TRADE & INDUSTRIAL POLICY STRATEGIES

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# A review of vanadium redox flow battery (VRFB) market demand and costs


## OVERVIEW

Renewable energy sources combined with energy storage play a vital role in South Africa's pursuit of energy security and achieving its net-zero objective by 2050. As South Africa grapples with a deepening energy crisis, energy storage technologies are gaining prominence, with batteries taking precedence in the short to medium term. Given the growing need for grid storage and the capability of VRFBs to meet demand for applications requiring extended storage duration, this policy brief investigates the potential benefits of VRFBs in addressing local market requirements for energy security. It examines the key cost drivers of VRFBs, with a focus on the vanadium price and provides recommendations for reducing the costs associated with VRFB systems.




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## INTRODUCTION

Battery energy storage systems (BESS) emerge as favourable options for South Africa due to their rapid deployment compared to other grid storage options, aligning with the country's electricity crisis (IISD, 2023).

Battery energy storage technologies are a comparatively cleaner technology, and can drastically alter South Africa's reliance on fossil fuel-based generators, and the amount of money spent to power these generators. Lithium-ion batteries (LIBs) and VRFBs are key battery technologies used in stationary storage, and both technologies present potential avenues to support the country's efforts. While LIBs cater to short-term storage needs, VRFBs could play a key role in South Africa's demand for long storage duration, particularly valuable for utility-scale projects requiring up to 10 hours of backup power.

To strengthen the case for adopting VRFBs in South Africa, establishing a local battery value chain takes on significant importance. As of 2021, South Africa ranked as the world's third-largest vanadium producer, contributing 7% of the global supply. This unique position offers the country a comparative advantage and a chance to grow a local VRFB industry. Notably, China, with its abundant vanadium resources, is the largest market for VRFBs. The country has implemented policies that prioritise the use of long-duration storage to stimulate demand for VRFBs. In China, the market for VRFBs is supported by locally manufactured batteries. It is reasonable to assume that a similar strategy could demonstrate possibilities for South Africa, offering the potential to stimulate economic growth, create employment, and promote investment in emerging technologies and new industries. Enabling a local VRFB industry opens avenues to supply batteries for microgrid-based behind-the-meter (BTM) applications, as well as for front-of-the-meter (FTM) customers across local and regional markets.

Nevertheless, the growth trajectory of the VRFB industry faces constrains in demand due to the relatively high cost of VRFB systems compared to competing battery technologies. This obstacle inhibits their widespread adoption and expansion. However, recent deployments indicate decreasing battery capital costs could possibly lower the cost of vanadium batteries, making them more cost competitive.

## BENEFITS OF BATTERY STORAGE TECHNOLOGIES

Battery storage technologies offer numerous advantages in the grid market. On a global scale, BESS rank as the second most prevalent form of energy storage technology, following pumped storage hydropower (PSH). Battery technologies have emerged as a critical solution for effectively integrating renewable energy into power grid systems and storing surplus electricity for future use when needed (Integra Source, 2021).

*VRFBs stand out for their safety features, scalability, flexibility, and extended lifespan. They offer a unique separation of power output and energy capacity, granting greater design flexibility to tailor power and energy increases to specific consumer demands.*

These systems also have a broad spectrum of applications across the electricity value chain. They encompass various roles, including bulk energy storage, customer energy management, and providing ancillary services to the grid, all contributing to enhancing reliability and stability of electricity supply (Fourie, 2018). Integrating energy storage technologies into the grid increases the system's overall value by expanding the stability and quality of electricity supply. Batteries can store surplus energy generated during high periods of renewable energy and discharge it during peak demand when renewable energy is not available, thereby effectively smoothing energy supply fluctuations. This improves grid stability, reliability, and optimising the use of renewable energy sources (He and Wang, 2018).

## EXPLORING BATTERY STORAGE SOLUTIONS

As South Africa struggles with daily scheduled blackouts, which can go up to 12 hours in a day, households and businesses have resorted to an array of solutions to mitigate these loadshedding events. These measures include solar PV panels, backup fossil-fuel powered generators, lead-acid batteries, and LIBs. Currently, for applications spanning one to four hours, lithium-ion technology remains the leading battery storage technology. VRFBs, while not competitive yet for such shorter durations, offer distinct advantages for applications requiring more extended discharge periods. This makes VRFBs a storage technology option for South Africa, especially taking into account the country's abundant vanadium reserves.

LIBs, specifically the lithium iron phosphate ($LiFePO_4$) battery chemistry, currently lead the BESS market for stationary storage applications (IndustryARC, 2021). Compared to alternative BESS, LIBs benefit from economies of scale resulting from their wide and progressive adoption. LIBs continue to lead the electrochemical technology landscape, attributed to their strong overall performance, high efficiency, cost-effectiveness, and extensive use across diverse sectors.

In contrast, VRFBs have comparatively lower efficiency levels compared to LIBs (BloombergNEF, 2019). Because of their low energy and power densities, VRFBs are not as well-suited for small-scale applications. Yet, VRFBs have numerous other benefits and are projected to experience significant growth expansion, particularly in the utility sector.

VRFBs stand out for their safety features, scalability, flexibility, and extended lifespan. They offer a unique separation of power output and energy capacity, granting greater design flexibility to tailor power and energy increases to specific consumer demands, see Table 1. Furthermore, this flexibility leads to a reduction in the cost per unit of electricity for VRFBs as they grow in size. This is because the size of the battery can be increased by integrating bigger electrolyte tanks and increasing the volume of the electrolyte solution, a process that can be relatively inexpensive, depending on how the electrolyte is procured (whether through leasing or other means) (Scott, 2023).

This flexibility is absent in LIBs and lead-acid batteries, both of which are constrained by their modular assembly with fixed rated storage capacity and power output. In addition, when assessed over a 25-year period in terms of total cost of ownership, VRFBs are more economical than LIBs. A detailed breakdown of the technical characteristics and performance attributes of lithium-ion and vanadium flow battery technologies is provided in Table 1.

According to Fourie (2018), VRFBs offer an array of suitable applications for the grid market, including energy time shifting (arbitrage)[1], load levelling, peak shaving[2], renewable energy integration and alleviating transmission and distribution congestion. Moreover, VRFBs can provide ancillary services such as frequency and voltage regulation, operating reserves[3], and black start capabilities[4]. Although LIBs can perform similar functions, they are better suited for short-term storage requirements (Fourie, 2018). These diverse applications for VRFBs are well-positioned to support the local grid effectively. However, a single technology that has the capability to meet all required uses does not exist. An energy mix comprising various technologies becomes imperative to support South Africa's energy roadmap, especially considering that South Africa's storage market is in its early stage of development.

[1] Energy time shift or arbitrage is the practice of buying low-cost electricity during off-peak periods to charge storage systems, enabling the stored energy to be used or sold when prices are higher.

[2] Load levelling involves optimising energy usage by scheduling to more optimal timeslots, while peak shaving aims to prevent spikes in energy demand.

[3] Operating reserve is surplus operating capacity that can instantly respond to a sudden increase in the electric load or a sudden decrease in the renewable power output (Homer Energy, n.d.).

[4] Black start is a process of restoring power after a blackout (loadshedding).

**Table 1. Technical metrics overview of battery technologies**

| | Conventional Lead-Acid Battery | Lithium-Ion Battery (Iron Phosphate) | Flow Battery (Vanadium) |
|---|---|---|---|
| **Power density** | 150 W/kg | 245-430 W/kg | 50 W/kg |
| **Energy density** | 25-35 Wh/kg | 100-265 Wh/kg | 10-30 Wh/kg |
| **Efficiency** | 45-85% | 85-95% | 65-85% |
| **Depth of Discharge (DoD)** | 50% | 85-95% | 100% |
| **Self-discharge** | 0.1-0.3% | 0.1-5% | Small |
| **Voltage, V** | 2.1 | 3.6 | 1.2-1.6 |
| **Thermal runway** | Yes | Yes | No |
| **Lifespan** | 3-5 years | 5-10 years | 20-25 years |
| **Cycle life*** | 1000 | 2000-4000 | >10000 |
| **Advantages** | Mature and low-cost technology<br>Low self-discharge<br>Modular scalability | High energy density<br>High efficiency<br>Low self-discharge | Long duration technology<br>Long life cycle<br>Safe<br>No degradation<br>High DoD<br>Design flexibility that allows independent sizing of power and energy<br>Lack of degradation in performance over time<br>Electrolyte is reusable and recyclable |
| **Disadvantages** | Low energy density<br>Low DoD<br>High maintenance<br>Improper disposal leads to environmental risk | Thermal runway<br>Relatively short-life cycle compared to sulphur and flow batteries<br>Transport restrictions<br>Raw materials subject to supply availability and socio-environmental challenges<br>Higher profit margins for new energy vehicles (NEVs) could potentially sideline grid systems in the LIB | High price of vanadium<br>High capital cost<br>VRFB supply chain is still fairly immature<br>Low power and energy density compared to LIB |
| **Application** | Uninterruptable power supply (UPS), black start and frequency regulation | UPS, load levelling, frequency regulation, voltage support, black start and energy arbitrage | Load levelling, UPS, back-up power supply and NEV charging |

*Source:* Compiled by author using various sources including BloombergNEF, 2019 and Bushveld Energy, 2018.
*Note* *Cycle life of a battery can be affected by factors such as aging, usage patterns, and environmental conditions.

## DRIVERS OF VRBFBs: TRENDS AND MARKET OUTLOOK

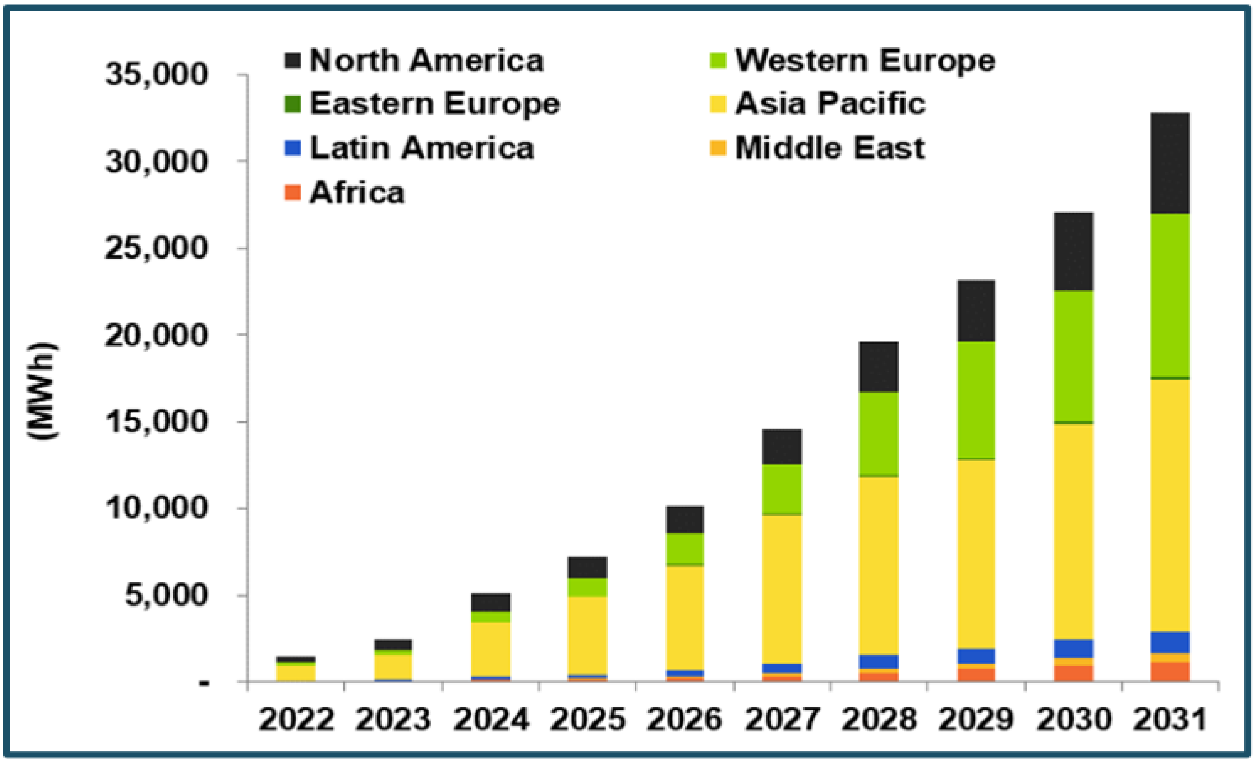
In recent years, the stationary battery market has witnessed remarkable technological advancements, fuelled primarily by the reduction in unit costs per kilowatt-hour (kWh). Other major driving factors for the growth of BESS globally are government policies for renewable energy and global commitment to decarbonisation; high adoption of microgrid and off-grid systems, which require add-on storage solutions; and the rising demand for a reliable, continuous and cost-effective power supply. Due to these demand drivers, the stationary BESS market is expected to strengthen overtime. The International Finance Corporation (IFC) reports that South Africa is expected to lead the African market for battery storage (IFC, 2017).

At least four key underlying factors are driving growth for batteries in global and local markets, notably:

1. Adopting low-carbon and sustainable solutions away from fossil fuels;
2. Rising demand for an accessible, reliable and cost-effective power supply;
3. Enhancing the efficiency of renewable energy (wind and solar) through integration into power grid systems (IRENA, 2022; Agese, 2022); and the
2. Decommissioning and repurposing of coal and gas power plants.

As battery prices continue to fall, flow batteries will benefit from this downward trend. The profitability of battery energy storage through LIBs, and the technological progress of VRFBs, potentially create a similar trajectory for flow batteries, mirroring the path LIBs took two decades ago.

**Figure 1. Annual installed VRFB utility-scale and commercial and industrial battery deployment energy capacity by region: 2022-2031**




*Source:* Gunjan et al., 2022.

Given the evident value and effectiveness of flow battery technology, a gradual rise in installed capacity, as shown in Figure 1, is expected. This suggests that as cumulative installed capacity doubles, there are possibilities for a corresponding decrease in the cost of VRFBs. According to a report published by Research and Markets in 2022, the global market for vanadium batteries is anticipated to experience a compound annual growth rate of 6%-7% from 2021 to 2031. VRFB manufacturing is dominated by major players such as H2 Inc., VRB Energy, E22 Energy Storage Solutions, Invinity Energy Systems, Sumitomo, and CellCube/Enerox, among others. These companies are looking to strengthen their presence in key VRFB markets across the world by expanding their manufacturing capacity and operations (PR News Wire, 2021; Renewables Now, 2021).

Asia Pacific, Western Europe and North America are leaders for VRFB deployments globally. By 2021, it is estimated that the Asia Pacific region will reach about 14.5GWh of annual VRFB installed capacity. North America is expected to reach 5.8GWh and Western Europe is anticipated to reach 9.3GWh. Africa is also expected to play a role in VRFB installed capacity by 2031 accounting for at least 1GWh VRFB projects. The potential opportunities associated with VRFB battery manufacturing in South Africa are estimated to reach 260MWh annually, resulting in potential revenue of R770 million (Customized Energy Solutions, 2023).

Based on the Vanitec database, there are currently more than 290 VRFB projects globally, as shown in Figure 2 (page 5). Out of these, 203 projects are already operational, 32 are under construction, and 44 projects have been announced. There are at least 10 VRFB projects in Africa, including installations at the Eskom Research and Innovation (ERIC) site, Thaba Eco Hotel, and various telecom locations in Gaborone and Johannesburg. China leads VRFB installations with a notable 42 operational VRFB projects.

## MARKET PROSPECTS OF VANADIUM FLOW BATTERIES

Opportunities exist within the local market to harness the potential of VRFBs. South Africa's energy crisis has already precipitated market demand for battery technologies or, at the very least, created the prospect of strong demand for BESS across different applications. With large-scale projects necessitating prolonged storage periods, vanadium batteries hold substantial advantages for the South African market, notably benefiting entities like Eskom and the mining sector. Before looking at the cost structure of

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**Figure 2. Operational VRFB project globally**


*Source:* Gunjan et al., 2022

vanadium batteries, it is essential to ascertain the presence of a viable market for these batteries in South Africa. This consideration is important, as the current market conditions will play a crucial role in determining the success of efforts to localise production.

## LEVERAGING SOUTH AFRICA'S PROCUREMENT PROGRAMMES FOR BATTERY TECHNOLOGIES

South Africa's Integrated Resource Plan 2019 (IRP2019), which aims to determine the country's future energy mix, made electricity provisions for an increased rollout of renewable energy-based generation, along with 2GW of new energy storage capacity by 2030. Demand-side procurement programmes, aligned to the IRP 2019 framework, seek to procure new energy technologies, including liquid and natural gas and battery technologies, with the aim "to enhance power supply and energy security in an efficient and sustainable manner" (World Bank, 2010).

There are several signs of strong local demand in South Africa including, but not limited to, Eskom's BESS programme, the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), the Risk Mitigation Independent Power Producer Procurement Programme (RMIPPPP), the Repowering and Repurposing of Eskom coal-fired power plants, the elimination of the 100MW generation threshold and, in the latest development, the Energy Storage Independent Power Producer Procurement Programme (ESIPPPP) Bid Window 1 announced in March 23 by the Department of Mineral Resources and Energy. The market for BESS in South Africa is also influenced by global financing, with various financial institutions including the World Bank partnering with South Africa and other countries in the region to implement battery storage technologies as a means of improving energy access.

All four procurement programmes outlined follow a technology agnostic approach, supporting the notion that there is no one-size fits all solution, and the choice for battery technologies should be determined on individual cases evaluated on specific criteria such as required scale (MW), performance attributes, investment costs, and geographical location. However, battery technologies must align with programme requirements specification. Flexibility in the selection of battery technologies permits various options, which is key for broadening the country's energy mix. It is important to regard storage technologies as complimentary measures in ensuring secure and reliable power for South Africa. That said, as technology continues to advance and our understanding of its diverse capabilities improves, it may become evident that a technology-agnostic approach may no longer be the most appropriate direction to take in the future.

## DRIVING BATTERY STORAGE THROUGH ESKOM AND GOVERNMENT PROGRAMMES

Eskom is a key catalyst for advancing battery storage within the South African market. Recognising the significance of battery storage for the grid, Eskom has also strategically increased investment in expanding battery storage capacity. As outlined in Eskom's Transmission Development Plan 2023, the increased investments are earmarked for storage generation capacity, distribution, and transmission.

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Eskom's BESS programme serves as a demonstration of successful adoption and implementation of battery storage in South Africa. The BESS programme is split into two phases. Phase 1 looks to install 199MW/832MWh of BESS power across multiple sites, while Phase 2 adds 160MW/640MWh of distributed battery storage and 60MW of solar PV, strategically chosen for optimal renewable energy integration into the national grid. The BESS mainly prioritises daily national peak shaving for four hours, along with additional functions for emergencies and backup power (Creamer, 2022a). In December 2022, construction began on Eskom's Phase 1 BESS facility at the KwaZulu-Natal Elandskop site, with an 8MW capacity equivalent to 32MWh, providing four hours of power to a small town (Hako, 2022). The initial phase aimed to achieve distributed battery storage capacity of 200MW/800MWh by December 2020, but the deadline was shifted to June 2023, and there is a potential further delay until December 2023. Phase 1 of Eskom's BESS enforces a 20% local content requirement, involving local suppliers and skill development (Creamer, 2022a).

Most of Eskom's initial projects within the programme are expected to employ LIB technology, covering all Phase 1 projects except the two that went through re-tendering. While the import of batteries might be essential during crises, there is evident local capacity and capabilities that should be harnessed in the medium to long term for supporting the local market through domestically assembled batteries. Despite the potential for the localisation of LIBs, as highlighted in the TIPS 2021 report by Montmasson-Clair, Moshikaro and Monaisa, Eskom contracted a South Korean company, Hyosung Heavy Industries, and Pinggao Group, to provide 180MW/687MWh LIB storage for the BESS programme. The cost of the installations is estimated at about R11 billion (US$6 000 per kW) and will be financed by the World Bank. As the BESS programme expands, commissioning more projects will become increasingly important, and VRFBs could be a viable option for bulk and large-scale projects.

Repurposing power stations using battery storage, along with substantial investment in renewable energy, could be an effective strategy for developing countries. Eskom's Komati coal power station in Mpumalanga was closed in October 2022 as part of the Just Energy Transition (JET) Strategy due to its age (Eskom, 2022). Komati will be decommissioned as a coal fired power station with the aim to shift it to providing renewable energy and battery storage, including 150MW solar PV, 70MW wind energy, 150MW/300MWh battery storage, and a SynCON[6].

This repurposing will leverage existing transmission infrastructure. Eskom's JET Strategy also includes repurposing Camden, Hendrina, and Grootvlei power stations, incorporating renewable energy generation capacity and BESS. The battery technology for the Komati project has not yet been confirmed. Considering the necessity of extended utility-scale storage, VRFBs might be a suitable option for a repurposed facility. The viability will depend on various factors like use-case, applications, services, and Eskom's technology preferences. However, unless vanadium battery costs decrease or there is recognition of their increased value-add (see Table 1), establishing a strong VRFB business case vis-à-vis other competing storage options will remain challenging. Also, repurposing coal-fired power stations requires thorough planning, including market analysis, feasibility studies, and regulatory compliance. Addressing socio-economic factors and government policies is vital for risk mitigation and funding. Managing impacts on coal value chains and communities necessitates strategic technologies and timelines for decommissioned plants.

## THE ROLE OF BATTERY STORAGE IN REIPPPP, RMIPP AND ESIPPPP

The REIPPPP and RMIPPPP are vital for securing renewable energy generation capacity. The use of batteries can optimise the use of renewable sources and increase investment in storage technologies. Under RMIPPPP, Scatec ASA signed a 20-year power purchase agreement for three Kenhardt projects, combining 540MW solar PV with 225MW/1140MWh BESS capacity (Scatec, 2022). Creamer (2022b) reports that Scatec plans to use LIBs for the hybrid project. While the selection process remains undisclosed, LIBs were found to be a suitable option for the project; however, given the project's scale and timeline, VRFBs could have been considered as they offer better cost competitiveness over a 20-year period.

The ESIPPPP specifies a 513MW/2052MWh BESS project requiring 730 cycles annually, each lasting at least four hours. LIBs could be deployed, but VRFBs are particularly well positioned due to their unlimited

[6] The repurposing of Komati also involves transforming the plant into a training centre to enhance the skills of both Eskom employees and the local community, enabling them to effectively manage renewable energy installations. It will serve as a manufacturing facility for the assembly of solar microgrids tailored for local use (Eskom, 2022).

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cycling capability and extended storage benefits. Incorporating BESS rounds into the REIPPPP signifies progress in combining renewable energy with battery storage in South Africa's energy mix. This propels battery technology advancement to manage renewables' intermittency and effectively support the grid.

Despite facing criticism, particularly in relation to the high number of foreign-owned IPPs, slow progress and stalled efforts, government procurement programmes continue to be important in boosting local demand for storage by providing a stable customer base and promoting economic development, particularly in the case of emerging industries and technologies.

## PIONEERING VRFBs IN SOUTH AFRICA'S MINING SECTOR

Amendment of South Africa's Electricity Regulation Act No. 4 of 2006, removing the 100 MW exemption for generation projects, has led to ambitious private renewable energy plans (Mackay, 2021). Over 13GW of private capacity is anticipated as of October 2023, mainly for energy-intensive users such as mining (SAREM, 2023). While a significant portion of these projects will revolve around harnessing solar and wind power, they will also call for a variety of storage solutions, such as PSH, hydrogen, gas, and battery storage. Implementing these projects is expected to reduce the cost of generating power and enable mining companies to take advantage of their own renewable power generation. VRFBs can contribute to micro-grids and off-grid systems, supporting decentralised energy setups across various sectors, including mining for example.

A notable case is Bushveld Energy's South African flagship VRFB project. The company is establishing a micro-grid with solar and VRFB storage at an alloy mine in North West. This venture is important, showcasing VRFBs' feasibility in power generation and its competitiveness with LIBs in mining grid applications. In addition, Bushveld Energy is developing a local electrolyte facility using domestically sourced vanadium feedstock (Bushveld Minerals, 2018). Developing local capacity to support local demand for VRFBs remains vital and has implications for reducing the high costs of VRFB systems.

Challenges persist in developing a BESS and VRFB market in South Africa. Adopting BESS is hindered by financial constraints, local skill gaps, understanding of the technology, integration into existing infrastructure and the need for a supportive regulatory framework.

In the present landscape, VRFBs pose an investment risk due to their relatively early-stage commercialisation. In addition, VRFBs lack the capacity to offer performance guarantees that can match those provided by LIBs. To overcome this, work is needed to develop the VRFB supply chain of established global suppliers. As a result, the demand from risk-averse utilities and project developers seeking to secure long-term deals with manufacturers has been limited (Gujan, et al., 2022). The successful expansion of short- and long-term energy storage technologies relies on dedicated policies and supportive regulations, as seen in China. To achieve substantial battery storage deployment in South Africa's energy sector and localisation of production, creating an enabling policy environment and attracting public and private investment is essential.

## ANALYSING THE COST OF VRFBs

This and the next section investigate the cost of VRFBs and what is required to make them cost competitive. To re-emphasise, and as noted in Table 1, there is no storage technology that is superior to the other, and selecting the appropriate technology depends on use requirements, cost and performance parameters.

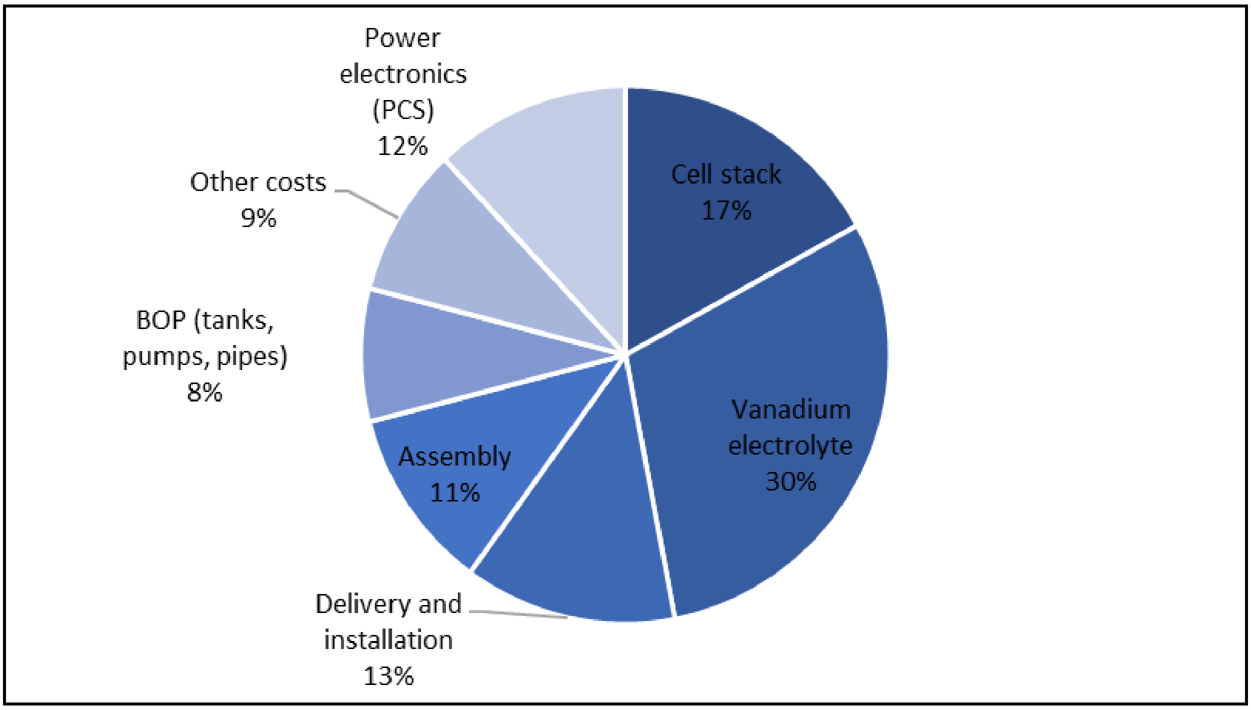
There is a strong correlation between the cost of a good and its market demand. VRFBs still require increased demand as well as substantial investment to move down the cost curve and lower their levelised cost of storage (LCOS) and compete against other battery options. As highlighted, the substantial upfront cost of vanadium batteries, among other factors, restricts their large-scale commercial expansion within the energy sector, with LIBs being the preferred choice for BTM and FTM applications due to their cost-effectiveness.

## DETERMINANTS OF VRFB TECHNOLOGY COSTS

Typically, flow batteries are made up of three core subsystems: the cell stack, electrolyte storage and the balance of plant. The cell stack is sealed using a polypropylene plastic frame, a graphite or carbon composite bipolar plate (bipolar plates can also be made from metallic materials for non-VRFB applications) and a polymer membrane or in some cases, a separator is used instead (Haoyang, et al., 2020)

The costs of a VRFB system are divided roughly into cell stack component costs (including the Balance of Plant, Power Conditioning System, electrolyte), assembly costs, and delivery and installation costs.

Figure 3.Average cost breakdown for a 250kW/four-hour VRFB system, AC installed




*Source:* Bushveld Energy 2018.

The vanadium in a VRFB system comprises most of the cost. The price of vanadium is highly volatile and has been on the rise due to increased demand for steel and vanadium batteries[7]. The steel industry dominates the demand base for vanadium, accounting for about 90% of total vanadium demand in 2019 (Ford, 2021). Thus, currently, the price elasticity of demand for vanadium is significantly influenced by the demand for steel (Ford, 2021). Even though South Africa holds significant vanadium pro-duction, the pricing of vanadium (along with other South African commodities) is determined by the import parity price[8].

From the VRFB system costs diagram shown in Figure 3, the component costs of the battery account for the highest proportion, at approximately 67% of the cost of the battery. Part of these component costs includes the vanadium electrolyte representing 30% to 65% of the total cost. The costs breakdown in Figure 3 is indicative for the industry. The actual breakdown varies based on the materials, technologies and components used by individual com-panies and the power to energy ratio of a specific battery (for example, in an eight-hour battery, the electrolyte makes up double the percentage of a four-hour battery) (Noack,, et al., 2016).

Cell stack components also have a high value representing 17% of total cost, followed by power electronics accounting for 12% of costs. Overhead costs including delivery and installation[9] and assembly are also relatively important costs in VRFB manufacturing, contributing 24% to the overall cost of the battery. Other costs are made up of energy, research and development (R&D) and administration. Reducing battery component costs is essential for the

research and development (R&D) and administration. Reducing battery component costs is essential for the
wide adoption of VRFBs. Lüth et al. (2018) note that the cost reduction on passive components (BoP, PCS) will not be realised in the same way as the cost reduction on the active materials (the membrane and electrolyte, for example). According to Lüth et al. (2018), this is due to most passive components being readily available and manufactured in large quantities. Hence, if the cost of active materials declines, the share of the passive components is estimated to increase from 18% to 46% (Lüth et al., 2018).

## THE LEVELISED COST OF STORAGE FOR BATTERY STORAGE TECHNOLOGIES

To appropriately compare and evaluate the costs and economic feasibility of energy storage technologies, understanding the LCOS for a specific project is essential. The LCOS model is a tool used to compare the unit costs of battery technologies over their life cycle (Schmidt et al., 2019). As the LCOS of battery technologies varies, selecting the use-case of a system becomes critical to ensure adequate cost-benefit and to be able to evaluate costs for different storage solutions with different performance attributes, in both BTM and FTM applications.

[7] The price of vanadium (V2O5) peaked at US$28.8 a pound (/lb) in 2018 and went to US$12lb in March 2022 to US$10/lb in February 2023, and US$7.7/lb in August 2023.

[8] This is the price at which a commodity would be sold in South Africa if it were imported and includes non-incurred costs such as shipping, insurance, and tariffs or taxes.

[8]The installation of VRFB systems can take place either on-site or off-site.

***The high cost of vanadium remains a significant challenge to the adoption of VRFB technology. However, innovative business models, such as vanadium electrolyte rental options, have emerged to address this challenge. Localising VRFB production can also help to reduce costs and create job opportunities.***

According to Schmidt, et al. (2019), the LCOS is defined as the discounted cost per unit of discharged electricity for a storage technology. The LCOS[10] is calculated as the lifetime cost of energy storage technology divided by the cumulative electricity delivered, using a discount rate,[11] while accounting for all technical performance parameters associated with installation through to termination of the storage technology (Schmidt et al., 2019; Fourie, 2015).

As indicated by Lazard (2017), Schmidt et al. (2019), and Invinity Energy Systems (2023), the components of LCOS encompass both technical and economic parameters that impact the long-term expenses of storage technologies. The assessment of LCOS involves several interconnected factors, including duty cycle, capital expenditure (CAPEX), operating and maintenance expenditure (O&M), charging costs, efficiency, replacement cost, asset lifetime, round trip efficiency (RTE) and the discount rate.

When evaluating the LCOS of LIBs compared to VRFBs, LIBs have a lower LCOS because the technology benefits of high efficiency and low charging costs, even though their end-of-life cost is shorter than VRFBs. VRFBs usually have some shortcomings, notably a higher CAPEX and a relatively lower efficiency which affects the charging price.

As production levels are not yet high, the unit cost of producing each battery may be relatively expensive, and the cost may not decrease at the same rate as production increases. The technology's shortcomings unfortunately contribute to the high LCOS of VRFBs over a specified period. Despite this, Fourie (2018) states that VRFBs could replace LIBs by 2030 as a competitive storage alternative, specifically for long-duration storage.

Invinity Energy Systems conducted an analysis that supports the views expressed by Fourie (2018), indicating that VRFBs demonstrate a more competitive LCOS compared to LIBs over a 20 to 25 year lifespan, particularly when taking into account expenses related to replacement and O&M costs. Invinity modelled a utility-scale battery that was installed alongside solar PV. The battery was designed to perform numerous cycles per day for wholesale or ISO/RTO and utility markets, which are typically markets that can handle high throughput (Invinity Energy Systems, 2023). This approach allowed the battery to undertake valuable tasks such as time shifting and energy arbitrage, which increased its revenue potential (Invinity Energy Systems, 2023). The model also assumed a 10MW/40MWh battery with high throughput capacity, equivalent to approximately 700 full DoD cycles annually, and a 6% discount rate over the project life of 40 years.

The CAPEX for the VRFB is estimated at US$83/MWh in the model, while the LFP system had a much lower CAPEX of US$53/MWh. As the price and CAPEX of VRFBs are almost certainly on a downwards trajectory, linked to a growing market and demand, VRFBs are more likely to benefit from increased demand and lower discount rates, further increasing their cost advantage (Rebel Group and TIPS, 2022). Still, it is not yet clear whether VRFB could compete against LIBs on CAPEX.

In terms of O&M costs, the VRFBs had a slightly lower expense of US$11/MWh, compared to US$13/MWh for LIBs. This is mainly due to the reduced number of auxiliary systems, such as fire detection and fire suppression, which require testing and maintenance over time for VRFBs (Invinity Energy Systems, 2023). VRFBs are known for their lack of degradation over time, resulting in zero degradation costs.

In contrast, LIBs are expected to degrade by about 4.7% a year based mainly on cycle count, which contributes to their end-of-life costs and increases their LCOS by US$6/MWh (Invinity Energy Systems, 2023). The vanadium electrolyte in VRFBs' reusability and recyclability reduces end-of-life costs. The initial RTE of the LIB is higher, but it degrades over time and is only marginally recovered through augmentation (Invinity Energy Systems, 2023). As a result, both batteries experience efficiency losses, with the VRFB costing US$16/MWh of throughput over its lifespan, compared to US$5/MWh for the LIB.

While the Invinity Energy data shows a positive outcome for VRFBs over a 40-year timeframe, which is not an unusual timeframe in the power sector, it is important to approach committing to a 40-year agreement carefully due to various factors and assumptions that impact a project's lifespan. Moreover, the dynamic nature of storage and battery technologies could present challenges for investors to commit to such a prolonged agreement.

[10] LCOS is measured in currency per unit of stored energy discharged (e.g. US$/MWh or £/MWh).

[11] Despite the increasing research on the LCOS, there is no unified understanding of the calculation method of energy storage costs. While some studies have ignored economic parameters such as replacement or charging costs, others have excluded technical parameters such as operational and maintenance costs and the self-discharge rate. Also, different studies use different discount rates.

**Figure 4: The LCOS for VRFB modelled over a 40 year lifecycle US$111/kWh**

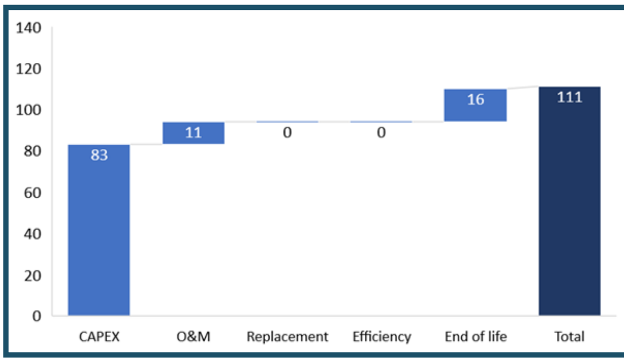
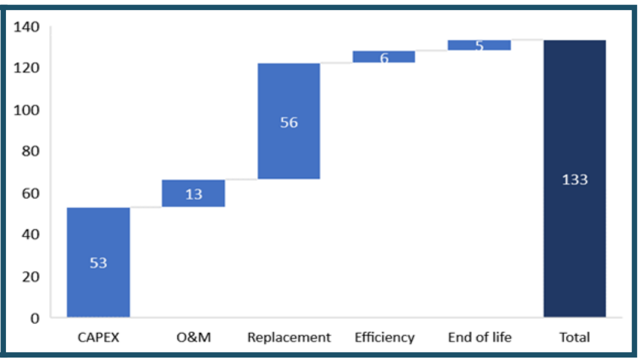



**Figure 5: The LCOS LIB (LFP) modelled over a 40 year lifecycle US$133/kWh**




*Source:* Infinity Energy Systems, 2023

The LCOS for both systems indicates a value of US$111/kWh for the VRFB and US$133/kWh for the LIB (see Figure 4 and Figure 5).

The cost estimation of battery storage relies significantly on the battery's operational characteristics and the technology employed. There are several options available, and the decision-making process involves evaluating trade-offs and making informed choices based on cost drivers and their interconnectedness. Understanding the cost drivers and evaluating the technology options makes it possible to make informed decisions, leading to better performance and return on investment for battery storage projects.

## SCOPE FOR REDUCING COST OF VRFBs

Strategies for countering the impact of high vanadium prices will be key for VRFB success. According to Schmidt et al. (2019) and Fourie (2015), there are opportunities for reducing the LCOS of storage technologies. To reduce the LCOS of VRFBs, cost reductions can be achieved through performance improvements through higher throughput, lower capital cost, longer lifespan, minimal degradation, higher RTE, lower charge price, lower discount rate, battery sizing, and innovative investment approaches[12] (e.g. electrolyte leasing). Costs could be minimised through improvements in RTE, reducing the unit initial investment cost (possibly through some kind of government support), and giving full play to the value-add and advantages of different technologies, and through localising value chains.

For example, with performance, a higher RTE for VRFBs, which could see increases in RTE from 73% in 2015 to 85% in 2030, would render VRFB technology more cost-effective than LIBs at high frequencies (Schmidt, 2019). However, these scenarios only consider the impact of performance improvements for one technology in isolation, which is not realistic. According to Schmidt, (2019) and Fourie (2018), it is more likely that each technology will have some degree of performance improvement and investment reduction as prices decline, which may further improve cost advantage in the long run.

By analysing the costs of different BESS, investors, policymakers and other stakeholders can help guide the development of energy storage policies, such as implementing a subsidy or tax policy, capital investment, storage procurement and pricing policies, and/or energy storage rebate programmes (Xu, 2022).

## CONCLUSION

The high cost of vanadium remains a significant challenge to the adoption of VRFB technology. However, innovative business models, such as vanadium electrolyte rental options, have emerged to address this challenge. Localising VRFB production can also help to reduce costs, create job opportunities, and accelerate investment in new technologies. Nevertheless, the issue of import-parity pricing in the local market remains unresolved and needs to be addressed to ensure the competitiveness of the local VRFB industry, including through possible integration in the value chain. Overall, the potential benefits of VRFB technology, such as its high efficiency and long lifespan, make it a promising solution for energy storage, and efforts to overcome the cost challenges will be crucial for widespread adoption. Predicting the future demand for any product is challenging. However, to capitalise on the advantages that come with the spread of energy storage technologies, South Africa should consider exploring ways to promote VRFB demand and local manufacturing. Therefore, there is a significant opportunity for South Africa to localise VRFB manufacturing, given the country's vanadium production, battery expertise and need for utility-scale battery technologies. In the context of local manufacturing, given that batteries embody a clean energy technology, it is equally important to prioritise low-carbon battery production. This emphasises minimising carbon footprints throughout the battery production process, which aligns with the broader objectives of decarbonising the grid market.

[12] The investment cost represents the largest LCOS component for nearly all technologies, thus reducing the investment cost of a project is significant to reducing the LCOS value.

## RECOMMENDATIONS

The initial recommendation pertains to the price of vanadium. By localising production, it may be possible to achieve cost savings that could reduce the price of vanadium and, consequently, the LCOS of vanadium batteries. South Africa's vanadium reserves offer the potential for gaining access to low-cost vanadium locally through a mine gate or export-parity price. It would benefit from forming a partnership or securing long-term contracts with local vanadium suppliers to be feasible (Rebel and TIPS, 2022). Still, there is no guarantee that a local VRFB original equipment manufacturer (OEM) in South Africa would be able to acquire vanadium at a preferential price. Vertical integration within the value chain also presents an alternative option to decreasing vanadium prices, thus aiming to achieve cost savings

Second, a strategic business model such as renting or leasing of the electrolyte could be considered. For example, Invinity Energy Systems and Bushveld Minerals have collaborated to establish Vanadium Electrolyte Rental Limited (VERL). The company offers an option for renting vanadium electrolyte to Invinity's clients (Slater, 2020). Renting or leasing the vanadium electrolyte may serve as a potential solution to address the instability in vanadium prices and the higher capex costs associated with VRFBs.

To encourage the adoption of VRFBs and strengthen the prospects of local VRFB manufacturing, policies must ensure the inclusion of long-duration storage. Such policies would grant VRFB technology and other long duration technologies a distinct advantage in long-term reliability, thereby enhancing the overall value of integrating renewable energy sources. It remains equally important that this is in accordance with the goals of energy planning within South Africa, and that comprehensive evaluations take place to determine the degree to which VRFBs and long duration systems adequately meet that demand.

Last, considering that batteries are a clean technology with the potential to foster the circular economy, attract investments, generate employment, and achieve energy security for South Africa, allocating a portion of the US$8.5 billion Just Energy Transition Partnership (JETP) funding to BESS projects, including those driven by VRFB technology, could aid in boosting market demand local manufacturing.

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***There is a significant opportunity for South Africa to localise VRFB manufacturing, given the country's vanadium production, battery expertise and need for utility-scale battery technologies.***


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