen1 will take up a majority share in the market, and a minor share will be taken up by Gen 3 electrolyte.

3.6. SWOT Analysis & Technology Risk Assessment for VRFBs

The SWOT analysis highlights the unique positioning of VRFBs in the evolving energy storage landscape. Internally, the technology exhibits strong reliability, safety, and flexibility features, making it highly suited for grid applications and long-duration use cases. However, challenges such as low energy density and higher upfront costs continue to limit broader adoption, especially in markets driven by cost metrics.

SWOT analysis of VRFBs

STRENGTHS

- Scalable and modular architecture.
- Independent sizing of power and energy capacities.
- High cycle life (15,000-20,000+ cycles) or long lifespan (15-20 years)
- Excellent safety and thermal stability (non-flammable electrolyte).
- Wide operating temperature range (-10°C to +55°C).
- 100% depth of discharge (DoD) without degradation.
- Recyclable electrolyte, enabling circular use and cost recovery.

WEAKNESSES

- Low energy density (25-35 Wh/L), requiring larger footprints.
- Higher initial capital expenditure (~$370–390/kWh) compared to Li-ion (LFP: ~110–130/kWh).
- Expensive and volatile pricing of vanadium pentoxide (V_2O_5).
- Lower energy-to-volume ratio, limiting compact deployment.
- Heavier and less portable, unsuitable for mobile applications.

OPPORTUNITIES

- Growing demand for long-duration energy storage (6–12+ hours).
- Applications in microgrids, solar/wind buffering, frequency regulation, peak shaving, UPS systems.
- ESG-driven demand for sustainable, non-toxic, and recyclable storage technologies.
- Domestic manufacturing potential and scope to reduce electrolyte costs (from $110 /kWh to $80/kWh by 2030).
- Favorable policy support for energy storage in India, US, EU (LDES mandates, incentives, energy security goals).
- Potential for low levelized cost of storage (as low as $0.10/kWh).

THREATS

- Dominance of lithium-ion technologies due to scale, cost, and established ecosystem.
- Slow commercialization pace; fewer large-scale reference projects and limited OEM availability.
- Emerging competition from alternative chemistries (e.g., zinc, metal-air, sodium-ion).
- Supply chain constraints and geopolitical risks due to concentrated vanadium production (mainly China, Russia, South Africa).

Comparison of VRFB with similar flow battery technologies such as Iron Chromium Flow Batteries (ICRFB)

VRFBs use vanadium ions in both electrolytes, which eliminates cross-contamination risks and makes them highly durable with cycle lives exceeding 15000-20,000 cycles. They are safe, non-flammable, and well-suited for large-scale grid storage due to the ability to scale power and energy independently, though they have relatively low energy density ~25-35 Wh/L and rely on a concentrated vanadium supply chain, making them more expensive upfront but cost-effective over their lifetime that is more than 20 years.

ICRFBs, on the other hand, use abundant and inexpensive iron electrolytes, making them a potentially lower-cost and more sustainable option. They are environmentally benign and safe but face technical challenges such as hydrogen evolution that affect efficiency. Unlike VRFB, the efficiency of ICRFB reduces drastically, which may increase only when the electrolyte is rebalanced. The rebalancing system is a small additional unit that helps maintain 100% capacity (and perfect electrolyte health) for 25-year lifespans. However, operating costs can escalate if rebalancing is not optimized. Poorly designed systems may require frequent chemical replenishment, undermining economic viability.

The energy density of ICRFB is significantly lower than that of VRFB (10-12 Wh/L) indicating larger requirement of space for installation when compared to VRFB.

ICRFBs operate optimally at around 40°-60°C, which is considerably higher than the 10°-50°C range of VRFBs. This makes ICFBs more suitable for hot climates but also restricts their deployment in cooler regions.

VRFBs are established, reliable, and widely deployed at commercial scale, whereas ICRFBs remain an emerging technology—promising lower costs and abundant materials but with limited large-scale deployments and still under development.

Technology Risk Evaluation of VRFBs

While VRFBs are considered technologically mature at the cell and stack level, their broader deployment still carries several system-level and strategic risks. Four major risk categories can be identified, as discussed hereinbelow.

1. Value Proposition

The value proposition of redox flow batteries is challenged by the rapid cost decline of incumbent technologies, particularly lithium-ion batteries like LFP. While VRFBs offer advantages such as enhanced fire safety, long-duration storage potential, and the use of non-constrained materials, these benefits are not yet fully monetized in current market structures.[72] The lack of revenue streams for LDES services like grid resilience and reliability, further weakens the business case. As a result, VRFBs are often seen as less economically attractive, especially for durations under 8 hours where LFP batteries dominate. This leads to a **high-risk** rating in the value proposition category.

2. Market Acceptance

Market acceptance for VRFBs remains limited. For example, despite over $500 million in U.S. investments over the past 15 years, the sector has seen company failures, mergers, and limited commercial deployments.[72] Investors are cautious, often adopting a 'wait-and-watch' approach due to the lack of operational data and proven large-scale deployments. However, there is growing interest in niche applications such as microgrids and fire-prone areas, where VRFBs' unique attributes are more valued. Demonstration projects, often supported by public funding, are critical to building confidence and improving bankability. Overall, market

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[72] Adoption Readiness Level Assessment of Redox Flow Batteries (PNNL - Sept 2024)

acceptance is rated as **medium risk**, with potential for improvement through targeted outreach and successful pilots.

3. **Resource Maturity**

VRFB technology is still maturing in terms of manufacturing scale, supply chain development, and cost optimization. The disparity in capital access compared to lithium-ion technologies has hindered the ability of VRFB developers to scale production and reduce costs. While there is diversity in chemistries apart from VRFB (e.g., zinc-bromine, iron-chromium, organic flow), this also fragments the market and complicates standardization. System components could be produced domestically with investment, but many are currently internationally sourced. The lack of large-scale manufacturing infrastructure and limited supply chain integration contribute to a **medium-to-high risk** rating in this category. However, strategic investments and government support could accelerate maturity.

4. **License to Operate**

This category, which includes regulatory, environmental, and community acceptance factors, is relatively favourable for VRFBs. Their non-flammable nature and potential for domestic manufacturing align well with safety and policy goals, especially in regions with LDES mandates or incentives like the investment tax credit. Community concerns about fire safety and environmental impact are less pronounced for VRFBs compared to lithium-ion systems, giving them an edge in gaining local support. As a result, the license to operate is generally considered a **low-risk** area for VRFB deployment.

3.7. Business Models for VRFB Adoption

A critical factor in VRFB commercialization is the strategy for acquiring vanadium, the system's largest cost component. Traditionally, manufacturers purchase vanadium pentoxide outright, ensuring full ownership but requiring high upfront capital. Alternatively, leasing models offer a compelling option for early-stage or cost-sensitive markets. Leasing reduces initial capital needs, improves project bankability by treating vanadium as a financial asset or collateral, and lowers entry barriers for customers uncertain about long-term VRFB performance. As the industry evolves, comparing leasing and direct purchase is essential to developing sustainable business models.

Leveraging Vanadium Electrolyte Recyclability: Business Models for a Circular Future

Vanadium electrolyte (VE) in VRFBs is neither consumed nor degraded, making it ideal for reuse, recycling, and redeployment in new systems or other industries. This recyclability supports circular business models that reduce environmental impact and lower lifecycle costs.

Industry leaders adopt three main models: [73] [74] [75]

I. **Sell-and-Buy-Back:** Users buy VE upfront while producers repurchase it later. It offers value recovery but maintains high initial cost and price volatility risk.

II. **Renting:** Producer retains VE ownership and charges rental fees, reducing user capital burden and price risk while ensuring material recovery.

III. **Leasing:** Involves a third-party lessor with sub-models –

   - Operational Lease: Lessor owns VE; user may buy at term end.
   - Financial Lease: User finances VE; ownership transfers after lease.
   - Vendor Lease: Producer and lessor jointly offer leasing options.

Renting and operational leasing are most suitable for VRFBs due to high VE cost and long battery life.

Vanadium Leasing Pathways: Comparing Manufacturer and End-User Models

To enable flexible and scalable deployment of VRFBs, two leasing models have been proposed based on who holds the lease for vanadium electrolyte (VE).

1. **Model 1: Leasing to VRFB Manufacturers**

In this model, VE is leased to OEMs, who integrate it into VRFBs and ensure its safekeeping. While it can make systems more attractive to customers by reducing upfront costs and improving bankability; OEMs gain little direct benefit. For them, production costs and margins remain unchanged, and managing third-party leasing and ownership adds complexity. Without added incentives like revenue sharing, guaranteed offtake, or working capital relief, OEMs may view this model as administratively burdensome with limited upside.

2. **Model 2: Leasing Directly to End Users**

Here, VE is leased directly to the end user, who owns the VRFB system but not the electrolyte.

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[73] documents1.worldbank.org/curated/en/099020324185517458/pdf/P174003-e1bed04f-b49a-4647-a3c2-4deb8aa275af.pdf
[74] Largo Physical Vanadium Validates its Unique Leasing Model
[75] Vanadium Electrolyte Leasing: Fuelling the DOE's Long Duration Storage Vision

Table 17: Comparative Approach to Vanadium Leasing Models

Feature	Model 1	Model 2
Leasing Party	Vanadium Electrolyte (VE) is leased to VRFB manufacturers	VE is leased directly to end users
Responsibility	Manufacturer integrates VE into VRFBs and is responsible for its safekeeping	End user owns the VRFB system but leases the VE
Advantages	Manufacturers have better access to local markets	Eliminates intermediary, increasing profitability for VE producers and reducing cost for end users
Disadvantages	Legal ownership and usage location differ, possibly lowering usage standards	End users must build customer base and compete with local manufacturers

Source: CES Analysis

Scenarios A, B, and C apply to both models - leasing to OEMs (Model 1) and to end users (Model 2), each defining how VE is circulated and reused:

- **Scenario A: Single Long-Term Lease**

Ideal for utility-scale projects (20–25 years), minimizing transport and recycling. The leasing companies typically manage price volatility and offer stable lease rates throughout the lease period. To further insulate customers from price swings, they often maintain strategic reserves of vanadium electrolyte acquired during low-price periods. Additionally, some lease agreements include indexed pricing clauses tied to vanadium market rates, but with built-in caps and floors to prevent extreme cost variations. These mechanisms collectively ensure predictable costs and make leasing a more attractive and resilient option for energy storage projects.

- **Scenario B: Multiple Short-Term Leases (5–10 years)**

Suited for industrial/commercial users with temporary needs; enables higher reuse but adds transport, recycling, and regulatory costs.

- **Scenario C: Regional Short-Term Leasing**

Targets industrial clusters or microgrids, reducing logistics and regulatory burden while boosting local economic benefits.

A comparative matrix with three leasing scenarios across the two circular vanadium ownership models, highlighting the LCOS and ideal use case, is shown.

Table 18: LCOS and Use-case Comparison Across Vanadium Leasing Models and Scenarios

Scenario / Model	Model 1: Leasing To VRFB Manufacturers	Model 2: Leasing To End Users
Scenario A: Single Long-Term Leasing	○ **LCOS**: Lowest due to minimal transport and recycling ○ **Ideal Use**: Utility-scale renewable energy storage (e.g., grid-level)	○ **LCOS**: Lowest due to long-term stability and direct use ○ **Ideal Use**: LDES for power producers or utilities
Scenario B: Multiple Short-Term Leasing	○ **LCOS**: Highest due to frequent transport and recycling ○ **Ideal Use**: Temporary industrial or commercial storage needs	○ **LCOS**: Highest due to short lease terms and logistics ○ **Ideal Use**: Short-term backup for small-scale industries or telecom
Scenario C: Short-Term Leasing in a Focused Region	○ **LCOS**: Medium; logistics optimized within region ○ **Ideal Use**: Regional microgrids or industrial clusters	○ **LCOS**: Medium; benefits from localized reuse ○ **Ideal Use**: Community-level storage or localized industrial parks

Source: CES Analysis

The choice among scenarios depends on user concentration and the balance of economic, environmental, and operational efficiency. These models are already in practice globally:

- **Invinity Energy Systems & Bushveld Minerals (UK):** Introduced a VE rental model via Vanadium Electrolyte Rental Ltd., reducing upfront costs for projects like Energy Superhub Oxford by leveraging Bushveld's supply chain.[76]
- **Panzhihua Group & Rongke Power (China):** Implemented a 100 MW/500 MWh VRFB project with a 20-year VE lease, sourcing from local reserves. The model

[76] Vanadium Electrolyte Rental / A New Option for Storage Projects - Invinity

integrates recycling and is backed by state-owned enterprises to support carbon neutrality goals.[77]

- **Imergy Power Systems (Emerging Markets**): Offered a leasing-based "power-as-a-service" for telecom infrastructure, charging by usage. Sourced vanadium from industrial byproducts and partnered with Juno Capital for scale, reducing upfront costs and ensuring reliable LDES in off-grid regions.[78]

3.8. Successful Case Studies in VRFB – Aiming towards Faster Commercial Adoption

In this section, a few case studies of successful VRFB deployments are highlighted, showcasing their innovations and unique aspects.

3.8.1. CASE STUDY 1: VRFB PROJECT IN CALIFORNIA [79]

Project Overview

In 2015, Sumitomo Electric, in collaboration with SDG&E and Japan's New Energy and Industrial Technology Development Organization, launched a VRFB demonstration project in San Diego, supported by California's Governor's Office of Business and Economic Development. This initiative achieved two major milestones: the first VRFB in the U.S. to receive **UL1973 certification (2017)** and the first to operate in **CAISO markets (2018)**. In 2021, the project expanded to include a microgrid, making it the first commercial distribution network in the U.S. and Japan to use storage batteries as the primary power source.

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[77] Panzhihua Urban Construction & Transportation Group and Rongke Power Collaborate on a Vanadium Flow Battery DemonstProject, Introducing an "Storage + Leasing" Business Model for Vanadium Electrolyte! | Vanitec

[78] Imergy's unique leasing option opens volume market for vanadium redox energy storage

[79] SDG&E's VRFB Project for Grid Stability in San Diego | Sumitomo Electric

Key Highlights: The system had a capacity of **2 MW × 4 hours = 8 MWh**, located at an SDG&E substation in San Diego. It maintained **99% uptime** over the last two years, with a design life exceeding 20 years and **99.2% recyclability**. Additional features included **black start capability** and seamless microgrid integration without power interruptions.

Unique Aspects: The VRFB actively participated in CAISO's energy and ancillary services markets, proving its commercial viability. During test runs, it powered 66 residential and commercial customers for up to 5 hours, demonstrating strong performance in real-world outage scenarios.

3.8.2. CASE STUDY 2: INVINITY ENERGY SYSTEMS VRFB AT ENERGY SUPERHUB OXFORD

Project Overview: Energy Superhub Oxford [80] [81] [82]

Launched in July 2022, the Energy Superhub Oxford (ESO) is a £41 million flagship urban decarbonisation project under the UK Government's **Prospering from the Energy Revolution** programme. It aims to decarbonise Oxford's electricity, transport, and heating systems through an integrated local energy network. At its core is a **hybrid BESS** combining - 50 MW/ 50 MWh lithium-ion battery (Wärtsilä) and 2 MW/ 5 MWh VRFB (Invinity Energy Systems).

Key Highlights

Invinity's VRFB uses **27 VS3 modules**, enabling deep daily cycling without degradation. It delivers **2 MW power and 5 MWh storage**, operating alongside lithium-ion to balance short- and long-duration needs. Energy management is optimised by **Habitat Energy's AI platform**, enabling market participation and grid services. In its first two years, the system delivered **2.75 GWh** and supported charging of **89,000+ EVs** at the UK's largest public EV hub.

Unique Aspects

ESO is the **world's first large-scale hybrid BESS** integrating lithium-ion and VRFB, setting a blueprint for future systems. The project reflects strong **public-private collaboration**, involving Oxford City Council, EDF Renewables, Habitat Energy, Kensa Contracting, Invinity, and the University of Oxford.

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80 Energy Superhub Oxford - Invinity Energy Systems
81 Energy Superhub Oxford - powering a cleaner, greener Oxford
82 Energy Super Hub Oxford - 3-year Report: June 2025

3.8.3. CASE STUDY 3: HOKKAIDO WIND INTEGRATION VRFB PROJECT [83]

Project Overview

In April 2022, Sumitomo Electric commissioned a **17 MW/ 51 MWh VRFB system** at the Minami-Hayakita Substation in Hokkaido, Japan. Developed with **Hokkaido Electric Power Network (HEPCO)**, the project supports integration of **162 MW of wind power from 15 wind farms** into the regional grid. It builds on Sumitomo's earlier **60 MWh VRFB project (2015)**, reinforcing its leadership in long-duration energy storage.

Key Highlights

- Operational Term: Designed for 21 years of continuous operation
- Grid Strategy: Instead of requiring each wind farm to install its own battery, HEPCO centralized storage at the grid level, reducing total battery requirements and operational costs.

Unique Aspects

This project is notable for **centralized grid-side storage**, enabling multiple wind farms to share a single large-scale battery system for cost and efficiency gains. Additionally, the VRFB was engineered for **cold-climate reliability**, proving its robustness in harsh winter conditions.

3.8.4. CASE STUDY 4: DECARBONISING OIL TERMINAL OPERATIONS IN SINGAPORE [84]

Project Overview

VFlowTech deployed a 400 kW/ 1.6 MWh VRFB system at an oil terminal in Singapore to demonstrate LDES for powering inductive pump loads and supporting industrial decarbonisation. The system was housed in a single 40-foot container, integrating PCS, transformers, and vertical electrolyte tanks.

Key Highlights

The system uses 558 cells in series. Electrolyte management includes **four vertical polyethylene-lined tanks**, gravity-based balancing, and auxiliary load under 3%. Thermal performance achieved **70% round-trip efficiency** in tropical conditions with minimal chiller

83 Hokkaido Electric Power Network Project for Wind Firm Integration | Sumitomo Electric

84 PowerPoint Presentation - VFlowTech

use, operating up to **47 °C without additives**. Future designs plan **20 stack containers (500 kW each)** with vertical stacking to reduce footprint.

Unique Aspects

Unlike typical grid or residential deployments, this project targets **energy-intensive oil terminal operations**, ensuring reliability for inductive loads. It achieved **<3% auxiliary consumption**, enhancing efficiency, and is designed for **demand response participation** in Singapore's market, offering financial incentives for load flexibility.

3.8.5. BUSINESS MODEL INSIGHTS FOR SCALABILITY

Based on the case studies presented, several business model insights emerge that can accelerate the commercial adoption of VRFBs.

I. A major driver for VRFB adoption is shifting from capital-intensive sales to **flexible financing models**. Leasing structures allow customers to deploy VRFBs without heavy upfront investment, appealing to commercial and industrial users who prefer operating expenses over capital expenditure. This significantly lowers entry barriers.

II. Additionally, grid-level and **centralized storage models** offer scalable, cost-effective deployment. The Hokkaido project demonstrates how substation-level storage reduces redundancy and operational complexity compared to distributed systems. This approach is particularly attractive for utilities managing large-scale renewable integration.

III. **Public-private partnerships and policy support** are critical for scaling VRFBs. Government-backed programs like Japan's NEDO and the UK's PFER have been instrumental in de-risking early projects and accelerating commercialization.

IV. Finally, **modular system architectures**, as seen in VFlowTech's industrial deployments, provide flexibility for diverse geographies and applications, enabling VRFBs to scale across multiple sectors.

Key Takeaways from Chapter 3

Chapter 3 underscored that VRFBs are technically well-suited for LDES applications, particularly in grid-scale and industrial settings. Their strengths lie in their long cycle life, high safety profile, 100% depth of discharge, and modular scalability. However, the report also highlights that despite these advantages, VRFBs face significant challenges in terms of energy density and upfront capital costs. Importantly, the chapter notes that no major technical breakthroughs are expected in the next 5–6 years that would drastically reduce the cost of VRFB systems. This positions VRFBs as a reliable but currently cost-intensive solution, especially when compared to increasingly competitive lithium-ion technologies like LFP.

To address the cost barrier, the chapter explores innovative business models that can enhance the commercial viability of VRFBs. These include leasing-based approaches such as operational and financial leases, as well as circular economy models like vanadium electrolyte renting and buy-back schemes. These models leverage the non-degrading nature of vanadium electrolyte, allowing it to be reused or recycled, thereby reducing lifecycle costs and improving project bankability. The report presents structured leasing scenarios, ranging from long-term utility-scale leases to short-term regional deployments, which can significantly lower the LCOS and make VRFBs more accessible to a broader range of users.

Furthermore, the chapter emphasizes that while technical innovation in VRFBs may be incremental, strategic deployment models and policy support can play a transformative role in accelerating adoption. Case studies from the UK, China, and emerging markets demonstrate how leasing models, centralized grid storage, and public-private partnerships have already enabled successful VRFB deployments. These examples illustrate that business model innovation, rather than purely technological advancement, will be the key driver in overcoming cost-related barriers and scaling VRFBs in the near to mid-term future.

Chapter 4: Risk Assessment and Market Barriers

4.1. Risk Parameters & Mitigation Strategies in VRFB Supply Chain and Manufacturing

The following section outlines key risk parameters across the Vanadium market, spanning from upstream resource availability to the final deployment of VRFB systems. It covers aspects such as the availability of Vanadium resources, particularly V_2O_5 production; the volatility in V_2O_5 pricing; technical risks associated with Vanadium electrolyte production; precedent-setting risk mitigation measures implemented in China to develop a comprehensive VRFB ecosystem; and global strategies aimed at stabilizing V_2O_5 prices and reducing CAPEX.

4.1.1 AVAILABILITY OPTIONS OF VANADIUM RESOURCE (VANADIUM PENTOXIDE PRODUCTION)

The vanadium market is facing significant supply constraints, particularly in producing high-purity vanadium pentoxide (98–99%), which is essential for battery applications. This level of purity is technically demanding and costly to achieve, requiring substantial investment and time from resource extraction to final product. Currently, primary vanadium production contributes only about 15% of the global supply and is concentrated in the first cost quartile, making it difficult to scale. Most of the supply comes from co-production such as VTM, which are not optimized for battery-grade purity, further complicating the supply landscape.

A) Supply constraints from low-cost primary Vanadium miners

According to the USGS 2024 report, global vanadium resources are abundant but not easily accessible. Vanadium is typically found in low concentrations - less than 2%, in host materials, making extraction both technically and economically challenging. Most vanadium is recovered as a byproduct of steelmaking, which limits the flexibility and scalability of supply.

To meet future demand, **there is a prioritised need for exploration and development of new vanadium mines**, along with investment in refining technologies capable of producing battery-grade material. Primary producers can consider VRFBs as a strategic alternative to the steel market, which would help diversify their customer base and reduce market risk.

South Africa's opportunity lies in high-grade deposits (>1.5% V_2O_5) and in secondary recovery (fly ash, slag, spent catalysts). A combined **beneficiation and recycling** program can structurally lower delivered cost for battery-grade vanadium while de-risking exposure to co-product cycles.

b) New mines and circular recovery from low-grade Vanadium sources leads to low-cost of production and sustained supply

Emerging primary producers in Western Australia and Queensland present both a threat and an opportunity. These regions claim they can produce vanadium pentoxide at competitive costs of $8–9/kg and have outlined pipeline targets equivalent to 1-2 GWh of VRB in Western Australia and 1 GWh in Queensland by 2030. They are also targeting export markets in Japan, the US, and Canada with an additional 2 GWh. If successful, these developments could disrupt traditional supply chains and offer more competitive options for VRFB manufacturers.

Beyond traditional mining, the supply of Vanadium is increasingly being supplemented by secondary sources. Companies like US Vanadium, Neometals, and AMG Lithium are actively investing in alternative extraction technologies, such as recovering Vanadium from steel slag and recycling residues from oil refining. These innovative approaches not only diversify the supply chain but also enhance sustainability by reducing reliance on primary mining operations. Notably, secondary production methods can yield Vanadium Pentoxide (V_2O_5) at competitive prices ranging from $8–9/kg to $13/kg, offering a cost-effective alternative to conventional mining. Traditional mining typically involves a lengthy process2 to 3 years for exploration, another 3 years for feasibility studies and securing investments, followed by 3 more years for construction and ramp-up to production resulting in a total lead time of up to 8 years. In contrast, secondary sourcing offers a more agile and environmentally responsible pathway to meet growing demand.

Although South Africa was among the earliest countries to recognize the strategic importance of vanadium for VRFBs, its market penetration has been limited. Despite hosting the world's largest high-grade vanadium resource base and operating three of the four primary vanadium processing plants globally, South Africa has struggled to convert this potential into significant domestic or export growth. The lack of a robust buying market, both locally and internationally, has hindered the scale-up of VRFB-related infrastructure and supply chains. While companies like Bushveld Minerals have made strides in developing the full VRFB value chain - including electrolyte production and downstream integration - the broader market uptake has not matched the country's resource potential.

4.1.2 VANADIUM PENTOXIDE PRICE VOLATILITY

Vanadium prices are highly sensitive to shifts in steel demand: The steel industry remains the largest consumer of Vanadium, especially for strengthening rebar in infrastructure projects. A surge in infrastructure projects or government spending typically drives up steel consumption, which in turn elevates Vanadium prices making it less economically viable for battery applications like VRFBs. However, the reverse is also true: during periods of subdued steel demand, Vanadium prices tend to stabilize or decline. This creates a favourable environment for VRFB development. Therefore, any accelerated progress or increased installation of VRFBs during such low-price phases serves as a strong indicator of market readiness and potential for broader adoption.

Alternative Market: VRFBs are seen as a secondary outlet for Vanadium, especially when steel demand softens and prices stabilize or drop.

Risks of VRFB System Integrators

VRFB systems exhibit a higher sensitivity to fluctuations in V_2O_5 prices, as ~29% of the electrolyte cost is contributed by V_2O_5. In contrast, lithium-ion systems typically show only 10–15% sensitivity to raw material price changes. This heightened exposure makes it essential for VRFB system integrators to hedge against Vanadium price volatility to maintain cost predictability and project viability.

4.1.3 TECHNICAL RISKS IN VANADIUM ELECTROLYTE PRODUCTION

Technical Expertise and Integration Risk: The successful synthesis of high-quality Vanadium electrolyte is a critical factor in the performance and reliability of VRFBs. Equally important is the broader acceptance and technical readiness of system integrators to adopt and deploy VRFB technology. Limited know-how or hesitation among integrators poses a significant risk to the scalability of the market, potentially slowing down commercial adoption despite favourable conditions.

IEC Initiates Global Standardization for Vanadium Electrolyte

The Vanadium electrolyte industry currently **lacks a unified global standard**, resulting in inconsistencies in quality, inefficiencies in production, and potential performance variability across battery systems. To address this, a dedicated working group comprising battery manufacturers and Vanadium producers is actively collaborating with the International Electrotechnical Commission (IEC) to establish standardized specifications for Vanadium electrolytes. These efforts aim to improve reliability, safety, and cost-effectiveness, ultimately supporting the broader adoption of VRFBs in the global energy storage market.

China has introduced its own Vanadium electrolyte standards, which permit a broader range of purity levels. While this approach may support cost reduction and supply flexibility, it also raises concerns about long-term battery performance. Impurities in Vanadium electrolyte can negatively affect energy capacity, obstruct electrolyte flow, and trigger undesirable chemical reactions ultimately compromising battery efficiency and lifespan. In contrast, the IEC is working to establish more stringent technical specifications aimed at minimizing these risks. By enforcing higher purity and performance benchmarks, the IEC standard seeks to ensure greater durability, safety, and operational consistency, thereby supporting the reliable scaling of VRFB technology in global energy storage markets.

To address the risks associated with inconsistent electrolyte quality, the IEC initiated efforts in March 2025 to develop a unified global standard for Vanadium electrolyte. This initiative, supported by contributions from the Fraunhofer Society and key industry stakeholders, is a pivotal step toward ensuring the commercial viability and scalability of VRFB. By establishing clear technical benchmarks, the standard aims to enhance performance reliability, safety, and cost-efficiency across the energy storage sector.

Vanadium electrolyte standards are not about China versus the rest of the world, but rather about the need for consistent quality benchmarks to support the growth of the VRFB ecosystem. Establishing standardized electrolyte specifications is essential for building investor confidence, guiding technological development, and enabling large-scale deployment. A unified approach to quality assurance will accelerate market adoption and strengthen the long-term viability of VRFBs in global energy storage applications.

4.1.4 MEASURES IMPLEMENTED IN CHINA TO DEVELOP THE END-TO-END VRFB ECOSYSTEM (RISK-MITIGATION PRECEDENT)

China has taken proactive steps to reduce risks associated with VRFB systems through targeted regional initiatives for developing the entire value chain. One key strategy is the cluster development around Vanadium-rich provinces like Sichuan, where local governments offer various incentives and subsidies. Programs such as the "Measures to Promote High-Quality Development of the VRFB Industry" aim to foster collaboration among Vanadium product manufacturers, electrolyte producers, and battery developers. The initiative encourages joint efforts in resource utilization, capital investment, and technological innovation. It also supports the expansion of Vanadium electrolyte production capacity and the creation of a robust industrial supply chain from Vanadium resource extraction to battery energy storage deployment to accelerate the growth of the VRFB ecosystem.

Overview of the Panzhihua–Dalian Rongke Partnership

An example of industry collaboration in China is the partnership between Dalian Rongke, a leading VRFB developer, and Panzhihua Iron and Steel Group Vanadium Titanium Resources for the supply of Vanadium Pentoxide. Under this offtake agreement, in 2023, Dalian Rongke procured 8,700 tonnes of Vanadium Pentoxide, supporting approximately 1.1 GWh of VRFB capacity. In 2024, the volume increased to 16,000 tonnes (around 2 GWh) at a contract value of $218 million, reflecting a unit price of $13.625/kg. In 2025, the supply further expanded to 20,000 tonnes, enabling 2.5 GWh of storage capacity. Overall, this collaboration supports over 5 GWh of VRFB deployment, underscoring the importance of strong, long-term relationships between developers and Vanadium suppliers. Such partnerships are essential for securing stable supply chains and enabling large-scale energy storage projects.

Also, Rongke purchases Vanadium pentoxide in a co-operative purchase mode for other electrolyte and VRFB System integrators for better negotiation of pricing as China has a healthy target of 12 GWh of VRFB projects by 2027.

Transferable levers for South Africa: Designated cluster SEZ; pooled offtakes; provincial grants for VE capacity; OEM & miner MOUs with floor/ceiling pricing; integrated recycling hubs.

4.1.5 GLOBAL STRATEGIES TO MITIGATE VANADIUM PENTOXIDE PRICE VOLATILITY AND LOWER CAPEX

Major Vanadium Pentoxide producers and system integrators are actively implementing innovative business models to support the scalability of VRFB technology. Notably, companies like Bushveld Minerals and Largo Physical Vanadium (LPV) have introduced leasing models for Vanadium Pentoxide, allowing system integrators to access the electrolyte without bearing the full upfront cost. LPV goes a step further by offering investors the opportunity to gain exposure to the underlying Vanadium commodity, creating a dual benefit of resource access and financial investment.

However, adoption of these models remains limited, with approx. 100–150 MWh of VRFB projects announced (as of August 2025)[85] under such schemes potentially due to lower scale and lower margins for project developers. Additional projects are in the pipeline, and broader implementation of these models could play a key role in accelerating market growth and reducing financial barriers for large-scale deployment. Leasing models for V_2O_5 are typically pursued during periods of price volatility or elevated market prices, as they help system integrators manage cost uncertainty and reduce upfront capital expenditure. However, during low-price environments, developers often prefer to purchase Vanadium Pentoxide outright, as it becomes more cost-effective and offers long-term ownership benefits.

Under the LPV model of purchasing physical vanadium as an investment, market activity remains subdued. Currently, LPV holds only 1.26 kt of vanadium pentoxide, enough for about 160 MWh of VRFB capacity, which is minimal compared to global targets. To build confidence among VRFB system integrators and mitigate raw material price volatility, accelerated growth is needed in both vanadium leasing and physical commodity investment models, as these mechanisms are critical for reducing CAPEX and stabilizing project economics.

4.1.6 GLOBAL EFFORTS TO SECURE VANADIUM SUPPLY

Outside China, efforts to ensure low-cost and stable Vanadium supply are also underway. A notable example is the royalty and technology licensing agreement between Invinity and Guangxi United Energy Storage New Materials Technology (UESNT). In July 2025, the agreement was executed, and it targets the production of at least 1.9 GWh of VRFBs by 2030,

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[85] CES analyses of company announcements or industry inputs

with an initial 300 MWh planned for 2026, subject to UESNT's confirmation. Total volumes depend on UESNT securing demand, so final quantities and timelines may vary. The agreement also allows Invinity access to a long-term, fixed-price Vanadium electrolyte supply or Vanadium products at a discounted market rate, sufficient to support 6 GWh of VRFB deployment.

Interestingly, in September 2020, the same company partnered with Bushveld Minerals to form Vanadium Electrolyte Rental Limited (VERL) for a 5 MWh VRFB project. However, further development of a sustainable project pipeline did not materialize. This highlights a key market insight: in 2020, Vanadium Pentoxide prices were elevated due to post-COVID demand recovery, prompting developers to opt for leasing models to hedge against price spikes. In contrast, during low-price environments, direct purchase of Vanadium becomes the more viable and preferred option.

4.2. Barriers to Large Scale Deployment of VRFBs

VRFBs are increasingly recognized for their suitability in LDES applications due to their scalability, safety, and extended cycle life. However, despite their technological maturity and operational benefits, large-scale deployment of VRFBs remains limited. A combination of economic, supply chain, regulatory, and perception related barriers continues to limit global adoption. Understanding and addressing these challenges is critical for enabling VRFBs to play a significant role in future energy storage infrastructure.

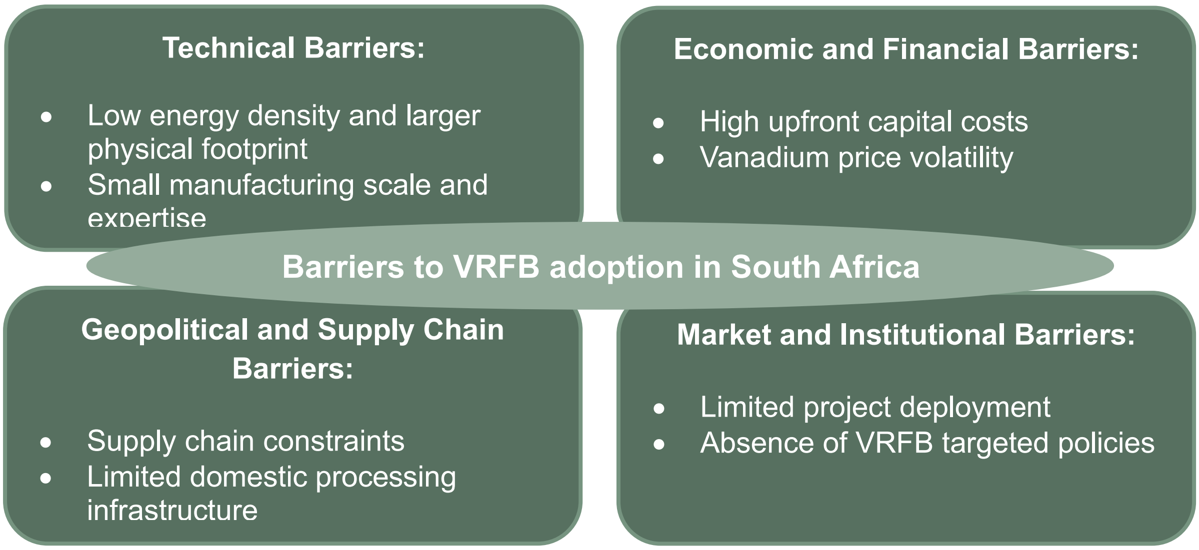

Figure 39: Barriers of VRFB adoption in South Africa

1) Low Energy Density and Larger Physical Footprint of The Battery

VRFBs have significantly lower volumetric energy density (35–60 Wh/L) compared to other BESS suitable chemistries such as lithium-ion (NMC and LFP) (300–700 Wh/L), sodium-ion (150–200 Wh/L), or sodium-sulphur (~376 Wh/L), resulting in much larger land requirements. A 1 MWh VRFB installation can occupy several hundred square meters, whereas lithium-ion systems can achieve similar capacity in less than one-third of the space. This stems from the need for large electrolyte tanks and auxiliary circulation systems. VRFBs can be scaled for long-duration storage by adjusting power and energy separately, but their large size limits use in space-constrained urban and behind-the-meter applications. As a result, VRFBs are better suited for greenfield, utility-scale, or remote projects with ample space, but remain less versatile in compact or mobile use cases.

2) Small manufacturing Scale and Expertise

Unlike lithium-ion batteries, which have matured through decades of investment, mass production, and a globally integrated supply chain, the VRFB industry remains at an early stage of industrial scaling. As of 2024, global VRFB manufacturing capacity is estimated at ~4 GWh, projected to rise to ~15 GWh by 2030, but this still lags far behind commercially mature technologies. Also manufacturing of key components such as electrochemical stacks, system hardware, and high-purity vanadium electrolyte is concentrated among a small number of specialized firms, limiting economies of scale and resulting in higher unit costs, longer lead times, and constrained service availability. While South Africa is among the world's largest producers of vanadium, it lacks full-scale VRFB manufacturing capability due to gaps in downstream technology know-how and a limited base of companies engaged in manufacturing of electrolyte and cell stack and the integration of whole system constraining its ability to fully capture value in the global supply chain.

3) High Upfront Capital Cost of VRFB

VRFB systems typically cost around $280–400/kWh, significantly higher than alternatives such as Li-ion (LFP & NMC: $100–160/kWh), Na-ion ($200–350/kWh), and NaS ($200–300/kWh). The main cost driver is the vanadium electrolyte, which can account for nearly 35% of the total system cost, along with expenses for electrochemical stacks, pumps, control systems, and civil works. Although VRFBs offer lifespans of 20+ years with minimal degradation, enabling competitive lifetime costs (LCOS), the high upfront investment and long payback period remain major barriers to adoption, particularly in markets focused on short-term returns. This challenge is further compounded by the lack of large-scale manufacturing and standardized electrolyte formulations, which adversely affects economies of scale and cost reductions, unlike the well-established lithium-ion industry.

4) Vanadium Price Volatility

The economics of VRFB projects are sensitive to vanadium price fluctuations, as the element forms the core active material in the electrolyte. On the demand side, pricing is influenced by the steel industry responsible for 90% of global vanadium consumption where shifts in steel production directly impact vanadium demand. On the supply side, although primary vanadium production has a lower cost base than co-production sources, the latter mainly from China and Russia, which together hold about 70–80% of global capacity plays a dominant role in market pricing. A sizeable portion of this co-production capacity remains underutilized and is often sold at lower prices, eroding the economic viability of primary producers. Compounding the challenge, most vanadium is obtained as a by-product of steelmaking or mining, making it unable to quickly scale the output in response to demand surges, thereby increasing market vulnerability. This volatility complicates project financing and undermines investor confidence, driving interest in mitigation measures such as long-term supply contracts and vanadium pentoxide (V_2O_5) leasing for electrolyte.

5) Supply Chain Constraints

The VRFB industry is highly exposed to supply chain risks because vanadium production is concentrated in a few countries, mainly China and Russia. Since vanadium supply is closely tied to the steel industry particularly in China any policy shifts or downturns in steel output can directly impact availability and pricing. This creates volatility and makes the market vulnerable to geopolitical disruptions. Diversifying supply through recycling technologies and expanding primary mining in underutilised regions is therefore critical. South Africa, with 8,000 metric tons of annual production (8% of global output produced through mining) and an estimated 430 thousand metric tons in reserves (2% of total world reserves), is one of the few countries engaged in primary vanadium mining. However, despite this resource advantage, limited local processing capacity and dependence on imported electrolyte and components constrain its ability to fully support VRFB deployment in the country. Additionally, South Africa faces export hurdles, including high logistics costs, high power costs, port inefficiencies[86] and regulatory bottlenecks, which limit its competitiveness in global vanadium markets and restrict its potential to become a larger supplier for the VRFB industry.

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86 https://www.trade.gov/country-commercial-guides/south-africa-market-challenges

6) Limited Domestic Processing Infrastructure of VRFB Companies

Globally, many companies in the vanadium supply chain face a bottleneck due to limited domestic processing infrastructure. While certain regions, such as China, many VRFB companies have built large-scale vanadium conversion and electrolyte production facilities, other companies still rely heavily on imports for processed vanadium products. In South Africa, despite being one of the few countries with significant primary vanadium reserves, the domestic processing and conversion infrastructure for VRFB applications remains underdeveloped (potentially due to mismatch in costs and technology). Most of the vanadium produced locally is exported without processing due to limited capacity for downstream conversion into high-purity vanadium electrolyte. As a result, South African VRFB companies are forced to rely on imports for critical processed materials, which adds cost, exposes them to global price swings, and creates delays in project execution. This gap not only slows down large-scale VRFB deployment but also prevents South Africa from fully leveraging its natural resource advantage to build a competitive domestic energy storage industry.

7) Absence of Targeted Policies for VRFB

Unlike lithium-ion batteries, which benefit globally from strong incentives, subsidies, and R&D support through EV and energy storage policies, VRFBs still lack dedicated policy backing. Regions such as the U.S., China, the U.K., the EU, and India have rolled out frameworks to encourage LDES, including funding, mandates, and demonstration projects that indirectly boost VRFB adoption. However, in South Africa, despite being one of the world's significant vanadium producers, there are no targeted policies that directly promote deployment of LDES or VRFB technologies, local electrolyte production, or manufacturing. This gap along with absence of a local Va industry champion (such as a large mining company or a VRBF project developer) limits investor confidence slows industrial growth, and risks South Africa the opportunity to leverage its resource advantage into a leading position in the global VRFB market.

8) Limited Project Deployment

For VRFB technology, limited global project deployment remains a key challenge to scaling adoption. Despite strong technical advantages such as long cycle life, deep discharge capability, and non-degrading electrolytes commercial uptake has been slow compared to lithium-ion systems. The global market has only a handful of large-scale operational VRFB projects, and many deployments are concentrated in demonstration or pilot phases. This limited track record makes it harder for developers to achieve economies of scale, attract large investors, or secure competitive financing for VRFBs.

4.3. Impact Assessment of Global Policies and Trade restrictions

Table 19: Risk Assessment & Opportunities for South Africa from Global Policy & Trade Dynamics

Region wise LDES pipeline by 2030	Key Countries with Battery Storage / LDES-Relevant Policies	Policy Support for LDES/VRFB	Impact on South Africa
North America (~65 GW)	United States	• DOE's Long Duration Storage Shot[87] • Inflation Reduction Act (IRA) • Tariffs on Chinese batteries (2025)[88]	Tariffs on China create opportunities for South Africa to supply vanadium-based batteries Recent country-wise Tariffs by USA on imported goods may restrict future Vanadium market development for South Africa.
Europe (~56 GW)	United Kingdom	• Faraday Battery Challenge[89] • LDES demonstration funding under Net Zero Strategy	UK exploring vanadium imports could open bilateral opportunities.
	European Union	• EU Green Deal[90]	EU demand may create niche export markets.

[87] US Dept. of Energy
[88] US Set to Impose 93.5% Duty on China Battery Material | Financial Post
[89] https://www.ukri.org/what-we-do/browse-our-areas-of-investment-and-support/faraday-battery-challenge/
[90] The European Green Deal - European Commission

		• Net-Zero Industry Act[91] • Innovation Fund grants for non-lithium storage	
Asia and middle east (~56 GW, China~200GW)	China	• Massive state-backed VRFB and Na-ion scaling • Export controls on graphite and vanadium	China dominates vanadium supply chain (upstream to downstream), leaving South Africa vulnerable despite resources. Future trade restrictions by China over vanadium metal or other VRFB components could hinder VRFB adoption in South Africa, since it currently depends on imports for other components.
	India	• PLI Scheme for ACC batteries[92] • Emerging LDES specific Tenders • Push for exploring mining assets abroad and as well in India to explore all kinds of battery technologies	India's policies may foster regional collaboration in BESS deployment. South Africa can leverage the opportunity to become a supplier for Vanadium to India
	Japan	• METI national subsidy programs for grid-scale storage (FY2021,2024)[93] • Tokyo Metropolitan Government subsidy for large-scale storage [94]	Japan's VRFB precedent strengthens South Africa's case as a secure vanadium supplier; could foster bilateral cooperation in raw material and electrolyte supply. There are few large-scale projects deployed in Japan. Japan may diversify supply from Australia or via domestic recycling, reducing reliance on South Africa.

91 Net Zero Industry Act - European Commission
92 Press Release: Press Information Bureau
93 https://japanenergyhub.com/news/fy2024-meti-grid-scale-storage-subsidy-results
94 https://www.investtokyo.metro.tokyo.lg.jp/en/oursupports/green-finance-subsidy.html

Australia (~12 GW)	Australia	• Federal Capacity Investment Scheme (CIS) underwriting dispatchable capacity[95] • NSW Long-Term Energy Service Agreements (LTESAs) supporting LDES[96] • ARENA & CEFC funding for LDES demonstrations[97]	Strong LDES policy signals could increase demand for vanadium; creates an opening for South Africa to supply VRFB materials and components. Australia also has large vanadium reserves and government-backed V_2O_5 projects could eventually challenge South Africa's dominance in VRFB / V_2O_5 supply for Australian market
South America (<1 GW)	Chile	• Law no 21, 505, (2022) [98] encouraging the participation of renewable energy in the electricity matrix by promoting storage technologies	Potential demand for large-scale, non-lithium storage could create an export opportunity for South African vanadium electrolyte/VRFB OEMs
Africa (<1 GW)	South Africa	• There is no specific policy support for LDES or VRFB, but most of the deployments are covered under South Africa's General Battery Storage Program (GBSP) and Energy action Plan[99] [100]	This general policy will support all types of technologies including VRFB, especially where South Africa can leverage its vanadium raw material manufacturing potential and adopt VRFB technology within the country as well.

Note: The cumulative LDES represents power-sector storage (excluding China) projected to reach ~390 GW by 2030, and does not include the industrial/thermal storage (~590 GW) which is also considered under the Accelerated case

95 https://www.dcceew.gov.au/energy/renewable/capacity-investment-scheme
96 Dept. of Climate Change, Energy, the Environment and Water
97 https://arena.gov.au/projects/hydrostor-broken-hill-advanced-compressed-air-energy-storage-demonstration
98 Annual Report | LDES Council
99 https://www.gov.za/blog/tapping-new-ways-storing%C2%A0energy
100 https://www.stateofthenation.gov.za/assets/downloads/Update_EnergyActionPlan_18Months.pdf

4.3.1. RISK ASSESSMENT FOR SOUTH AFRICA (GLOBAL POLICY & TRADE DECISIONS)

While global policy support creates opportunities, South Africa also faces significant risks. A key concern is policy dependence, as global LDES growth is largely driven by strong incentives and mandates in the U.S.A, EU, China, and India. **If these policies shift, slow down, or favour domestic supply chains, South Africa's export potential may be curtailed.**

- This risk is compounded by domestic policy gaps that is, **South Africa lacks a clear, long-term LDES/VRFB deployment roadmap, which could limit attraction of local market and industrial investment.**
- Furthermore, **favouring one technology such as towards lithium-ion, in major global markets could reduce VRFB demand despite vanadium abundance**.
- Resource concentration risk will exist, since a handful of countries (China, Russia, South Africa) dominate vanadium production, making the market highly sensitive to price volatility, trade restrictions, or geopolitical tensions.
- Emerging trade restrictions and tariffs, like the recent U.S.A tariff hikes on Chinese batteries, signal a trend toward **protectionism in clean energy supply chains; if extended to vanadium products, South Africa may face limited market access despite having reserves, affecting its competitiveness and revenue potential.**

Managing global policies and navigating trade restrictions present inherent risks; however, South Africa has the potential to convert these challenges into strategic opportunities, strengthening its position and emerging as a prominent global leader in the VRFB sector.

4.4. Sustainability and Recycling Considerations for Vanadium Electrolyte

Vanadium electrolyte in VRFB systems can be recovered and reused. The recyclability of vanadium electrolyte allowing it to be recovered and reused without performance loss, is a major advantage of VRFB technology when seen as a viable alternative to other major storage systems.

4.4.1. HOW DOES RECYCLABILITY OF VANADIUM ELECTROLYTE BECOME A KEY ADVANTAGE OF VRFB?

- Lowering electrolyte cost via domestic manufacture and recycling materially improves project economics. Vanadium electrolyte used in VRFBs is highly recyclable; pilot and early-stage commercial processes report recovery rates ~97% for vanadium from spent electrolyte. [101]
- Economic Value Retention: Electrolyte retains much of its original value even after decades of use, providing a potential secondary revenue stream for operators. When a VRFB system reaches end-of-life, the electrolyte can still hold significant value - not only for the raw vanadium it contains but also because it is already in a ready-to-use dissolved form. Even when the electrolyte itself reaches the end of its usable life, it retains value-not just for the vanadium content, but also because it can be regenerated or reused in new systems.[102]
- Reduced Waste Footprint: Minimal solid waste generation during recycling compared to lithium-ion batteries.[103]

The leasing model also plays a crucial role in electrolyte recycling. Unlike lithium-ion batteries, where active materials degrade and require complex recycling, vanadium electrolyte remains

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101 https://usvanadium.com/u-s-vanadium-successfully-recycles-electrolyte-from-vanadium-redox-flow-batteries-at-a-97-recovery-rate/

102 Hasiao et al., Recovery of V_2O_5 from spent catalysts and its application in vanadium electrolytes for vanadium redox flow batteries. J. Ener Storage 2025

103 Ebner et al., How Green are Redox Flow Batteries? ChemSusChem, 2023

chemically stable and can be directly reprocessed and leased to new users. This closed-loop reuse lowers long-term costs, minimizes waste, and improves the economic viability of VRFBs for large-scale applications. In contrast, lithium-ion end-of-life recovery is resource- and labour-intensive, adding significant expense.

4.4.2. WHY IS ELECTROLYTE REPROCESSING REQUIRED?

Over the lifetime of a battery, the electrolyte requires maintenance to restore its performance. US Vanadium LLC has successfully demonstrated this process at its facility in Hot Springs, Arkansas.

1) **Removing solids**: Over time, particles can form in the electrolyte. These can be removed using ultrafiltration.
2) **Address degradation during battery life:** Over time, VRFB electrolyte can degrade due to contamination, side reactions, or imbalances in vanadium oxidation states. Recycling is possible, but only if these changes are corrected before reuse.
3) **Remove precipitated solids via ultrafiltration:** During operation, some impurities or degraded products may precipitate in the electrolyte. Using ultrafiltration removes these solids, ensuring the electrolyte remains clean and stable for re-use.
4) **Restoring chemical balance**: If the balance between the positive (catholyte) and negative (anolyte) electrolyte changes, part of the solution can be replaced with fresh electrolyte to restore it.
5) **Correct valence imbalance:** In VRFBs, the electrolyte contains vanadium in different oxidation states (V^{2+}, V^{3+}, VO^{2+}, VO_2^+). Over time, these states can get out of balance. This can be corrected by replacing part of the spent electrolyte (especially the V^{5+} portion) with fresh electrolyte of around 3.5 average valence to restore the chemical balance.[104]

4.4.3. OPTIONS FOR ELECTROLYTE MANAGEMENT AT BATTERY DECOMMISSIONING

At the end of battery life, the electrolyte must be managed in a manner that is both economically viable and environmentally responsible (as per Appendix C).

Two primary options are available:

I. **Direct Supply to Vanadium Producer**: The electrolyte can be transported to a vanadium production facility for reprocessing if there is no immediate demand in the market.

[104] Zuo et al., Sustainable recycling and regeneration of redox flow battery components. Future Batteries,.2025

- Advantage: Enables recovery and reuse of vanadium.
- Challenge: Electrolyte is heavy and contains a lot of water, making shipping expensive. This is one of the biggest hurdles for centralized recycling. Shipping large volumes of liquid incurs transportation costs.

II. **On-Site Conversion to Solid Form:** The vanadium can be converted into a solid form (precipitate) at the battery site and then transported to a processing facility.

- Advantage: Reduces shipping costs compared to transporting liquid electrolyte.
- Challenge: Generates large amounts of liquid waste, which require careful handling and disposal.

From a recycling perspective, the acidic composition presents both opportunities and challenges. On one hand, the dissolved vanadium is readily recoverable in a form that can be directly processed for reuse, enhancing overall resource efficiency. On the other hand, handling and transporting large volumes of acidic liquid involve additional safety requirements and cost considerations, making logistics a critical factor in end-of-life management.

Key Takeaways from Chapter 4

Table 20: Key Factors, Trends, and Implications for South Africa's VRFB market till 2030

Key Factor	Trend	Implications on South Africa's VRFB Market Until 2030
Global Demand for VRFB	Rising demand due to grid instability, renewable integration, and decarbonization goals globally. Global cumulative demand between 40-120 GWh by 2030.	South Africa can tap into export markets and regional demand but must overcome domestic deployment gaps and cost barriers.
Global Policy Incentives for Energy Storage Technologies	Countries like China, Japan, Australia, and the US have strong policy backing (mandates, funding, strategic mineral designation).	South Africa lacks similar instruments. Strategic designation of vanadium, pilot projects, and export incentives are needed to stimulate domestic and regional demand.
Technology Preference Trends in Major Markets	Lithium-ion continues to receive dominant support globally, with emerging interest in flow batteries and other alternatives.	If global policies favour lithium-ion over flow batteries, VRFB demand may stagnate despite South Africa's vanadium reserves. Strategic positioning and niche targeting (e.g., high-temp, long-duration) are essential to remain relevant.
Competing Battery Technologies and Market Positioning	Lithium-ion dominates but has limitations in high-temperature, fire-prone, and long-duration applications.	VRFBs have niche advantages. South Africa can target mining, fire-prone applications, telecom, and industrial zones to build early markets.

Innovative Business Models for VRFB Deployment	Electrolyte leasing and energy-as-a-service models reduce upfront costs but may increase LCOS.	Short-term deployment can be accelerated through leasing. Long-term viability depends on value stacking (e.g., grid services), policy support, project incentivization etc.
Vanadium Pricing and Upstream Cost Dynamics	Chinese V_2O_5 prices have been low in last 2 years (~$10–$11/kg), but South Africa's production costs are high ($30–$33/kg). China uses co-production from steel slag to reduce costs.	South Africa's upstream competitiveness is limited. Without secondary recovery (e.g., fly ash, slag) or cost innovation, it will struggle to compete.
Cost Trends in Non-Electrolyte VRFB Components	Non-electrolyte components (stack, BoP, PCS, assembly) make up 65% of system cost.	South Africa can focus on R&D and manufacturing innovation in membranes, modular BoP, and PCS to reduce system-level costs.
Technology Partnerships and Midstream Manufacturing Capacity	Global OEMs (Sumitomo, Rongke Power, Solibra) dominate stack/component manufacturing. South Africa lacks midstream capacity.	Strategic partnerships and tech transfer are essential to build local manufacturing and reduce import dependence.
Emerging Trade Barriers and Supply Chain Risks	US tariffs on Chinese batteries (2025), China's export controls on vanadium and graphite, and EU's push for domestic supply chains.	While US tariffs may open short-term opportunities for South Africa, future restrictions on vanadium products could limit market access and revenue. South Africa must diversify trade partners and invest in refining and recycling to mitigate risks.

Chapter 5: Strategic Pathways for Scaling South Africa’s VRFB Ecosystem

South Africa stands at a pivotal moment in shaping its future within the global energy transition, with VRFBs offering a strategic opportunity for sustainable energy storage. This chapter explores the enablers, challenges, and strategic actions needed to unlock South Africa’s potential in scaling VRFB deployment and building a resilient ecosystem.

5.1. Strategic Enablers for Scaling VRFB Deployment

This section synthesizes the key findings into a strategic framework for reducing the capital expenditure of VRFB systems. By leveraging supply chain efficiencies, advancing core technologies, and reimagining business models, the path toward cost-effective, scalable energy storage becomes clearer.

5.1.1. PRODUCTION OPTIMIZATION VIS-À-VIS TECHNOLOGICAL INNOVATION

Optimizing electrolyte production, through better purification, lower chemical costs, or scaling, offers only incremental capex reductions. With **V_2O_5 prices already at a 5-year low ($10-$11/kg)** and constrained by global supply and Chinese co-production dominance, further cost cuts are limited.

South Africa holds some of the world's richest vanadium ore (>1.5% V_2O_5), but current processing yields lag global benchmarks. Improving recovery requires **customized, proprietary extraction and refining methods**, integrating optimized roasting, selective leaching, and advanced precipitation. These flowsheets are highly specialized, necessitating **technology transfer, partnerships, or licensing**. Collaborative R&D can help adapt these methods to local ore, improving efficiency and reducing energy intensity, enhancing competitiveness against Chinese producers whose advantage lies in scale.

Even with optimized electrolyte costs, VE accounts for only **~35% of total system cost**. The remaining 65%, i.e. stacks, BoP, PCS, and assembly, offers greater cost-reduction potential. **R&D in membranes, modular BoP, and power electronics** could lower total system costs by **20-26%**, delivering a far greater impact than electrolyte savings.

5.1.2. COST REDUCTION POTENTIAL IN NON-ELECTROLYTE COMPONENTS OF VRFBS

As of 2024, 65% of cost of VRFB systems is attributed to non-electrolyte components (Figure 28) with assembly and construction comprising the largest share at 25%. Power electronics, including the PCS, contribute around 18%, while pumps, piping, and tanks make up 12%. The stack, consisting of membranes, electrodes, and plates - represents the final 10% of the non-electrolyte cost distribution.

By focusing on material innovation, system design, and component integration, significant savings can be achieved across key subsystems.

Table 21: Potential Cost Reduction Estimates of Non-Electrolyte Components of VRFB System

Non-Electrolyte Component	Key Innovations	Potential Cost reduction
Stack (Membrane, Electrodes, Bipolar Plates)	PBI & non-fluorinated membranes; carbon felt & graphite composites	20–50%
Balance of Plant (BoP)	Modular design; composite/polymer tanks; low-friction pumps; optimized flow fields	15-25%
Power Electronics (PCS)	Standardized PCS; integration with renewable inverters; bidirectional converters	~15%
Assembly & Construction	Prefabricated, containerized systems; automated assembly	20-30%
30-40% cost reduction in non-electrolyte Components will reflect to 20-26% reduction in overall cost of the system		

Estimated System-Level Cost Reduction

If ongoing R&D efforts succeed in reducing the cost of non-electrolyte components by 30-40%, which is a realistic target based on current technological trends; the overall cost of VRFB systems could see a substantial decline.[105] Given that non-electrolyte components account for approximately 65% of the total system cost, a 30% reduction in this segment translates to a 19.5% decrease in total system cost (i.e. $306/kWh), while a 40% reduction yields a 26% decrease (i.e. $281/kWh).

Therefore, through focused innovation in areas such as stack design, balance of plant, power electronics, and system assembly, a system-level cost reduction of 20 - 26% is achievable.

Although, production optimization in electrolyte is necessary, it is likely to be inadequate. The more transformative lever for reducing VRFB capex lies in R&D and manufacturing innovation across non-electrolyte components.

105 https://sumitomoelectric.com/press/2025/02/prs016

5.1.3. ROLE OF INNOVATIVE BUSINESS MODELS IN ACCELERATING DEPLOYMENT

Innovative business models - such as electrolyte leasing, energy-as-a-service etc can play a critical role in reducing upfront costs and improving bankability. These models lower the capex barrier, making VRFBs more attractive for early-stage or capital-constrained projects. However, these models often increase the LCOS over the project lifetime due to leasing fees, interest, or service charges. This means the total cost of ownership (TCO) may be higher, especially for long-duration projects.

So, how impactful are these models?

Time Period	Degree of Impact	Observations
Short-term	High	They enable faster market entry, especially in regions with limited financing options.
Long-term	Moderate	They require compensation mechanisms or value stacking (e.g., grid services, resilience credits) to justify higher LCOS.

Activating Innovating Business Models through Niche Applications in South Africa

Highlighting niche, high value applications is a smart strategy to justify premium pricing and alternative business models. As noted previously in few case studies, VRFBs offer unique advantages in:

- High-temperature environments: Operate reliably between +10°C to +50°C, unlike lithium-ion systems which degrade above 40°C. Lithium-ion systems also draw more auxiliary power while operating in high-temperature environments.
- Fire-prone or hazardous zones: Non-flammable electrolyte makes VRFBs ideal for industrial parks, oil terminals, and remote microgrids.
- Remote or off-grid locations: Long cycle life and deep discharge make them suitable for mining operations, rural electrification, and telecom towers.

South Africa has high solar irradiance and growing renewable penetration, industrial zones with fire risk (e.g., mining, petrochemical), and remote communities needing resilient storage. If paired with compensation mechanisms, such as capacity availability incentives, or tariff premiums - these niche applications could form a viable early market for VRFBs. Hence, these models can unlock deployment if supported by policy instruments and market incentives.

5.2. South Africa's Strategic Position in the Vanadium Value Chain: Is the Outlook Favourable?

South Africa's potential to gain prominence in the global vanadium value chain must be assessed across three distinct segments: upstream (mining and V_2O_5 production), midstream (VRFB component manufacturing), and downstream (VRFB deployment and export). While the country possesses clear geological advantages, its current standing across the full value chain is mixed, and the outlook is strategically viable but challenged.

5.2.1. UPSTREAM: MINING AND VANADIUM PENTOXIDE (V_2O_5) PRODUCTION

South Africa has a strong foundation in the upstream segment. It holds approximately 2.4% of global vanadium reserves, with several high-grade deposits such as Vametco, Brits, and Steelpoort drift, some exceeding 1.5% V_2O_5 content - which is significantly higher than Australia's majority grade of <1%.

However, the challenge lies in cost competitiveness. Chinese producers dominate global supply through co-production of vanadium from steel slag, which allows them to offer V_2O_5 at lower prices due to shared infrastructure and economies of scale. As of 2024, China accounted for 67% of global vanadium production, primarily through co-production. South African V_2O_5 production, relying on primary mining, faced higher operating costs - estimated between $33–$30/kg in 2022 and 2023, compared to corresponding Chinese market prices of $18–$16/kg.[106]

Furthermore, the closure of Bushveld Energy's operations in 2025 signals financial and operational stress in the upstream sector, despite access to high-grade ore. Without significant policy support or cost innovation, South Africa risks being undercut by Chinese and Russian producers.

[106] Bushveld-Minerals-Annual-Report-2023.pdf

CES' Take: South Africa's upstream outlook is resource-rich but economically constrained. Without cost innovation or policy support, it risks being outcompeted by lower-cost producers. Here, the country can leverage its superior vanadium ore grades by investing in advanced beneficiation, leaching, and refining technologies to improve recovery rates. Enhancing yield efficiency through such innovations would reduce per-unit costs and strengthen the competitiveness of its downstream VRFB products.

5.2.2. MIDSTREAM: MANUFACTURING OF VRFB COMPONENTS

South Africa's midstream capabilities are currently limited and underdeveloped. As mentioned previously, electrolyte production is highly concentrated, with 93–95% of global capacity held by eight manufacturers - six of which are in China. South Africa's only notable player, Bushveld Energy, had a modest capacity of 8 million litres/year (~0.11 GWh equivalent) before ceasing operations.

In terms of stack and component manufacturing (membranes, electrodes, bipolar plates), South Africa lacks industrial-scale facilities. Countries like Japan (Sumitomo), China (Rongke Power), and Germany (Solibra) have invested in proprietary technologies and vertically integrated manufacturing. These players benefit from decades of R&D, government support, and established supply chains. Australia's Future Battery Industries CRC has also supported integrated vanadium projects such as Australian Vanadium Ltd., combining mining, electrolyte production, and battery assembly with public funding.

South Africa's absence so far in this segment means it cannot currently compete on cost, scale, or technology. Without midstream capacity, it remains dependent on imports, which undermines localization goals and limits economic value addition.

CES' Take: South Africa's midstream outlook is currently weak, with limited industrial capacity and no significant OEM presence. To address this gap, building targeted research and technological innovation capabilities are needed, which is aimed at developing midstream products and electrolyte chemistries that capitalize on its high-grade vanadium ore. With several deposits exceeding 1.5% V_2O_5 content, South Africa holds a strategic advantage in feedstock quality. By bringing in investment in R&D for advanced beneficiation, purification, and electrolyte synthesis, South Africa can improve downstream output and reduce per-unit costs, thereby enhancing the competitiveness of its VRFB components.

5.2.3. DOWNSTREAM: VRFB DEPLOYMENT AND EXPORT POTENTIAL

South Africa's downstream potential is promising but largely underutilized. The country faces growing energy storage needs due to grid instability, renewable integration, and decarbonization goals.

However, domestic VRFB deployment has been minimal. While Asia accounts for 97% of global VRFB deployments, with South Africa barely registering. Export potential is also constrained by the lack of competitive manufacturing and cost parity. To compete globally, South Africa must reduce system costs to $220/kWh or lower, which requires both upstream and midstream optimization.

Countries like China, Japan, and Australia have aligned policy, funding, and industrial strategy to support VRFB deployment. For example, China's Dalian project (200 MW / 800 MWh) is state backed, California's 1 GW LDES mandate supports flow battery pilots, while Australia's Future Battery Industries CRC funds integrated vanadium projects.

South Africa lacks similar policy instruments, incentives, or mandates to stimulate domestic demand or attract global buyers.

CES' Take: The downstream outlook is viable but underdeveloped. With targeted policy incentives in upstream, midstream and innovative business models, South Africa could become a regional hub for VRFB deployment and export.

With targeted interventions, the opportunity exists to evolve from a raw material supplier into a high-value player within the VRFB ecosystem.

Segment	Current Standing	Outlook	Intervention Needed
Upstream	Strong reserves, high cost	Challenging	Cost innovation, secondary recovery
Midstream	Weak manufacturing base	Lagging	R&D, infrastructure, partnerships
Downstream	High potential, low deployment	Untapped	Policy support, incentives, pilots

5.3. Strategic Recommendations for South Africa's VRFB Ecosystem

After assessing the potential of cost reduction of VRFBs and developing a critical view of South Africa's current positioning, this section frames some of the key interventions for advancing South Africa's VRFB Ecosystem.

Context and Strategic Imperative

South Africa is uniquely positioned in the global vanadium value chain, with 2.4% of the world's reserves and a legacy of vanadium mining and processing. However, the competitive landscape in the global VRFB market is challenging. China is leveraging its steel industry to promote co-produced vanadium, significantly lowering the cost of V_2O_5 used in VRFB electrolytes. This strategy poses a direct challenge to South Africa's primary vanadium producers, whose cost structures are less flexible and more exposed to market volatility.

While vanadium contributes significantly to VRFB costs, the system is not solely dependent on it. Non-electrolyte components, making up 65% of the total cost – offer considerable potential for cost reduction through targeted R&D and manufacturing innovation. Achieving a 30-40% reduction in these areas could lower overall system costs by 20–26%. This presents a critical opportunity for South Africa to remain competitive, not by undercutting China on vanadium pricing, but by innovating across the rest of the value chain.

5.3.1. SUPPORT IN R&D FOR NON-ELECTROLYTE COST REDUCTION

To offset the competitive disadvantage in vanadium production economics (through primary method), South Africa may focus on reducing costs in other parts of the VRFB system. This includes:

- Supporting R&D in membrane and electrode materials to reduce stack costs. For example, Japan's Sumitomo Electric has commercialized phosphoric acid-stabilized electrolytes and proprietary membranes that enhance performance and reduce costs.
- Encouraging modular BoP designs using locally available materials (e.g., polymer tanks instead of steel).
- Promoting digital control systems and bidirectional inverters to reduce power electronics costs.

Global Precedent: The U.S. Department of Energy's ARPA-E program has funded companies like ESS Inc. and Primus Power to develop low-cost flow battery stacks and BoP systems, achieving significant cost reductions through design innovation and material substitution.

5.3.2. ESTABLISH A VANADIUM ELECTROLYTE LEASING AND RECYCLING ECOSYSTEM

Given that vanadium electrolyte is 100% reusable and retains value over decades, South Africa may:

- Facilitate the creation of leasing models for vanadium electrolyte, reducing upfront capex for developers and improving project bankability.
- Position itself as a global supplier of high-purity, recyclable electrolyte, leveraging its mining and refining capabilities.

Global Precedent: Invinity Energy Systems (UK/Canada) and Bushveld Energy (South Africa) previously piloted a leasing model through Vanadium Electrolyte Rental Ltd., which helped reduce project costs and attract financing.

5.3.3. INCENTIVIZE DOMESTIC MANUFACTURING AND VERTICAL INTEGRATION

To build a resilient and competitive VRFB ecosystem, South Africa can bring in targeted measures such as –

- Offering tax incentives, grants, or preferential procurement policies for locally produced VRFB components can stimulate industrial growth and attract investment.
- Demonstrating full vertical integration - from vanadium mining to battery deployment, through pilot initiatives can showcase feasibility and build confidence in local capabilities.
- Encouraging collaborations between domestic firms and global OEMs can facilitate technology transfer, enable joint manufacturing, and accelerate ecosystem development.

Global Precedent: Australia's Future Battery Industries CRC has funded vertically integrated vanadium projects (e.g., Australian Vanadium Ltd.) that combine mining, electrolyte production, and battery assembly with government support.

5.3.4. MITIGATE SUPPLY CHAIN RISKS AND PROMOTE SECONDARY VANADIUM RECOVERY

To reduce reliance on primary mining and enhance sustainability, South Africa could invest in research and development focused on secondary vanadium recovery from sources such as fly ash, spent catalysts, and steel slag. Additionally, public-private partnerships may be explored to establish refining capacity for battery-grade vanadium, supporting a more circular and resilient supply chain.

Global Precedent: U.S. Vanadium in Arkansas has developed a high-purity vanadium recovery process from industrial waste, supported by federal critical minerals policy.

Demand Side: Suggested 'Industry Support' Interventions

These interventions - strategic mineral designation, pilot project support, and export hub development, are proven levers used globally to accelerate industrial ecosystems around emerging technologies. For South Africa, they offer a pathway to move beyond raw material exports and build a competitive, value-added vanadium battery industry.

5.3.5. LEVERAGING VANADIUM'S DESIGNATION AS A STRATEGIC MINERAL FOR ENERGY

Leverage vanadium's recent recognition as a 'moderate to high' critical mineral under South Africa's Critical Minerals and Metals Strategy.[107] This status may be used to accelerate policy support for beneficiation and refining projects under critical mineral programs, prioritizing R&D and infrastructure for vanadium electrolyte production and recycling, while attracting global partnerships and negotiating trade agreements for VRFB components and electrolyte exports.

Global Precedent: In the United States, vanadium has gained strategic recognition due to its role in both defence and clean energy. The U.S. Department of the Interior expedited permitting for vanadium-uranium projects like Velvet-Wood in Utah, while lawmakers called for stockpiling vanadium for military and civilian use.[108] [109] Australia has also identified vanadium as a critical mineral, supporting exploration and downstream development.[110]

5.3.6. SUPPORT PILOT AND ANCHOR PROJECTS

The government can fund anchor projects in mining zones, industrial parks, and renewable energy corridors. These projects can serve as proof-of-concept for grid-scale storage, microgrids, and industrial applications. Public procurement mandates (e.g., for Eskom or municipal utilities) can be used to create demand and de-risk early deployments.

Global Precedent: In 2022, the U.S. Department of Energy launched a $355 million Energy Storage Demonstration and Pilot Grant Program to fund projects that improve grid reliability, integrate renewables, and support microgrid.[111] In 2023, UK's Invinity Energy Systems won

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107 https://www.gov.za/news/media-statements/minister-gwede-mantashe-approval-critical-minerals-and-metals-strategy-south

108 US approves Velvet-Wood uranium-vanadium mine to bolster mineral security.

109 Ark. lawmakers call for vanadium stockpile - Metal Tech News

110 https://www.ga.gov.au/scientific-topics/minerals/critical-minerals

111 https://www.naseo.org/data/sites/1/documents/publications/NASEO_Energy%20Storage_v2.pdf

UK government funding (funding from the Department of Energy Security and Net Zero) to install a 7 MW/ 30 MWh VRFB on the National Grid.[112]

5.3.7. ENABLE EXPORT HUBS FOR VANADIUM-BASED ENERGY STORAGE

South Africa can position itself as a regional export hub for vanadium-based energy storage systems, serving markets in Africa, the Middle East, and beyond. Establishing Special Economic Zones (SEZs) dedicated to energy storage manufacturing including Vanadium, can attract investment and foster innovation. To support global competitiveness, the country could also offer export incentives and trade facilitation for vanadium electrolyte, stack components, and fully assembled VRFB systems. Furthermore, collaboration with regional bodies such as the African Union and SADC could promote the deployment of energy storage solutions across the continent, leveraging South African technology and expertise.

Global Precedent: Germany's Energiewende policy has made it a top destination for energy storage companies seeking to enter the European market. According to the German Energy Storage Association (BVES), the energy storage market grew by 46% in 2023.[113]

5.4. South Africa's Multi-Horizon Strategy for Development & Growth of VRFB Ecosystem

From local deployment to global partnerships, South Africa may aim to position its vanadium value chain to serve short-term domestic & regional needs, medium-term European demand, and long-term U.S. energy storage ambitions.

In the short term, South Africa may prioritize domestic and Southern African deployment of VRFBs to build scale, credibility, and industrial momentum for future

112 https://renewablesnow.com/news/invinity-wins-uk-govt-funding-for-7-mw30-mwh-vanadium-battery-820250/
113 https://www.climate17.com/blog/overcoming-the-obstacles-in-the-german-energy-storage-sector

exports. Vanadium's critical mineral status may be leveraged to secure government-backed incentives, reduce financing risk, attract global partnerships and negotiate trade agreements for VRFB components or electrolyte exports. This domestic foundation is essential not only for proving technical viability but also for enabling cost reductions through R&D in non-electrolyte components and manufacturing innovation. Moreover, focusing on niche applications such as mining, telecom, and fire-prone industrial zones in the country and Southern African regions can showcase VRFBs' unique advantages over lithium-ion technologies, positioning South Africa as a credible supplier in the regional ecosystem.

The United Kingdom and European Union present attractive medium-term opportunities for South Africa's VRFB exports, despite their relatively smaller market sizes. Both regions have already seen successful VRFB deployments and R&D facilities, while trying to demonstrate benefits for end users in terms of safety, long-duration performance, and operational reliability.[114] This increases the likelihood of favourable compensation for project developers in future. Moreover, the UK and EU have shown openness to international collaboration - evident in multiple partnerships involving financing, technology transfer, electrolyte sourcing, and offtake agreements. Such collaborative momentum signals a strong willingness to engage with foreign suppliers, making these regions viable and strategic export destinations for South Africa's vanadium and VRFB technologies.

United States remains South Africa's most promising medium to long-term export market for vanadium-based energy storage, despite current volatility around tariffs and trade restrictions. The scale of the U.S. LDES market, driven by initiatives like the DOE's Long Duration Storage Shot and the Inflation Reduction Act, offers significant volume potential. The maturity of its electricity markets enables robust revenue stacking opportunities, such as grid services, capacity payments, and resilience credits - which align well with the strengths of VRFBs.[115] While recent tariffs on Chinese batteries may temporarily disrupt supply chains, they also create openings for alternative suppliers like South Africa. With strategic positioning and policy alignment, South Africa can become a key player in supplying vanadium, electrolyte, and even assembled VRFB systems to the U.S. market.

Dual-incentive Framework

To catalyse ecosystem development, South Africa can implement a dual-incentive framework that links foreign investment in upstream vanadium mining with export rebates or preferential trade terms for downstream VRFB products targeting strategic markets like the U.S. and EU. This approach would encourage global players to invest in South Africa's high-grade vanadium resources by offering tangible benefits - such as tax relief, expedited permitting, or co-investment opportunities, if they commit to downstream value creation and export-oriented manufacturing.

Mechanisms for implementation could include –

A. Special Economic Zones (SEZs) focused on vanadium and energy storage manufacturing, offering fiscal incentives and infrastructure support.

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[114] Bushveld PowerPoint Presentation – March 2023

[115] Electricity Markets and Long-Duration Energy Storage: A Survey of Grid Services and Revenue Streams | Current Sustainable/Renewable Energy Reports

B. Export-linked rebate schemes, where companies exporting VRFB systems or components to net-zero aligned markets receive rebates based on volume or value thresholds.

C. Bilateral trade agreements or green industrial partnerships with the EU and U.S., positioning South African VRFB products as part of their clean energy supply chains.

D. Conditional grants or concessional financing for overseas investors who commit to local beneficiation, technology transfer, and workforce development.

By aligning upstream resource development with downstream export competitiveness, South Africa can build a vertically integrated, globally relevant VRFB ecosystem. This scale and integration would not only reduce costs and improve technology access but also create a resilient domestic market capable of serving regional needs competitively.

APPENDIX A: Vanadium Production Flow Charts

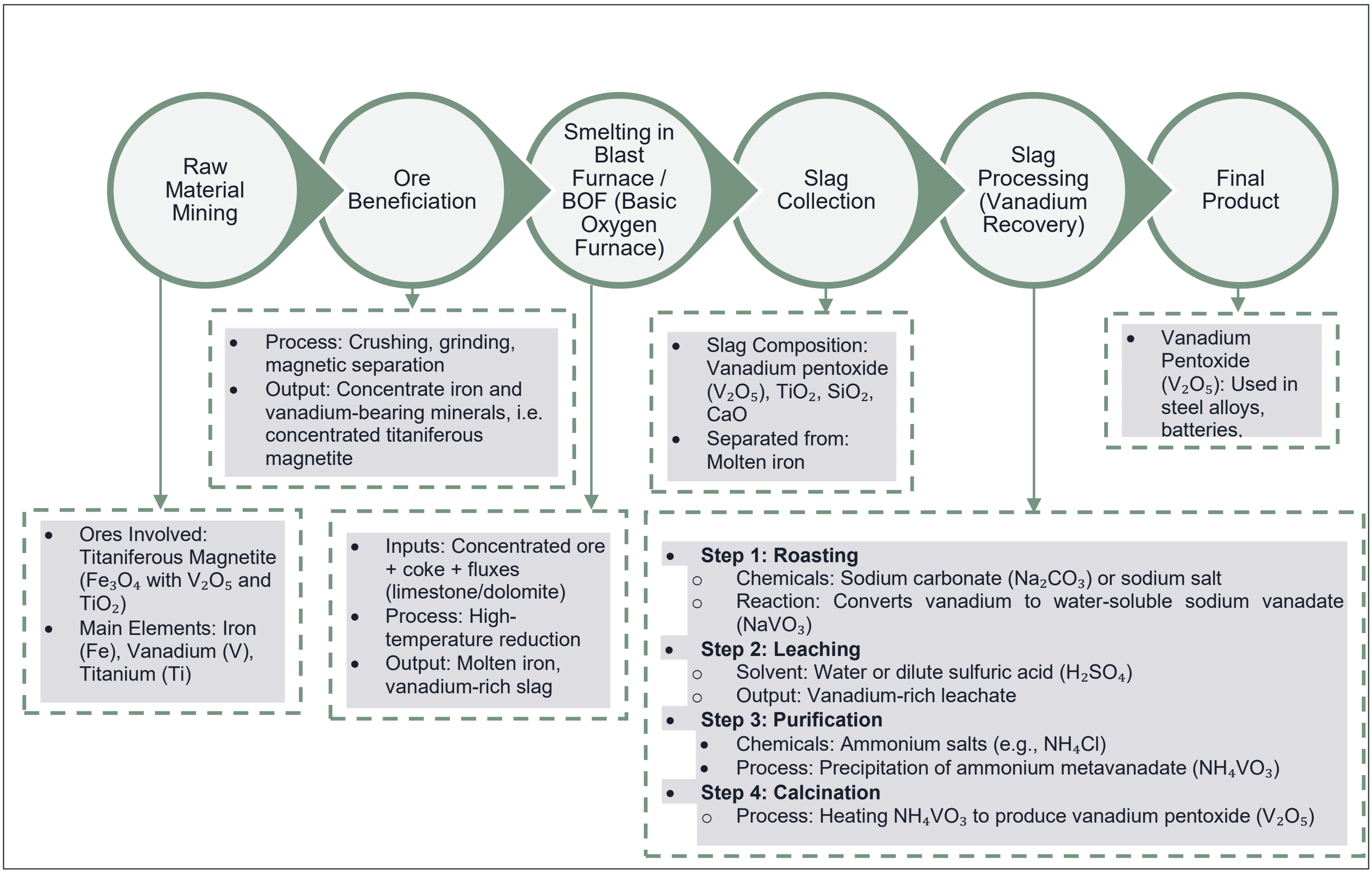

Figure 40: Co-Product Vanadium Production Flow Chart

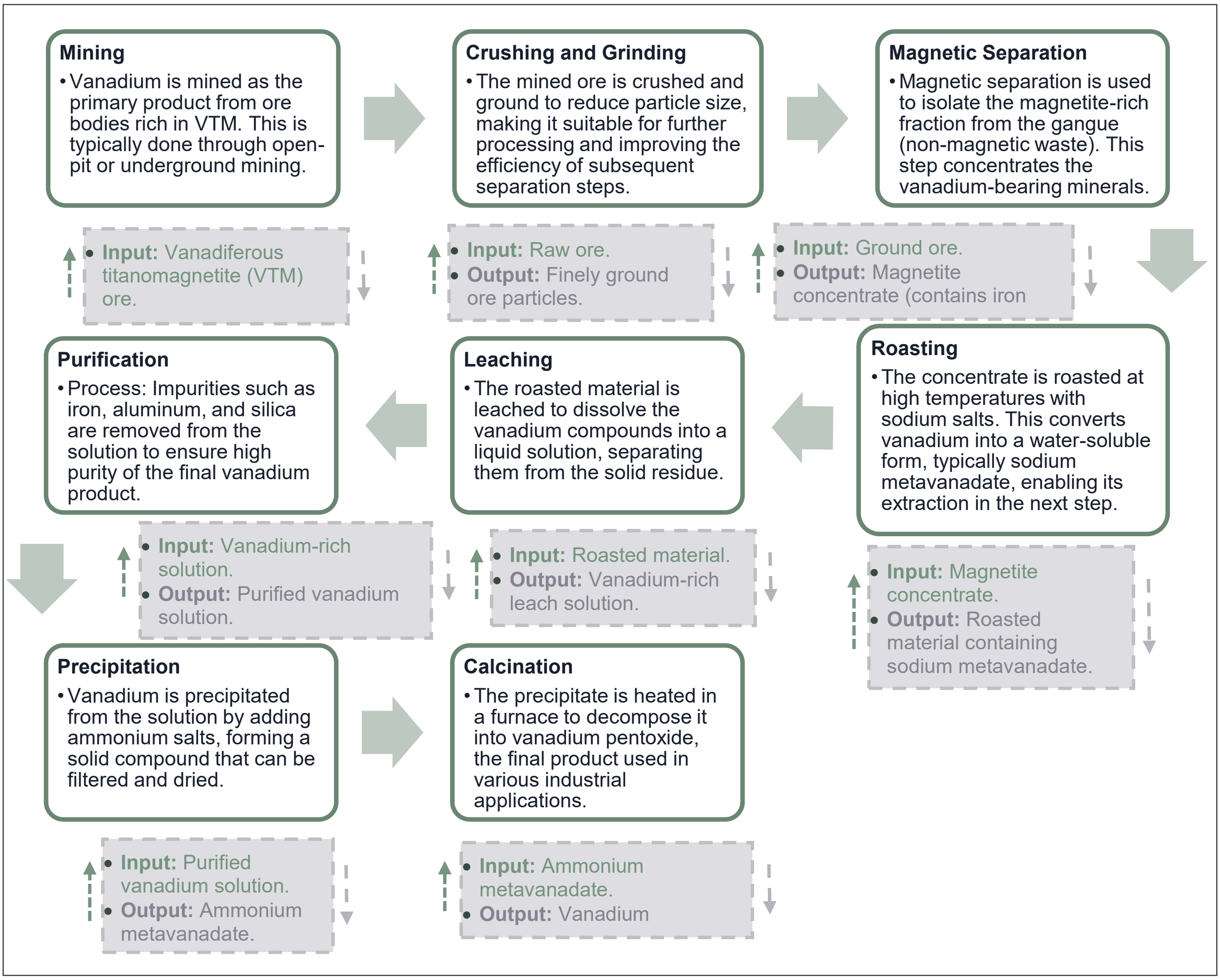

Figure 41: Primary Production of Vanadium Flow Chart

Source: CES Analyses

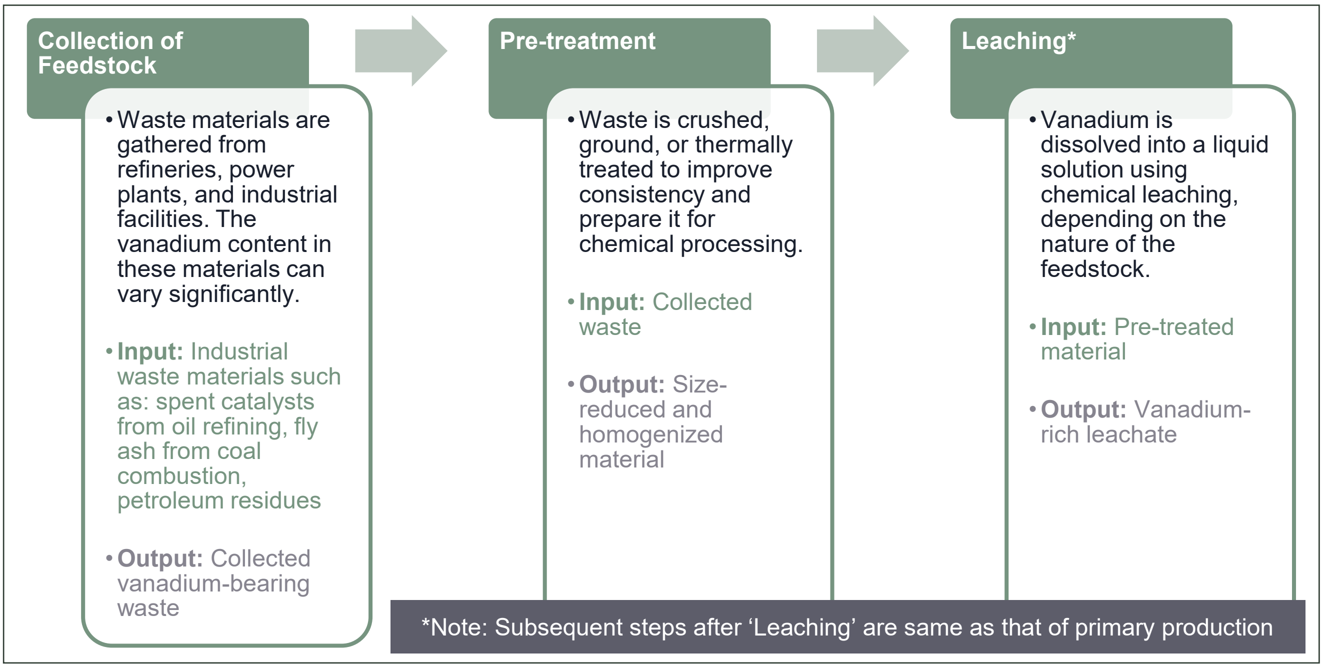

Figure 42: Secondary Production of Vanadium Flow Chart

Source: CES Analyses

APPENDIX B: Technological Development in VRFB Electrolytes

The key differences between VRFB generations lie in the electrolyte chemistry, particularly in the choice of supporting acids ranging from single inorganic acids like sulfuric acid to mixed-acid formulations that combine sulfuric and hydrochloric acids to enhance performance. Figure 43 outlines the progression of VE from Gen 1 to Gen 3, with improvements aimed at enhancing solubility, temperature stability, and energy density. During 2025-2030 we expected Improved Gen 1 to be commercialized, while Gen2 & 3 are expected to be commercialized beyond 2030.

Gen 1 uses sulfuric acid (H_2SO_4) as the supporting electrolyte, offering a safe and stable medium. It was estimated that approximately 70 litres of electrolyte are required per kWh of VRFB capacity. This consumption rate reflects the typical system design and energy density characteristics associated with Gen1 VRFB electrolyte It supports vanadium redox reactions efficiently, with a temperature range of 15 - 40°C and energy densities up to 33 Wh/L. Early Gen 1 electrolyte used $VOSO_4$ dissolved in H_2SO_4 to reach 2 M vanadium ion concentration, but due to its high cost, a cheaper electrochemical method using V_2O_5 powder was later developed. This breakthrough proved the commercial viability of VRFBs. Other vanadium sources like ammonium metavanadate were also explored.[116]

[116] Future Battery Industries CRC. Development of electrolytes for vanadium redox flow batteries | October 2023

	Gen 1 is the first formulation to be developed and industrially accepted	A modified Gen 1 is the mostly accepted at this point	Gen 2 electrolyte is highly chemically reactive and causes formation of bromine gas and corrosion; also, more costly to produce	Gen 3 is more corrosive and more complicated to 'unscramble'
Parameter	**GEN 1 All-Vanadium**	**Improved GEN 1**	**GEN 2 (Vanadium-Polyhalide)**	**GEN 3 (Mixed Acid)**
Electrolyte composition	V/sulfate in both side	V/sulfate in both side	V/HBr/HCl solution in both side	V/H_2SO_4/HCl in both side
Negative Couple	V(III)/V(II)	V(III)/V(II)	V(III)/V(II)	V(III)/V(II)
Positive Couple	V(IV)/V(V)	V(IV)/V(V)	$Cl^-/ClBr^{2-}$	V(IV)/V(V)
Vanadium Concentration (M)	1.5 – 2	2 – 3	2.0 – 3.5	2.0 – 2.7
Supporting Electrolyte	H_2SO_4	H_2SO_4	HBr, HCl, NaCl, KCl, NaBr, KBr	H_2SO_4 and HCl
Temperature Range (°C)	15 - 40	10 – 40	0 - 50	-5 - 50
Specific Energy (Wh/kg)	20 – 25	25 - 40	25 - 50	35 - 55
Energy density (Wh/L)	20 - 33	30- 50	35 - 70	30 - 40
Positive overcharge reaction	Oxygen	Oxygen	Bromine	Chlorine
Advancement	First Electrolyte	Use an additives to stabilized the V ions into the solution	Increase the operational temperature range and reduce the volume	Use an acidic mixture to increase the V solubility over broader range of temperature. No cooling or heat exchanger needed.
Charge/Discharge Efficiency (%)	86%	>85%	80 - 83%	80-85%
Innovator	Skyllas-Kazacos & co-workers	**Improved GEN 1**	Skyllas-Kazacos	Pacific Northwest National Laboratory

* For our analysis we have taken Gen1 electrolyte
M : Mole, 'Polyhalide ion :$BrCl_2^-/Cl^-$, $ClBr_2^-/Br^-$ and Br_3^-/Br^-

- Electrolytes generally used by different companies

Figure 43: Comparison of Electrolyte Generations in VRFBs

Source: CES Analyses based on company reports and industry inputs

The **Improved Gen 1** formulation enhances the original sulfuric acid-based formulation by incorporating additives that stabilize vanadium ions across all four oxidation states. This improvement allows for a slight increase in vanadium concentration (≥ 2 mol/L), broadening the operational temperature range to 10 - 50°C and achieving energy densities of up to 50 Wh/L. Phosphoric acid has emerged as an effective stabilizing agent and is now widely used in commercial electrolytes, including those produced by companies like Sumitomo and Mitsubishi. These firms have commercialized VRFB systems based on Gen 1 chemistry, with enhanced thermal and chemical stability achieved through proprietary additive formulations. While detailed compositions are typically not publicly disclosed, industry literature and patent filings confirm the use of phosphoric acid and ammonium-based salts to improve the performance and longevity of standard Gen 1 electrolytes. Today, most commercial VRFB systems utilize a sulfuric acid-based electrolyte, often supplemented with phosphoric acid to enhance stability under varied operating conditions.[117]

Gen 2 introduces hydrochloric acid (HCl) and bromide salts to significantly enhance vanadium solubility (up to 3.5 M), especially at high temperatures. This allows operation from 0 - 50°C and boosts energy density. However, the system is more chemically reactive, with bromine gas formation leading to additional corrosion and safety risks. The use of hydrochloric acid further introduces environmental and industrial challenges: HCl handling can result in chlorine

[117] Y. Guao et. al., Research progress in preparation of electrolyte for all-vanadium redox flow battery. J. Indus & Engg. Chem. 118 (2023) 33-43

emissions and corrosive waste streams, making large-scale deployment difficult. Moreover, most primary vanadium producers do not use HCl in their feedstock processing routes for V_2O_5 production, which limits its practicality for large-scale electrolyte preparation.118

Gen 3 combines hydrochloric and sulfuric acids to create a mixed-acid electrolyte, improving hydrogen ion concentration and vanadium solubility. Vanadium concentrations can reach up to ~2.7 M (vs. <1.6 M limit in Gen 1 electrolyte) and the electrolyte remains stable across a wide operating temperature range of –5°C to 50°C. UniEnergy Technologies adopted a Gen 3 mixed-acid electrolyte formulation in their VRFB system.

[118] Maria Skyllas-Kazacos, Novel vanadium chloride/polyhalide redox flow battery, Journal of Power Sources, 124(1), 299–302.

APPENDIX C: Recycling and Reprocessing Electrolyte

At the end of battery life, the electrolyte must be managed in a manner that is both economically viable and environmentally responsible.

Two primary options are available: direct supply to vanadium producer and on-site conversion to solid form.

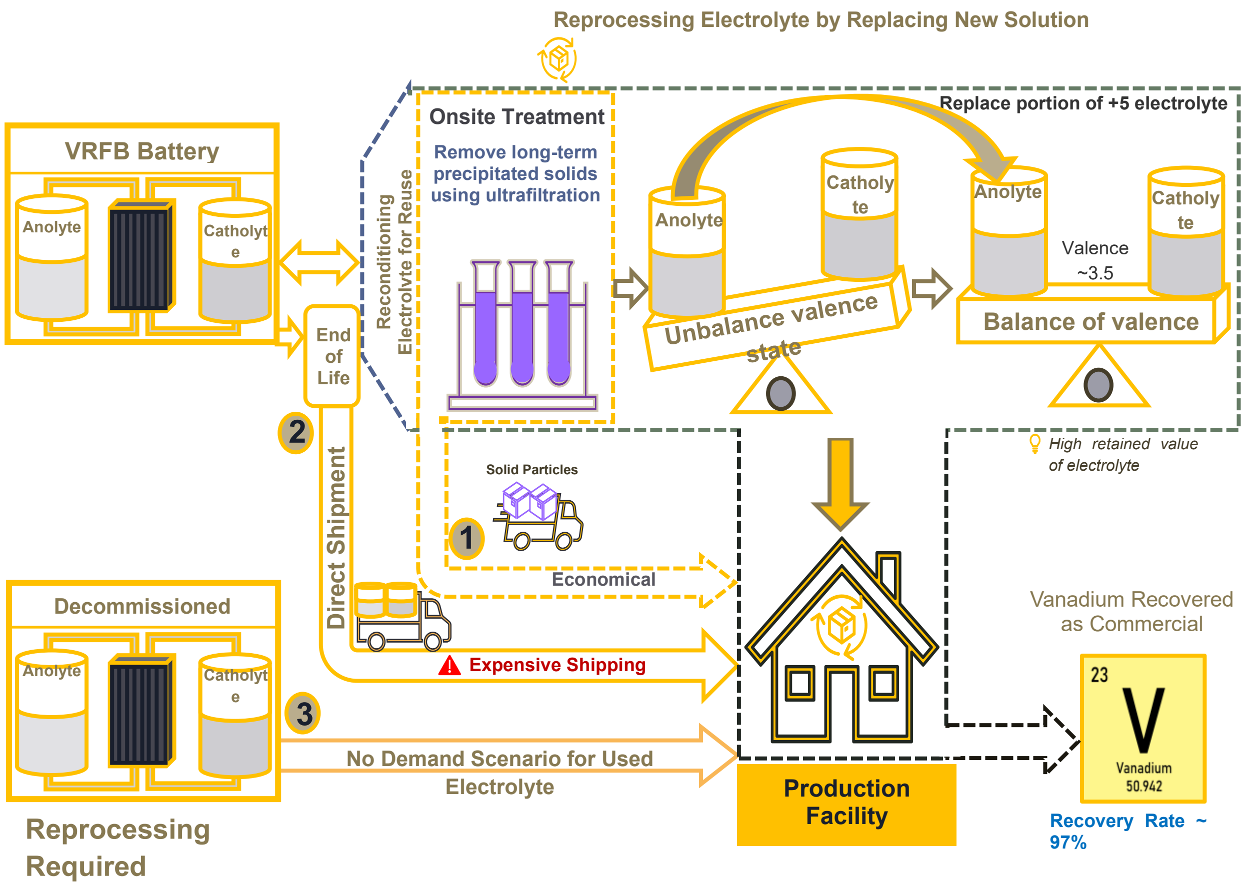

Figure 44: Recycling and Reprocessing of Electrolyte from VRFB Batteries

Source: CES Analyses based on Industry Reports

Pathways for VRFB Electrolyte Reprocessing

1) **Feedstock Utilization**

Some vanadium processing facilities, such as US Vanadium's plant in Hot Springs, Arkansas, can use spent electrolyte as a direct feedstock. The economic viability depends on their processing costs and the cost of the raw feedstock it replaces. Based on historical raw material costs for vanadium producers, the electrolyte would be valued at roughly 20-50% of the London Metal Bulletin published price for V_2O_5 (Delivered Duty Paid) at the processing facility.

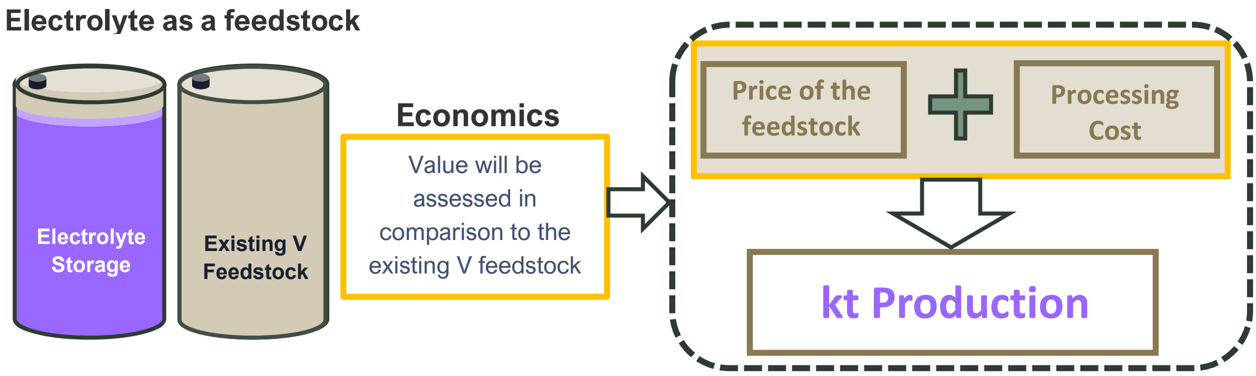

Figure 45: Process Flow of Feedstock Utilization

Source: CES Analyses based on Industry Reports

Most vanadium facilities do not have spare storage tanks for spent electrolyte, meaning new tanks or additional totes would need to be purchased for onsite storage. Therefore, additional capital would be needed to install a dedicated storage tank or to procure sufficient extra totes for on-site storage.

2) **Oxidation Methods for Electrolyte Reuse**

Spent electrolyte typically has a net valence of around 3.5, requiring oxidation to the 5-valent state before reuse. Laboratory tests have shown that this oxidation can be achieved in an acid solution using sodium hypochlorite (bleach) or sodium chlorate at approximately 65 °C. Oxygen gas could also be effective; however, it may require pressure digestion, which involves higher capital and operating costs.

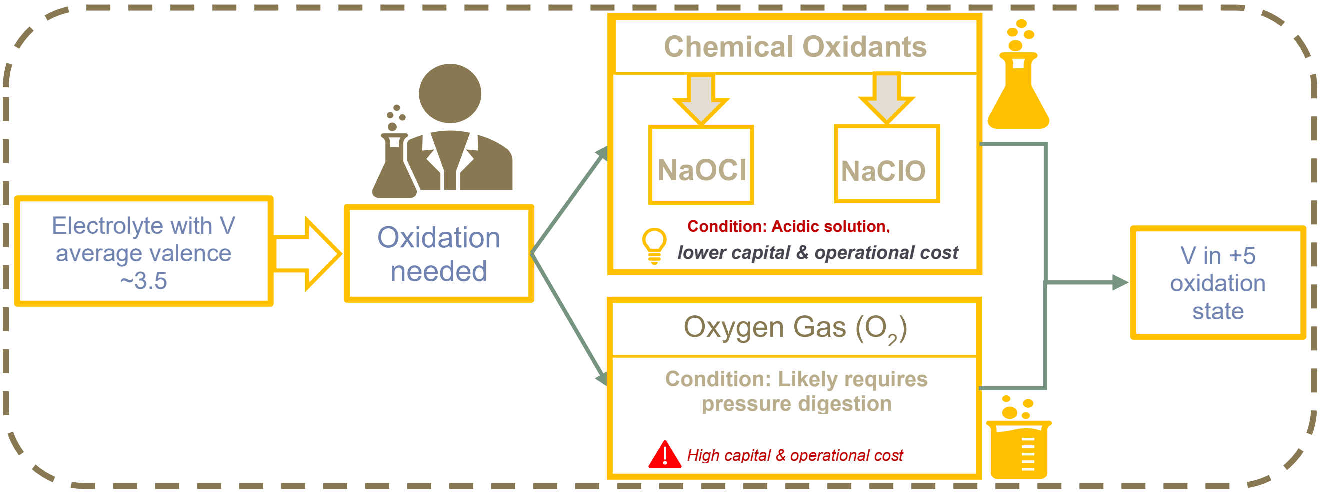

Figure 46: Oxidation Methods for Electrolyte Reuse

Source: CES Analyses based on Industry Reports

Overall, spent electrolyte can serve as a valuable input for vanadium production, offering both material recovery and cost advantages when market conditions are favourable. Nevertheless, factors such as storage requirements, pre-treatment through oxidation, and associated capital and operating costs must be carefully considered. The pathway chosen for reuse will ultimately depend on the balance between processing economics and the prevailing price environment for vanadium.

Optimizing Vanadium Recovery: Mainstream Electrolyte Processing vs. Mixed Acid Challenges

Processing of H_2SO_4-Based Electrolyte: The Mainstream Approach

Sulfuric acid-based vanadium electrolyte is the dominant choice in commercial VRFB systems due to its recovery efficiency and operational simplicity. A key advantage is that vanadium is already in solution, eliminating the need for solubilization and avoiding losses common with primary producers. Recovery efficiency is high, with both lab and commercial operations (e.g., US Vanadium) reporting ~97% recovery—broken down as ~1% loss in solvent extraction, ~1% in the finishing circuit, and ~1% during handling such as tote transfers. Among all vanadium feedstocks, H_2SO_4-based electrolytes deliver the highest recovery rates, making them commercially attractive.

Challenges with Mixed Acid Electrolyte Processing

Mixed acid systems, while explored for specific applications, introduce processing complications that affect efficiency and environmental compliance. For example, hydrochloric acid (HCl) leads to elevated chloride levels in production circuits, interfering with equipment and downstream processes. Nitric acid (HNO_3) causes nitrate accumulation in zero-discharge plants and generates problematic effluents in conventional systems.

Thus, as a secondary feedstock, vanadium electrolyte enables high recovery rates with minimal process losses, and its long service life ensures that much of its original value is retained even after decades of operation. At the same time, challenges such as handling mixed-acid formulations, managing acidic solutions safely, and investing in additional storage infrastructure must be addressed to fully realize this potential.

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To apply for support please visit https://www.lsf-sa.co.za/applytolsf. Please read the Application Requirements to understand what LSF supports and what it does not.


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