TRADE & INDUSTRIAL POLICY STRATEGIES

LOCALISING VANADIUM BATTERY PRODUCTION FOR SOUTH AFRICA'S ENERGY SECURITY

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ABBREVIATIONS AND ACRONYMS

AC	Alternate Current
AES	AES Corporation
ARENA	Australian Renewable Energy Agency
AVL	Australian Vanadium Limited
BESS	Battery Energy Storage Systems
BHT	Butylated Hydroxytoluene
BMS	Battery Management System
BOP	Balance of Plant
BTM	Behind-the-Meter
BYD	Build Your Dreams
CAES	Compressed Air Energy Storage
C&I	Commercial and Industrial
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CBAM	Carbon Border Adjustment Mechanism
CEC	California Energy Commission
CIMC	China International Marine Containers
CSIR	The Council for Scientific and Industrial Research
CSP	Concentrated Solar Power
DMRE	Department of Minerals and Energy
DoD	Depth-of-Discharge
DSI	Department of Science and Innovation
dtic (the)	Department of Trade, Industry and Competition
ELIDZ	East London Industrial Development Zone
EMS	Energy Management System
EPC	European Patent Convention
EPRI	The Electric Power Research Institute
ESG	Environmental, Social and Governance
ESIPPPP	Energy Storage Independent Power Producer Procurement Programme
ESMAP	Energy Sector Management Assistance Program
ESS	Energy Storage Systems
EV	Electric Vehicle
EY	Ernst and Young
FTM	Front-of-the-Meter
FYP	Five-Year Plan
GHG	Greenhouse Gas
GVC	Global Value Chain
GW	Gigawatt
GWh	Gigawatt hours
IDC	Industrial Development Corporation
IEA	The International Energy Agency
IFC	International Finance Corporation
IP	Intellectual Property
IPF	Intellectual Property Families
IPM	Isondo Precious Metals

IPP	Independent Power Producer
IRP	Integrated Resource Plan
ISO	Independent System Operator
JET	Just Energy Transition
JV	Joint venture
KW	Kilowatt
KWh	Kilowatt-Hour
LCOS	Levelised Cost of Storage
LIB	Lithium-ion Battery
METI	Ministry of Economy, Trade and Industry (Japan)
MCEP	Manufacturing Competitiveness Enhancement Programme
MWh	Megawatt-Hour
MW	Megawatt
MT	Megatonne
NECSA	South African Nuclear Energy Corporation
NEV	New Energy Vehicle
O&M	Operating and Maintenance
OEM	Original Equipment Manufacturer
PCS	Power Conditioning System
PFSA	Perfluorosulfonic Acid
PSH	Pumped Storage Hydropower
PV	Photovoltaic
R&D	Research and Development
RE	Renewable Energy
RFB	Redox Flow Battery
RMIPPPP	Risk Mitigation Independent Power Producer Procurement Programme
REIPPPP	Renewable Energy Independent Power Producer Procurement
RTO	Regional Transmission Organisation
RTE	Round Trip Efficiency
SA	South Africa
SADC	Southern African Development Community
SDG	Sustainable Development Goals
SEZ	Special Economic Zone
SMME	Small Medium and Micro Enterprises
SynCON	Synchronous Condenser
TCO	Total Cost of Ownership
TDP	Transmission Development Plan
TIPS	Trade and Industrial Policy Strategies
TVM	Thermal Valve Manufacture
UK	United Kingdom
UPS	Uninterrupted Power Supply
US	United States
USD	United States Dollar
USGS	United States Geological Survey
VERL	Vanadium Electrolyte Rental Limited
VRB	Vanadium Redox Battery

EXECUTIVE SUMMARY

South Africa is facing an electricity crisis due to the underinvestment in electrical infrastructure. South Africa’s Integrated Resource Plan (IRP) of 2019 aims to transition to renewable energy, including battery energy storage systems (BESS), to limit carbon emissions. In line with the IRP, Eskom’s Battery Energy Storage Project outlines the integration of 800 megawatt-hour (MWh) of battery storage in phase one, and 640 MWh of battery storage combined with 60 MWh of solar generation in phase two of the programme. The BESS market in South Africa is growing due to increasing demand for stable electricity supply and private sector investment.

The crisis presents an opportunity for the widespread adoption of BESS, as BESS have an integral role in the renewable energy value chain, including stabilising the national grid, reducing energy costs, and decentralising energy production and supply. As the demand for stationary BESS increases, specifically in Africa where renewable energy generation projects are on the rise, alternative mechanisms to store energy and reliably discharge and transfer energy are being sought out. While lithium-ion batteries (LIBs) and lead-acid batteries dominate the BESS market, the rising costs of electricity generation and the current electricity crisis in Sub-Saharan Africa, particularly in South Africa, have led to a review of the possibility of integrating various storage technologies throughout the South African market.

The primary debate about batteries is whether to use LIBs or vanadium redox flow batteries (VRFBs) in consumer and grid markets. LIBs and VRFBs are key battery technologies used in stationary storage and both technologies present potential avenues to support the country’s efforts. The use of VRFBs and complementary technologies in the energy market has gained significant attention. This is due to their capability to effectively support renewable energy generation, and particularly for South Africa, their potential for localisation has been a key focal point. VRFBs offer significant advantages over LIBs when it comes to large-scale and utility-scale[1] projects. They possess favourable technical characteristics that make them well-suited for long-duration applications. In addition, VRFBs have a lower total cost of ownership (TCO) compared to LIBs over the lifespan of the system. These advantages make VRFBs an attractive option for energy storage in projects in which high-capacity and long-duration storage are necessary. While cost is crucial, it is equally essential to explore methods of enhancing the value proposition of VRFBs, which would “allow” their deployment at higher costs. Another aspect of value is the emphasis on the long lifespan of VRFBs. The development of a domestic battery industry aligns with South Africa's vision to transition towards green industries. These industries possess the potential to not only advance the country's decarbonisation endeavours but also generate employment, facilitate technology transfers, and attract investments in innovative 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 places the emphasis on minimising carbon footprints throughout the battery production process, which aligns with the broader objectives of decarbonising South Africa’s grid market.

In comparing the various battery technologies, VRFBs have a longer lifespan and the electrolyte is easily reusable, and unlike lithium-ion or lead-acid batteries, VRFBs also have longer operating hours, ranging from four to 12 hours, whereas LIBs are usually limited to four hours. However, VRFBs are more expensive at present than LIBs due to their higher capital expenditure, with the most expensive component being the vanadium electrolyte and cell stack. Nonetheless, there is a possibility of cost reduction in VRFBs, through preferential raw material pricing policies or

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[1] Utility-scale is typically greater than 1MW, but for South African municipalities, guidelines are set to 10MW.

by implementing innovative business models such as electrolyte leasing that enables the reuse of vanadium electrolyte, thereby reducing the overall expenses incurred throughout the lifespan of the battery.

Despite the high cost of vanadium battery systems, the declining costs of (lithium-ion) batteries are driving the growing adoption of batteries, including VRFBs, in the market. The profitability of battery energy storage through LIBs, and the technological progress of VRFBs, potentially creates a similar trajectory for flow batteries, mirroring the path LIBs took two decades ago. VRFBs 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 the installed capacity of flow batteries continues to rise, the price of VRFBs is expected to decrease with the increase in cumulative capacity. Localising manufacturing would also be highly beneficial for South Africa as the country is the third-largest global vanadium minerals producer behind China and Russia. South Africa’s high mineral reserves have enabled it to have prominent capabilities in producing vanadium batteries. To increase the demand for VRFBs within the broader market, reducing the cost of battery production and cell stack components is necessary. The value chain for VRFBs is reviewed and analysed in this report from mining and processing to the end-of-life prospects of VRFBs, with original equipment manufacturers (OEMs) playing a central role.

The discussion about VRFBs and their potential contribution to building a new manufacturing industry in South Africa centres around their cost-effectiveness, among other added economic and environmental benefits. The production and development of VRFBs would require investment in research and development (R&D) as well as specialised knowledge and expertise, some of which can be drawn from South Africa’s existing lead-acid, fuel cell and LIB industries. However, establishing local manufacturing can be challenging, particularly in the absence of incentives on the supply side. Thus, acquiring financing and establishing strategic collaborations and agreements among multiple stakeholders become essential.

Government policies and local procurement targets play a vital role in driving the storage market. Through the implementation of roadmaps and policies, governments can decrease uncertainties and the associated risks involved in investing in battery technologies.. In South Africa, the government has implemented storage targets, particularly for utility scale, outlined in the IRP 2019. These targets aim to facilitate the integration of renewable power generation into the grid and enhance grid stability and reliable electricity supply.

In addition to direct government support, is the adopting of strategic partnerships between local and international stakeholders across the value chain, with international OEMs and local companies collaborating to integrate knowledge and expertise for manufacturing critical components such as cell stack components. This strategy helps promote skills development and expand the local skill set, reducing the reliance on specialised international labour and offsetting cumulative investments. Partnerships and collaborations can be advantageous if they align with local industrial policy and national priorities, aiming to integrate local firms into the value chain while supporting the industrial development of VRFBs and local renewable energy markets.

Recommendations for supporting the development of a local VRFB industry in South Africa include:

1. Establishing a local market for VRFBs: Includes long-duration storage in policies to encourage the adoption of VRFBs and support the prospects of local VRFB manufacturing. Requirements of specifications for BESS need to be inclusive of both LIBs and VRFBs.
2. Emphasising VRFBs’ long lifespan: Develop policies to include, alongside short-term storage, storage systems that prioritise long lifespan systems, and consider the extended lifespan of VRFBs compared to other battery technologies.

3. Lowering the price of vanadium: Explore options for local production and vertical integration in the value chain to achieve cost savings and reduce the price of vanadium.
4. Introducing strategic business models: Consider rental or leasing options for VRFB electrolytes to reduce the initial capital costs associated with VRFBs.
5. Establishing a supportive policy framework: Provide financing, strategic industrial policy interventions, and leverage existing incentives like tax allowances, Manufacturing Competitiveness Enhancement Programme and Special Economic Zone (SEZ) policies to attract investment and support local VRFB manufacturing.
6. Promoting R&D and capacity building: Fund research and development initiatives, promote partnerships with international companies, and develop training programmes to enhance skills and knowledge in VRFB technology and manufacturing.

INTRODUCTION

The underinvestment in generation, transmission and distribution infrastructure, along with growing populations and economies, has caused power utilities to fall short in meeting demand, resulting in electricity rationing and recurring blackouts (Kuhudzai, 2022). South Africa's electrification efforts remain constrained by the lack of adequate generation, poor infrastructure systems with limited distribution networks and a lack of investment in clean energy alternatives. Nevertheless, South Africa and the region have the potential to enhance electricity access and reliability, and expand its generation efforts using renewable energy, coupled with energy storage technologies. In 2020, only 9% of all energy generated in Africa came from renewable sources, and Africa's renewable energy potential is still largely untapped (ESMAP, 2018).

Renewable energy, such as solar and wind power, offers an opportunity to generate clean, affordable and sustainable energy, which could help address the region's energy crisis. Moreover, the integration of energy storage technologies, such as lithium-ion or vanadium-based batteries, would ensure that renewable energy is harnessed efficiently and cost-effectively. Energy storage would allow electricity to be stored during periods of excess generation and supplied during periods of high demand, providing flexibility and stability to the power grid. This approach could reduce dependence on traditional fossil fuel-based energy sources and improve energy security in the region. By embracing renewable energy and energy storage technologies, the region could unlock its potential for sustainable and reliable electricity generation, paving the way for socio-economic development.

The shift towards renewable energy sources to reduce greenhouse gas emissions has prompted a demand for highly efficient and long-lasting batteries to store and stabilise the energy grids. In the South African market, the mainly coal-dominated energy grid is being integrated with renewable energy sources to reduce carbon emissions and costs, with battery technology emerging as a vital complement to the energy transition. While LIBs dominate the battery energy storage market, VRFBs are emerging as a breakthrough technology for energy integration, voltage regulation, grid stabilisation, and black start applications. Increased adoption of renewable energy adoption improves prospects for VRFBs. Thus, the future demand for VRFBs is indicative of the continent's wide shift in industrial and energy policies aimed at shifting to renewable energy and providing broader electrification.

This research reviews the expansion of a South African VRFB value chain that would also provide regional benefits. The research explores the practicality of developing a sustainable VRFB market and supply chain in South Africa, integrated with renewable energy generation, while improving energy supply and security.

South Africa's VRFB value chain currently lies in raw material output, electrolyte production, and locally manufactured balance of plant (BOP) components. However, there is potential for a more significant role to be played along the value chain. To foster the growth of a domestic VRFB industry, it is crucial to implement measures that support both demand and supply. The increasing demand for electrification in Africa creates an opportunity for VRFBs to enhance energy supply through renewable energy sources. In addition, developing a South African VRFB industry becomes crucial for effectively supplying the region with storage systems, thereby playing a pivotal role in supporting broader electrification initiatives in the region.

The research is structured as follows:

PART ONE: VRFB MARKET DEMAND

Section 1: Why energy storage systems are crucial for South Africa's future

Section 2: Exploring energy storage technologies and market demand opportunities

Section 3: Driving factors for a stationary battery storage market

Section 4: VRFBs and market demand: A key driver for adoption

Section 5: Levelised cost of storage for LIBs and VRFBs

PART TWO: VRFB SUPPLY AND LOCAL MANFUACTURING OPPORTUNITIES

Section 6: Building a local VRFB industry: Exploring opportunities for localisation

Section 7: Proportion of vanadium cost in VRFB

Section 8: The VRFB value chain analysis

Section 9: Potential for strengthening local capabilities in the VRFB value chain

Section 10: Scope of VRFB manufacturing and assembly in South Africa

Section 11: Conclusion and recommendations

1. WHY ENERGY STORAGE SYSTEMS ARE CRUCIAL FOR SOUTH AFRICA'S FUTURE

South Africa has among the highest electrification rate in Africa. Nonetheless, the country grapples with power shortages, which have worsened since 2022, with daily planned blackouts being common. In 2022, South Africa experienced at least 121 days of loadshedding, more than twice the number in 2021, which stood at 48 days (BusinessTech, 2022a). The severity of loadshedding persisted into 2023, leading to the temporary declaration of a State of Disaster by South Africa's President Cyril Ramaphosa in February 2023 (Parliament of South Africa, 2023).

South Africa's economy is among the most coal-intensive in the world and the country's move away from coal has been shaped by the global climate emergency (Makgetla and Patel, 2021). Until recently, electricity generated using fossil fuels was relatively cheap, but global efforts to transition away from fossil fuels advanced investment in renewable energy, increasing the flexibility of electricity generated from renewable sources. South Africa's heavy reliance on coal for generating power, coupled with investment in the Medupi and Kusile power stations[2] increasingly raised energy costs along the coal value chain, contributing to increasing electricity prices that have put Eskom, the national grid and the economy under increasing pressure[3] (Makgetla and Patel, 2021). Under these circumstances, demand for coal has stagnated over the past decade, while renewable technologies have seen unprecedented growth. According to Makgetla and Patel (2021), Eskom's attempts to maintain large-scale coal plants during the 2010s caused it to become less competitive and more disruptive to the overall economy. In 2022, Eskom's total nominal capacity dropped to about 46 000 megawatt (MW) (down from 50 000MW in 2019), and at least 40% of that capacity is usually unavailable due to maintenance and breakdowns.

Further, South Africa has some of the highest coal consumption per capita compared to other upper-middle-income countries excluding China (Makgetla and Patel, 2021). To fulfil the global agreement on climate change, South Africa committed to significantly reducing all its carbon emissions generated by fossil fuel electricity,[4] thereby intensifying the country's coal demand challenges.

As a consequence of these difficulties, Eskom resorted to loadshedding from 2008. This rationed electricity, and caused lengthy power outages for households and businesses that depend on the power utility (Makgetla and Patel, 2021). The economic impact has varied substantially and continues to worsen. The almost daily loadshedding is said to cost the country's economy up to R4.6 billion (US$270 million) a day (Kuhudzai, 2022). In 2023, South Africa has experienced the worst period of loadshedding to date, which equalled 1 296 hours or 54 days of no power (BusinessTech, 2022a)

To mitigate the impact of frequent blackouts and power outages in South Africa, for the few who can afford them, households and businesses have been relying on solar photovoltaic (PV) panels, back-up generators, lead-acid batteries and LIBs as a coping strategy. While LIBs and lead-acid batteries are suitable for behind-the-meter (BTM)[5] applications, which include residential, commercial and industrial (C&I) infrastructure that need short discharge durations lasting one to four hours, VRFBs

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[2] Medupi and Kusile are two of Eskom's newly built power stations. Medupi and Kusile were projected to reach full completion in 2023 and 2026, respectively.

[3] The stations energy costs along the coal value chain in South Africa was also attributed to an inadequate tariff methodology, along with corruption (Interview with Gaylor Montmasson-Clair (TIPS) in 2023).

[4] The Department of Forestry, Fisheries and the Environment GHG Inventory Report (2020) establishes that 94.7% of the country's greenhouse gases come from the energy sector, while 53,6% of these emissions come from electricity generation and liquid fuel production.

[5] A BTM system provides power that can be used on-site without passing through a meter, while a front-of-meter system provides power to off-site energy users.

and sodium sulphur batteries are more appropriate for applications that require longer discharge durations, typically at the utility-scale level. This aspect carries significance as the need for storage solutions in South Africa incorporates both BTM and front-of-the-meter (FTM), which include utility-scale applications connected to electricity generation or transmission. Storage demand in South Africa is currently being driven by Eskom, private sector and the residential markets. However, for Eskom and the private sector, their primary focus mainly lies in procuring both short-term and long duration, flexible and safe battery storage that can efficiently provide backup power over an extended period, which is crucial for grid stability and the smooth integration of renewable energy.

The TIPS report on the coal value chain by Makgetla and Patel (2021) states that Eskom experienced mounting financial strain due to increasing breakdowns, leading to a reliance on diesel generators to fill the electricity supply gap, which incurred high running costs. The report further indicates that Eskom's use of diesel generators surged by over 10 times, from 118GWh in 2018 to 1 328GWh in 2020, resulting in costs increasing rapidly from R320 million to R4.3 billion. In addition, generators have drawbacks such as noise pollution, emitting carbon, and being unsustainable due to the escalating price of fuel. In the long run, batteries have the potential to outperform generators in cost-effectiveness, while also providing clean solutions with reduced carbon emissions.

The electricity crisis in South Africa is hindering the country's growth potential, causing disinvestment, business closures, employment losses, and a limited tax base to fund new projects. The lack of immediate action by the government to recover the situation at Eskom will continue to negatively affect the economy. However, there is an opportunity for significant government-led investments in the renewable energy sector, supported by energy storage systems such as pumped storage hydropower (PSH), gas, hydrogen or batteries. Decarbonising the power sector by adopting renewable energy and energy storage technologies is essential, not only to solve the electricity crisis but also to meet South Africa's emission reduction targets as part of the Paris Agreement and the net-zero commitment.

Addressing loadshedding has emerged as a top national priority. South Africa's energy crisis has already precipitated market demand for battery technologies, or, at least, created the prospect of strong demand for BESS. There are multiple indications of strong local demand in future, including but not limited to Eskom's BESS programme, the Risk Mitigation Independent Power Producer Procurement Programme (RMIPPPP), the Renewable Energy IPP Procurement Programme (REIPPPP), Eskom's repurposing strategy, and the recent Department of Mineral Resources and Energy (DMRE) request for proposals for a 513MW/2052MWh battery storage tender under the Battery Energy Storage Independent Power Producer (IPP) Programme, as per IRP2019.

An opportunity arises to tackle the crisis by localising battery systems, especially in the long run. Energy storage systems, especially batteries, hold promise for resolving South Africa's electricity crisis. Notably, the availability of battery minerals in the country could be crucial in creating local value chains to support this. The country and the broader African continent have abundant battery minerals for both LIBs and VRFBs, which are crucial for battery energy storage technologies. However, for localisation, demand must be fulfilled to ensure localisation is adequately supported.

The next section focuses on the demand for battery storage in the South African market, particularly for long-duration storage, which is well-suited for large-scale and utility-scale projects. It begins by emphasising the significance of energy storage technologies in the electricity and renewable energy value chains, with a specific emphasis on battery technologies. The section following that examines the local battery market and identifies the types of battery technologies that can fulfil the needs of key customers in the storage market.

2. EXPLORING ENERGY STORAGE TECHNOLOGIES AND MARKET DEMAND OPPORTUNITIES

2.1. The role of energy storage in the integration of renewables and grid stability

The demand for energy storage systems (ESS)[6] is increasing across various sectors, including stationary applications, transportation, and consumer electronics (He and Wang, 2018). ESS are crucial in facilitating the shift towards decarbonisation and a green energy transition, while also supporting investment in new industries (He and Wang, 2018). Further, ESS are significant in facilitating renewable energy integration, allowing storage to integrate with a wide variety of renewable resources such as solar photovoltaic (PV) and wind. The development of utility-scale energy storage technologies combined with renewable energy would enable the energy system, particularly electricity generation, to shift away from the dominance of coal-based power generation. Complementing the deployment of renewable energy-based electrical generation options with storage technologies offers an effective way to overcome resource variability and intermittency, as well as the need for sub-optimal operating reserves (Fourie, 2018).

According to Fourie (2018) and Yuksel (2020), energy storage technologies share similarities in their ability to perform three fundamental processes: charging, storing, and discharging electrical energy as needed. However, their use cases differ in technical performance and economic value, which considers factors such as the required scale in MW, response times, discharge duration, and cost of investment (Fourie, 2018). In addition, energy storage technologies can offer ancillary services to the grid, in particular balancing electricity supply and demand, ensuring power system reliability and stability, and improving energy security. As energy storage performance varies widely by application, it is crucial to conduct a comprehensive analysis of applicable technologies before selecting and deploying a specific energy storage technology at a site, as there is not a single technology that can meet all the required uses of consumers and utilities (Fourie, 2018).

Energy storage technologies have the potential to enhance power system reliability and performance. They can be applied to various use cases such as power peak shaving, load levelling and new energy vehicle (NEV) charging. Figure 1 illustrates the storage technologies that can provide a wide range of services throughout the energy system value chain, including bulk energy storage, customer energy management, and ancillary services (Fourie, 2018). Energy storage applications are typically categorised as high power or high energy applications. High power applications require a large amount of power (MW) over a short discharge duration (seconds, minutes or less) and are commonly used for voltage support, frequency regulation and black start, as shown in Table 1. High energy applications require large amounts of energy (MWh) for longer durations, usually an hour or more, and are used for peak shaving, load levelling and the integration of renewable energy, among others (Intelpower, 2018).

2.2. An overview of energy storage technologies: characteristics and comparisons

A range of storage technologies are available in the market, which can be broadly categorised into mechanical (such as PSH, compressed air energy storage (CAES) and flywheels), electrochemical (including high-temperature and secondary batteries, as well as flow batteries), and electrical and thermal technologies (as outlined by the World Bank International Finance Corporation (IFC) in 2020,

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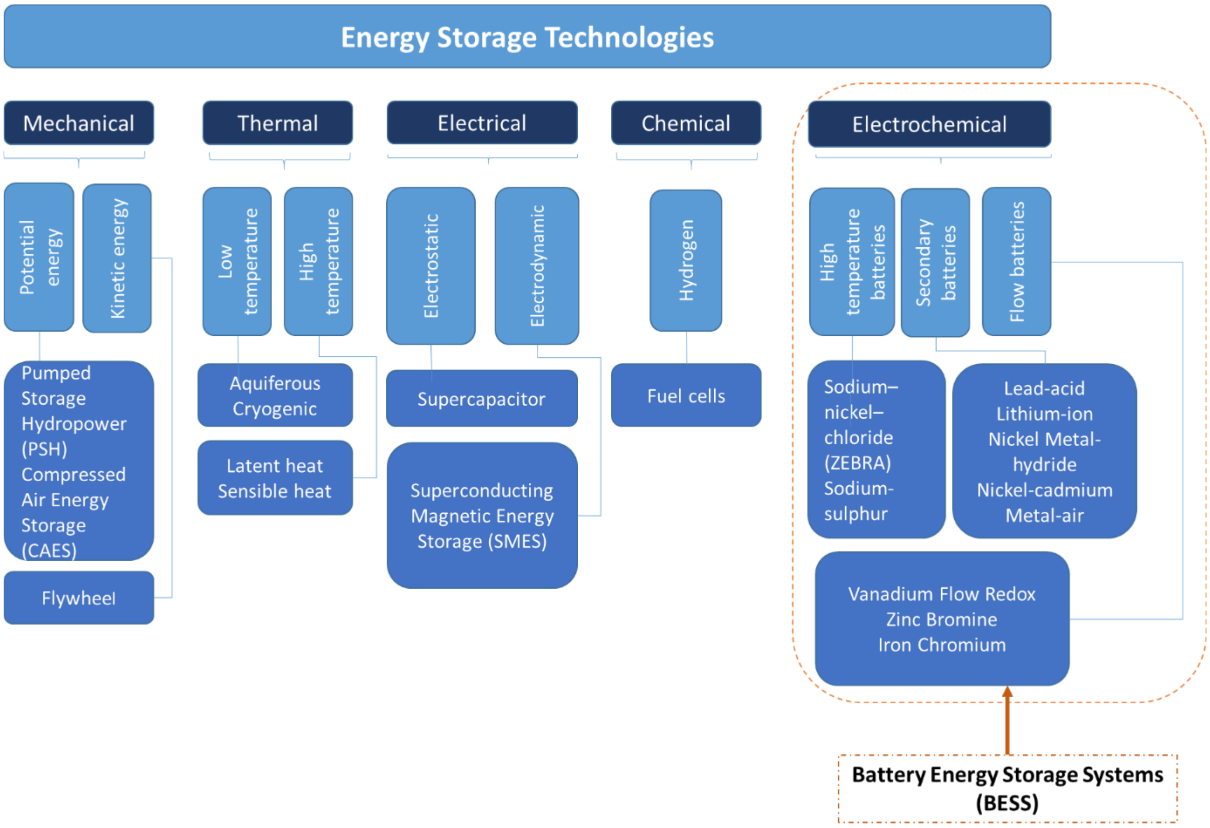
[6] Energy storage is measured both in terms of the maximum rated power capacity (for storage charge/discharge) measured in megawatts (MW) or in terms of energy storage capacity over time, measured in megawatt-hours (MWh).

depicted in Figure 1). The diverse technologies serve different purposes, as detailed in Table 1 (Dehler et al., 2017; Dehler et al, 2017).

Figure 1: Energy storage technologies



Source: Authors, Fourie, 2018.

PSH is the most widely used storage method, used in nearly 94% of all grid-storage applications[7] (Conca, 2019; Blakers et al., 2021). PSH is a proven and reliable technology providing benefits such as high efficiency and large storage capacity, and is relatively cost-effective in the medium to long term. Still, the development of hydropower faces significant limitations, notably extensive construction periods and adverse ecological consequences related to the disturbance of aquatic ecosystems, depletion of biodiversity and, in certain circumstances, the relocation of indigenous communities living in areas where PSH facilities are built (Figgener et al., 2020; EASE, 2021; Conca, 2019). Electrochemical, electrical and chemical technologies do appear to offer more uses to meet electrical power requirements for both small and utility-scale applications due to their flexibility in energy and power capacity (MW and MWh ratings) across most markets.

Next to PSH, BESS is the second most used form of energy storage technology. Battery storage systems do not need to be centralised like other forms of storage, such as PSH for example. There are many benefits that a decentralised energy storage system can provide, particularly for micro-grids used to power C&I sectors, and remote healthcare centres. This supports not only energy generation infrastructure but also allows for the more efficient use of transmission and distribution infrastructure, consequently reducing costs. As of the end of 2020, the total installed capacity of energy storage systems globally had reached 191GW, with BESS accounting for approximately 17GW (IEA, 2021). Although BESS makes up only a small proportion (8.9%) of the overall energy storage market, there is still considerable potential for further deployment of battery storage technologies.

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[7] PSH only works in places with the right topography and water resources.

This could yield significant benefits for the energy landscape in South Africa where, as in other countries, competitive and reliable renewable energy is a vital component of the energy strategy (Fourie, 2018). However, it is worth noting that like other energy storage technologies, BESS has raised social and environmental concerns. The use of certain minerals in battery components can lead to the production of substantial amounts of toxic pollutants in the environment by the BESS industry (Dehghani-Sanij et al., 2019).

The widespread demonstration, commercialisation and uptake of appropriate large-scale energy storage technologies has started to feature and grow in many parts of the world but has not yet received serious consideration for incorporation into the South African electrical energy landscape (Broughton and Van der Walt, 2022). A highly limited number of projects have thus far been implemented in South Africa. Fourie (2018) notes that the integration of ESS into South Africa's electricity system is lacking and that the country is stalling in adopting BESS for both aggregated BTM and FTM applications. This could possibly be attributed to insufficient knowledge of the technical ability and the economic feasibility or cost competitiveness of such technologies.

South Africa's ESS market can be segmented into mainly three storage technologies: PSH, molten salt thermal storage, and electrochemical technologies such as lead-acid batteries and LIBs, mainly used for stationary applications and for NEV applications, in the case of LIBs.

Box 1 illustrates the capacity and utilisation of PSH in South Africa, particularly in its contribution to addressing loadshedding.

Box 1: PSH in South Africa

According to Van Dongen and Bekker (2020), South Africa has limited PSH potential, with the expansion of PSH in the country mainly associated with the development of primary water supply infrastructure and inter-basin transfers. Small-scale hydropower schemes can, however, play a crucial role in providing energy access to remote areas in South Africa as standalone, isolated mini grids (Van Dijk et al., 2014). Internationally, small hydro storage is the best proven renewable energy technology, ideal for the electrification of remote communities (Loots et al., 2015).

The total installed PSH in South Africa is about 2 912MW, which includes the Ingula Pumped Storage Scheme, a 1 332MW hydro power scheme that is also the largest hydroelectric power plant in South Africa. Other PSH schemes are the Drakensberg Pumped Storage Facility (1 000MW), Palmiet Pumped Storage Scheme (400MW), and the Steenbras Hydro Station with capacity of 180MW (Van Dongen and 2020). PSH power stations have the advantage of a quick response time that enables them to respond swiftly to sudden changes in consumer demand and emergencies. Ingula and Drakensberg, are significantly large hydro power stations that have assisted in minimising loadshedding at a national level.

In addition despite not being dependent on hydroelectricity, the City of Cape Town depends on the 180MW Steenbras Hydro Pump Station, located in close proximity, to meet its hydroelectric power needs. The scheme operates four gas turbines to generate electricity (Le Roux, 2022). The hydro power station functions efficiently and can be used to offset high tariffs and periods of high electricity demand. According to O'Regan and Ngcuka (2022) in 2022, by using hydro power, the City of Cape Town was able to keep its customers from experiencing as much loadshedding.

PSH is a long duration storage technology that remains important in the electricity market. PSH allows energy to be stored for a prolonged period, on average ranging from several hours up to several days. Although relatively very small in size, PSH technology has the potential to effectively address the impacts of loadshedding both at a national and city level. This is because PSH serves as a backup power source that can be relied upon during times of grid instability.

2.3. Applications of energy storage technologies

As illustrated in Table 1, bulk energy and ancillary services are used in the electric system to ensure the provision of a combination of flexibility, stability and reliability of the power grid and in response to real-time variances in power supply and demand. Ancillary services often require a fast response time and short discharge duration, achieved through various applications including frequency regulation, voltage support and black start, i.e. the process of restoring power after a blackout (NREL, 2023). Battery technologies used for ancillary services[8] have no rotating parts and can ordinarily respond within fractions of a second. Their operating flexibility allows batteries to take over the role of both spinning and non-spinning reserve.[9]

Table 1: Energy storage applications in the electricity market

Application	Description
Bulk Energy Services	
Energy Arbitrage	Energy arbitrage is the time shifting of energy where energy is purchased from the grid at a low price (off-peak), and then sold back into the grid at a higher price (peak) (Zhang et al., 2021).
Load Levelling	Load levelling usually involves storing electricity during off-peak demand to then supplying the electricity during periods of high demand.
Peak Shaving	Peak shaving works by levelling out peaks in electricity use.
Back-Up Power	By operating as an uninterruptable power supply (UPS), ESS can supply (emergency) backup power in case of an electricity grid failure.
Integration	Enhances the efficiency of renewable energy through the integration of technologies such as PSH, CAES and batteries with renewable energy generation (wind and solar).
Seasonal Storage	The purpose of seasonal storage is storing renewable energy during one season (for example summer) and discharges the stored energy in another (for instance winter), depending on the load demand, specifically when solar PV is low.
Customer Energy Management	
Power Quality	Provision of high-power quality and grid improvement.
Ancillary Services	
Spinning Reserve	Spinning reserve is a set of ancillary services in which unused power capacity is activated to respond to system disruptions, such as a sudden loss of generation or a rapid change in demand.
Frequency Regulation	Maintains grid frequency to ensure the balance between electricity supply and demand at all times. For example, when supply exceeds demand, the electric grid frequency increases to balance the power system.
Black Start	Restoring power generation or parts of the power system after a total shutdown, without the need to use external electricity networks.
Voltage Support	Keeping the grid frequency and voltage within strict limits, thereby maintaining the stability of the grid.

Source: Authors based on various sources: Zhang et al., 2021; Bergland, 2017; EPRI, 2021, NREL, 2020.

Bulk energy services tend to focus on applications that require long discharge duration and high energy, with the end goal of supporting electricity generation and transmission, namely through load levelling and peak shaving, for example. With the advent of energy storage for use in FTM and BTM applications and the increased volatility in electricity prices, energy storage technologies may

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[8] Ancillary services refer to functions that help grid operators maintain a reliable electricity system.

[9] Spinning reserve is intended to help the system respond quickly to forced outages or other contingency events, while non-spinning reserves, while non-spinning reserve is the extra generating capacity that is not connected to the system but can be brought online after a short delay.

provide a business opportunity that allows energy and power utilities to take advantage of market prices and generate profits through arbitrage (Fourie, 2018). The strategy of energy arbitrage involves purchasing energy during off-peak periods when prices are low, storing it, and then selling it during peak demand when prices are high. This approach makes it cost-effective to provide load shifting energy services to the electricity market over time (Fourie, 2018). However, while energy arbitrage can be a cost-effective way to provide load shifting energy services to the electricity market, it is crucial to acknowledge that energy arbitrage can have adverse effects, leading to electricity shortages if is not managed properly. Therefore, it is important to carefully consider the potential risks and benefits before implementing an energy arbitrage strategy (Birge, et al., 2018).

Energy storage offers a wide range of services to the electricity market, including centralised, distributed, and decentralised energy systems. Energy storage systems can be used across different segments for numerous applications. Figure 2 illustrates that the energy storage system has the capability to serve the entire power grid, from generation, transmission, and distribution. Energy storage systems can provide 14 services or uses, to utilities, customers and to Independent System Operators/Regional Transmission Organisations (ISOs/RTOs), at four different levels including off grid, BTM and at distribution or transmission levels.

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Customer services: Customer services are deployed on customer premises (on-site); this could be for residential, commercial and industrial end-users seeking storage solutions. The primary driver for BTM customers is backup power, bill management or reduction, and providing opportunities for increased solar PV for self-consumption. BTM can be aggregated to provide a viable alternative for system-level energy storage (Fourie, 2018). BTM can also act as storage systems for NEV charging and marine systems to provide services to customers. BTM applications are, however, not integrated into the transmission and distribution power system, as shown in Figure 2.

Utility services: Utility-scale generation and storage, also considered FTM, is deployed off-site, and can be connected to the transmission and distribution power network, or to power generation assets (Connected Energy, 2022). Storage systems are also known to support remote power systems or micro-grids that operate or can operate independently from the national grid system (Fourie, 2018). Remote power systems are traditionally used for commodity extraction (mining, oil operations), physical islands, and electrification of remote villages/rural electrification with benefits including improved electricity access and enhanced productive use of electricity for households and businesses (Fourie, 2018; Eller and Gauntlett, 2017).

ISO/RTO[10]: ISO/RTOs are responsible for overseeing electricity transmission and operating wholesale markets across RTO regions[11] (American Public Power Association, 2022) (Greer, 2012). ISO/RTOs

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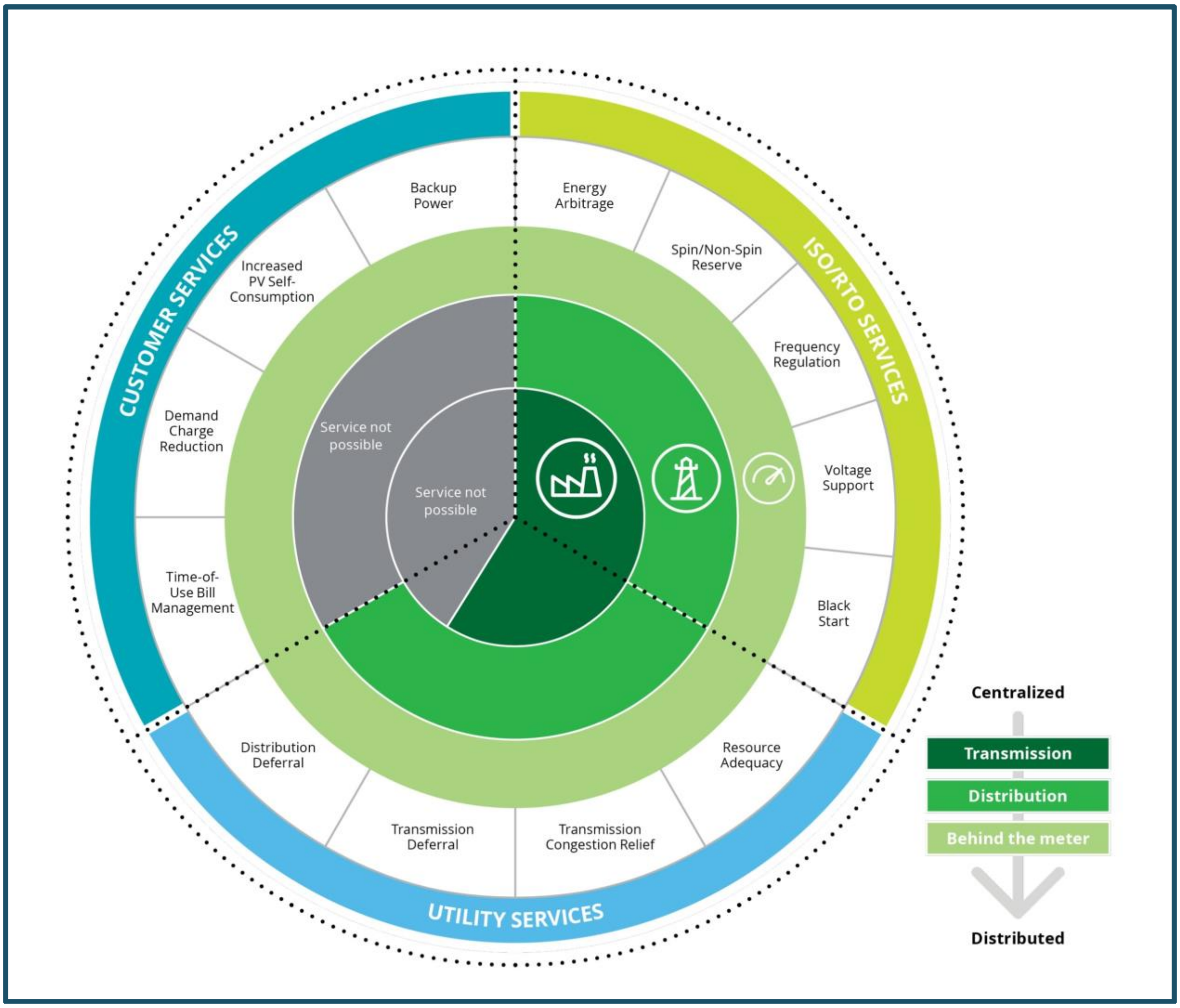
[10] RTOs were formed as some state regulators changed retail electricity markets rules to encourage or require traditional vertically integrated utilities to sell their generation facilities and give retail utility customers the ability to purchase power from other generators. As a result, private utilities were mandated to purchase their power on the wholesale market (American Public Power Association, 2022).

[11] There are 10 ISOs/RTOs in North America serving two-thirds of electricity consumers in the United States and more than 50% in Canada, which include Alberta Electric System Operator (an ISO), California Independent System Operator

operate the electric grid to ensure reliability by managing the flow of electricity through providing ancillary services. ISOs/RTOs perform the same functions as the vertically integrated utilities. Additionally, ISO/RTOs do not sell electricity to retail customers, instead power is purchased from generators, and resold to utility providers for distribution, who then resell it again, but to customers (Blumsack, n.d.). The inclusion of ISO/RTOs, despite not being relevant in the South African context, serves the purpose of illustrating the energy storage value chain in Figure 2.

Figure 2: Energy storage value chain illustrating BTM and FTM applications for various stakeholders



Source: Fitzgerald, et al., 2015.

The increased investment and popularity for energy storage technologies will benefit both BTM and FTM applications. Increasing energy prices, specifically electricity in this instance, and the commitment to greening the economy, has made being able to save on electricity and control energy usage a priority for electricity customers. Energy storage technologies are also subject to cost implications; their costs differ widely by use application as they are influenced by technological capabilities, application needs and various other cost and performance parameters (Fourie, 2018). The cost of an energy storage system, together with its technical characteristics, is an essential

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(California ISO), Electric Reliability Council of Texas (an ISO) and the Ontario's Independent Electricity System Operator (an ISO) to name a few (U.S. Energy Law: Electricity, n.d; Helman et al., 2009.

determining factor of its potential commercialisation, economic feasibility and competitiveness relative to alternative solutions. This will be explored further in the next section, which looks into the different types of battery storage technologies commercially available.

Energy storage systems offer various beneficial uses that can improve electricity generation, transmission and distribution by providing relief for stakeholders characterised by grid constraints. This results in bringing benefits to customers, ISOs/RTOs and utility companies seeking to control energy usage, reduce electricity costs, and improve energy flexibility, accessibility and security. Further, energy storage systems can enable additional revenue streams for utilities, deferred investments into new grid capacity and ultimately bring about technological progress, economic growth and environmental sustainability.

2.4. The growing market for stationary energy storage: Opportunities and challenges

Although transport applications should remain the key demand driver for energy storage going forward, Broughton and Van der Walt (2022) note that stationary energy storage is expected to lead a huge market for energy storage systems. According to Europe (2020) and Precedence Research (2020), stationary storage is expected to grow to US$224billion in revenue by 2030, marking a significant increase from its US$25billion revenue in 2020 (see Figure 3). The particular focus of this study is on battery storage technologies designed for FTM applications, with some attention given to BTM applications, in the case of micro-grids and mini-grids.[12]

Figure 3: Stationery energy storage market size, 2020-2030 (US$ billion)

Source: Precedence Research, 2020.

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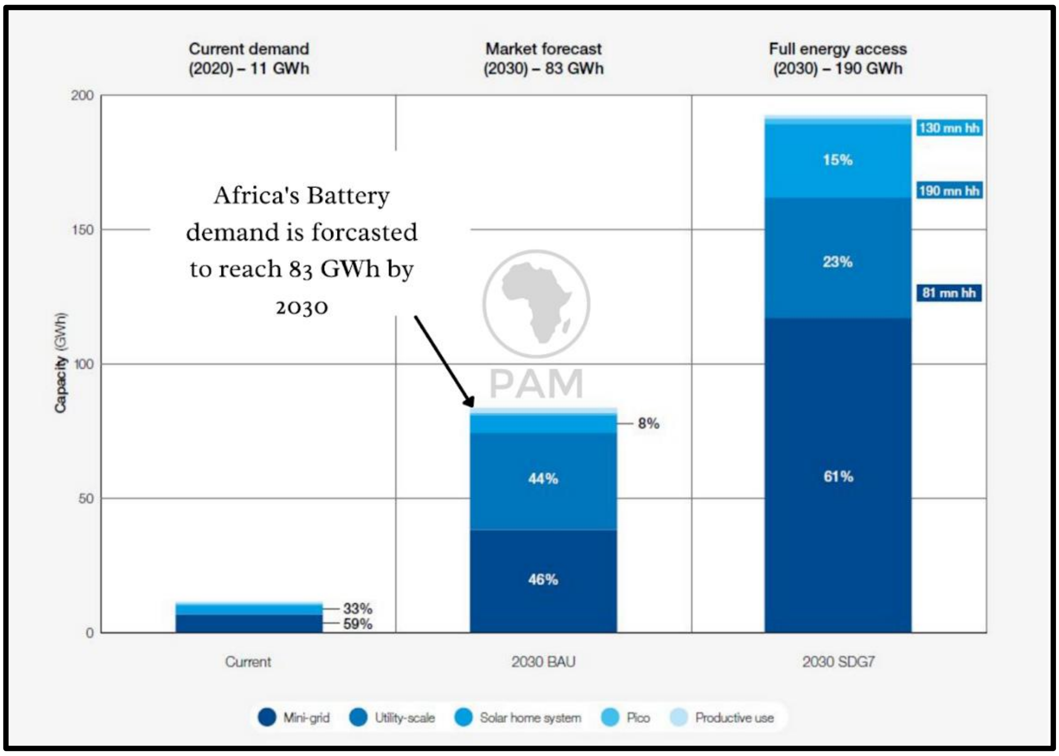
[12] A mini-grid is a small-scale electricity generation system linked to a distribution network, supplying power to a local group of customers independently of the national grid. Mini-grids can range from a few kilowatts up to 10 megawatts. Smaller grids are called "micro-grids", with generation capacity of 1-10kW (AfDB, 2017).

2.3.1. Stationary battery capacity in Africa: Growth potential and market forecasts

South Africa and Africa more generally present opportunities for energy storage systems, mainly in battery technology. The IFC forecasts that South Africa will be the largest market for battery storage in the region by 2030 (IFC, 2017). In the region, South Africa holds a prominent position as a pioneer in the adoption of renewable energy and energy storage. Recognising the nation's capacity to develop battery value chains, there is potential for South Africa to extend these chains to encompass additional countries rich in essential minerals and capabilities. Furthermore, the country could also serve as a battery supplier to other parts of the continent.

Market forecasts by the WEF shown in Figure 4 illustrate that demand for batteries in Africa will reach 83GWh by 2030. Stationary battery capacity in Africa could grow by 22% annually to 2030, due to demand from grid applications where mini-grids alone could represent 46% of the 2030 market, followed by utility-scale applications which could account for 40% of battery demand (WEF, 2021). Box 2 demonstrates the prospective need for BESS in Africa by showcasing ongoing upcoming projects involving battery storage across the continent. Vanadium batteries could have a significant impact on the utility market in Africa.

Figure 4: Demand for battery energy storage in Africa



Africa's Battery demand is forcasted to reach 83 GWh by 2030

Source: Agese, 2022.

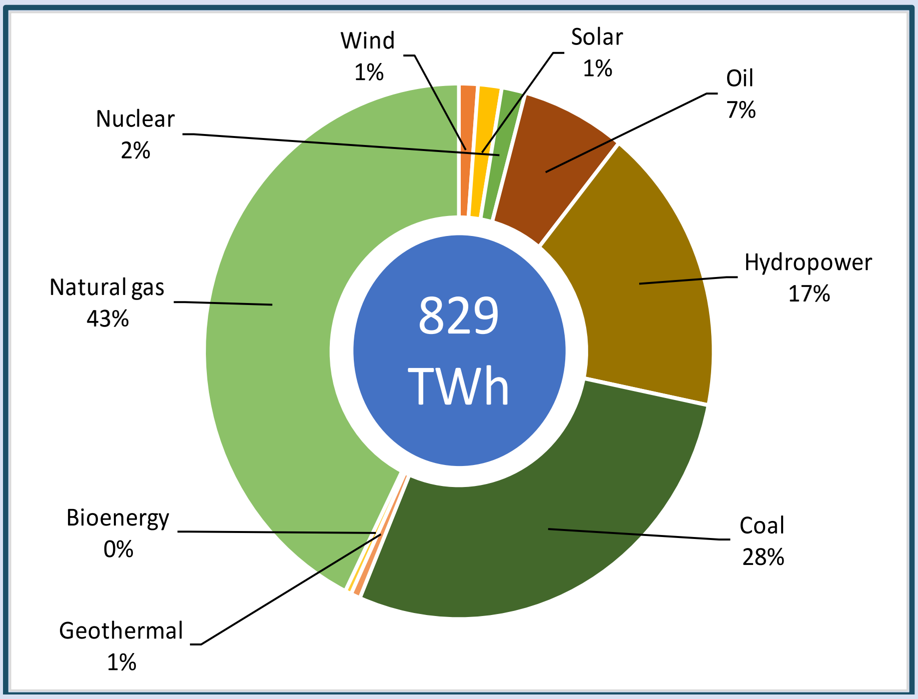
Box 2: Demand for BESS in Africa

The demand for batteries with a long lifespan and efficiency has increased in Africa due to the energy crisis and unreliable energy supply challenges. The continent mainly produces electricity from non-renewable sources, but renewable energy has the potential to meet more than 80% of energy demand. Apart from hydropower, renewable energy technologies like solar, wind, geothermal, and bioenergy play a minimal role in Africa's energy mix (see Figure 5).

Africa contributes to less than 3% of the global installed capacity for electricity generation from renewable energy technologies (IRENA, 2022). However, has been a notable increase in renewable energy deployment has increased notable in recent years, with a 7% growth in renewables-based generation capacity across the continent between 2010 and 2020 (IRENA, 2022). The recent growth has been primarily driven by large-scale projects in individual countries, particularly in utility-scale hydropower, solar and wind. Moreover, the implementation of storage technologies has the potential to improve this progress (ESI Africa, 2021). In terms of regional breakdown, Southern Africa led in total renewable generation capacity in 2020 with 17GW installed capacity, followed by North Africa (12.6 GW) (IRENA, 2022).

Poor electrification rates across the continent present opportunities for BESS to offset the lack of widespread distribution, and the shift to renewable energy makes BESS more viable for electric grid development and stabilisation.

Figure 5: Electricity generation in Africa, by energy source, 2019



Source: IRENA, 2022.

The interest in storage in Africa is on the rise as more countries pursue and extend renewable energy strategies as well as expand on-grid and off-grid solutions. Although battery deployment in Africa is small and underdeveloped, African countries exploring battery storage is a signal of a positive understanding of the opportunities that this new industry brings and the potential to position the region as a player in clean energy generation and storage. African countries are also investing in other storage technologies, including hydropower, thermal storage and hydrogen.

According to the World Bank report on BESS in Africa, South Africa has the opportunity to assume a significant role in the global battery value chain. By 2030, South Africa could see a domestic demand of 10-15GWh for battery energy storage (Customized Energy Solutions, 2023). In Southern Africa, the battery market demand reached 170MWh in 2020, driven mainly by the need for backup power applications in sectors such as telecommunications, residential systems and micro-grids. It is projected that the battery market in the region could grow to 1.5GWh by 2030, in a best-case scenario, with the demand for FTM applications expected to accelerate from 2027 (Customized Energy Solutions, 2023).

The World Bank and other financial institutions have established projects to address electrification challenges in Africa. Burkina Faso, Gambia, Senegal, Mali, and Zanzibar are among the countries that present opportunities for the adoption of BESS, especially for micro-grids as well as in remote areas. In Mali, private sector investors have invested in battery storage, particularly in the mining sector. For instance, Wärtsilä Energy deployed a hybrid project involving 30MW solar PV plus a 17MW/15.4MWh LIB at the Fekola gold mine (Smart Energy International, 2022). The LIB technology offers the mine a range of applications, such as reserve capacity, renewable energy integration, and time shift, among others (Carmen, 2021). Similarly, Syama Gold Mining is developing a hybrid project consisting of a 40MW thermal power plant and a 10MW LIB storage system, with plans for an additional 20MW of solar power (Carmen, 2021). The primary use of the project is spinning reserve, which both LIBs and VRFBs can provide.

3. DRIVING FACTORS FOR STATIONARY BATTERY STORAGE MARKET

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

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

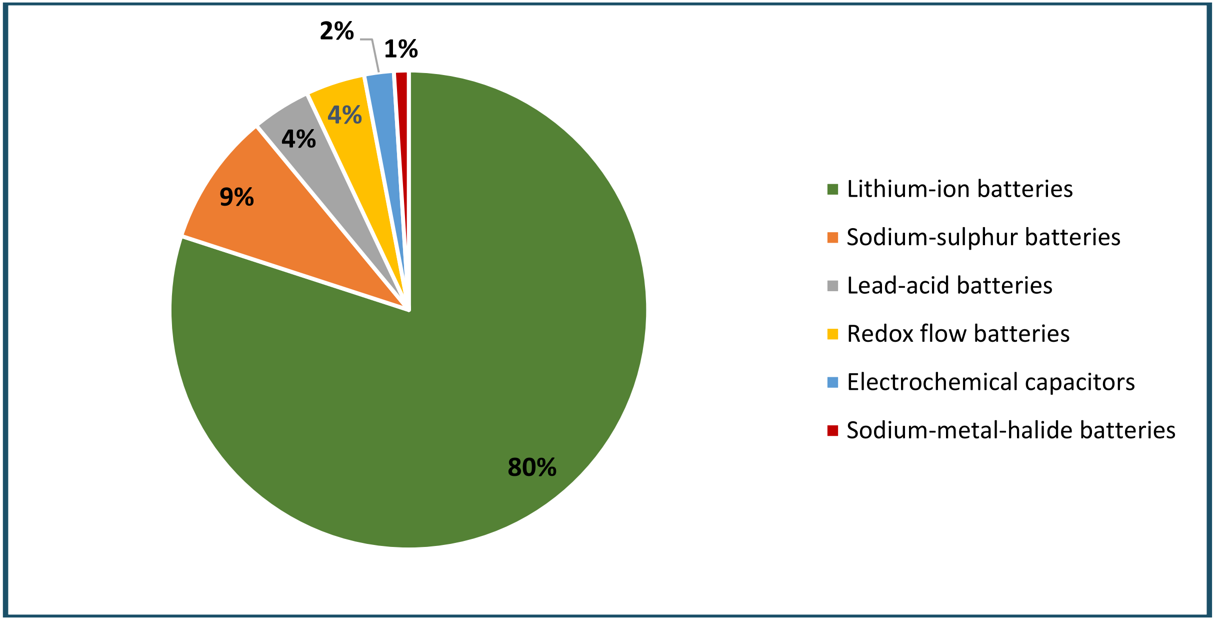
3.1. Evaluating the potential of VRFBs in competing with LIBs in the storage market for large-scale projects

Currently no single technology is better than another across all grid applications. However, of the energy technologies outlined in Figure 1, electric, chemical and electrochemical batteries have the most potential to make a significant contribution to the electricity market and the promotion of accessible clean energy. This study focuses on three distinct categories of electrochemical batteries: high-temperature batteries, secondary batteries and flow batteries, as illustrated in Figure 1. While other types of batteries, such as electrochemical supercapacitors, molten-salt batteries and hydrogen fuel cells, also play a role in battery storage technologies, they are beyond the scope of this research.

Battery technologies can effectively complement renewable power generation for BTM and FTM applications, particularly at the utility level. By facilitating more efficient use of renewable energy, battery storage systems offer considerable value to the grid. They can help mitigate the challenges associated with variable generation, which often results in significant fluctuations in electricity supply. Battery energy storage can also optimise renewable energy production by storing energy during low demand periods and discharging it when demand for power is high. In addition, battery technologies can alleviate pressure on the main grid and enhance the resilience of the power grid, especially for critical operations such as hospitals, mining, telecommunications and manufacturing plants. Given the benefits of battery storage, it is essential for utilities, C&I and other customers to explore how these technologies can improve operational efficiency, ensure electricity supply, and lower costs. With a proven track record of delivering numerous benefits, battery storage is a promising technology for the future of energy storage. Overall, battery energy storage technologies are critical in providing energy security and reducing carbon emissions in energy generation.

In terms of the number of projects, energy capacity, and electric power capacity, the most commonly deployed electrochemical technologies to date have been LIBs, flow batteries, sodium sulphur batteries, and lead-acid battery technologies. Figure 6 shows that, in 2018, the market for utility-scale projects was dominated by LIBs, which accounted for around 80% of installed power output. Sodium sulphur batteries made up 9% of all BESS installations, with lead-acid batteries and flow batteries accounting for 4% each.

Figure 6: The technological mix of installed battery storage technologies for long-term storage systems – 2019



Source: Girschik et al., 2021.

3.1.1. A comparative analysis of electrochemical batteries for stationary storage application

Of the three different types of electrochemical battery technologies, sodium-sulphur batteries, LIBs and VRFBs are selected for the purpose of this comparative analysis. According to Fourie (2018), these technologies offer excellent technical capabilities, are technologically mature, cost-competitive (with potential for further cost reductions) and deliver high performance for FTM and BTM applications, such as integrating renewable energy, providing backup power, peak shaving, among others. Furthermore, these technologies can be scaled to provide higher energy and/or power capacity.

Secondary rechargeable batteries, with examples including lead-acid and lithium-ion batteries, store electrical energy from an external electrical source in the battery during charge, and then supplies the energy to an external load during discharge (Buckley, et al., 2019). High temperature batteries typically contain sodium and are batteries that can provide a long cycle life, high efficiency and high-power density, at a relatively low cost (Buckley, et al., 2019). Because these batteries require high temperatures to operate (>300 degrees), their use is limited to large, stationary applications, such as distribution grid support (Gao, 2015). According to Buckley et al (2019), flow batteries are similar to a conventional rechargeable battery in that the battery system can be repeatedly charged and discharged. However, in the case of VRFBs, the flow battery technology relies on a reversible electrochemical reduction-oxidation (redox) reaction between two vanadium electrolytes in different valence states (Haoyang, et al., 2020). Several types of flow batteries are available in the market at present, while others are still in the developmental stage. Examples of commercially available flow batteries are the all-vanadium flow battery, zinc-bromine flow battery, and all-iron flow battery (Buckley et al., 2019; Fourie, 2018).

The comparative analysis assesses three types of batteries, namely sodium sulphur battery, LIB and VRFB, by examining their performance parameters, which include round-trip efficiency (RTE)[13], safety, life cycle, depth-of-discharge (DoD), energy, and power densities. In addition, the analysis provides an overview of the capabilities, operation, advantages, disadvantages, developments, and practical applications of these battery technologies. Although lead-acid batteries are commonly used in stationary applications, this study uses them as a benchmark against the other three technologies, but they are not part of the comparative analysis.

3.2. Evaluating battery technologies for grid applications

While lead-acid batteries are widely used in energy storage because of their low cost, Table 2 shows that the lead-acid battery has low efficiency, poor discharge and a short life cycle of between 3-5 years (BloombergNEF, 2019). In addition, lead contains high levels of toxicity and causes considerable harm and damage to the environment (BloombergNEF, 2019). Lead-acid batteries hold a relatively large share in the expanding stationary market but fall behind LIBs. Compared to lead-acid batteries, LIBs, VRFBs and sodium sulphur batteries offer superior efficiency and reliability, among other qualities.

LIBs currently dominate the energy storage market, specifically the lithium iron phosphate (LiFePO4) battery chemistry, mostly because of its low production costs, evaluated effective stability and safety (IndustryARC, 2021). LIBs can be considered as fully mature technology in the case of portable or mobile applications because of their lightweight design, making them ideal for consumer electronics and NEVs (Zheng et al., 2018; Duan et al., 2020; Riaz et al., 2021). LIBs have the highest power storage efficiency, with a charging efficiency of nearly 95% (BloombergNEF, 2019).

VRFBs have lower efficiency and density rates than LIBs, but they are considered among the safest battery technologies available as they do not experience thermal runaway (BloombergNEF, 2019).

Sodium sulphur batteries have favourable technical characteristics such as high roundtrip efficiency, high power density and very low discharge, with benefits of a long-life cycle, relative to LIBs. However, there are also safety concerns associated with these batteries due to their high operating temperatures and the lack of manufacturer competition,[14] which raises costs and has limited commercialisation of the battery technology.

Lithium-ion and lead-acid batteries are appropriate for applications requiring short discharge durations, while VRFB and sodium sulphur batteries are more appropriate for applications requiring longer discharge durations. LIBs and sodium sulphur batteries are considered relatively developed technologies in stationary storage while VRFBs would be considered the least mature technology of the four (Chen et al., 2021).

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[13] Round-trip efficiency represents the proportion of electricity initially stored then later recovered. A higher round-trip efficiency the less energy is lost during the storage process.

[14] Hittinger et al. (2012:437) and Poullikkas (2013:781) note that utility-scale commercially available sodium sulphur batteries are limited to one manufacturer, namely NGK Insulators from Japan. Increased technology deployment and the expiry of NGK Insulators' patent on NaS batteries could provide room for increased competition and commercial production, innovation and accelerated cost reductions for these batteries (Suberu et al., 2014:504; World Energy Council, 2016:37).

Table 2: Technical metrics overview of battery technologies

	CONVENTIONAL LEAD-ACID BATTERY	SODIUM SULPHUR BATTERY	LITHIUM-ION BATTERY (IRON PHOSPHATE)	FLOW BATTERY (VANADIUM)
Power density	150 W/kg	150 W/kg	245-430 W/kg	50 W/kg
Energy density	25-35 Wh/kg	110 Wh/kg	100-265 Wh/kg	10-30 Wh/kg
Efficiency	45-85%	75-90%	85-95%	65-85%
Depth of Discharge (DoD)	50%	80%	85-95%	100%
Self-discharge	0.1-0.3%	20%	0.1-5%	Small
Voltage, V	2.1	2.7	3.6	1.2-1.6
Thermal runway	Yes	Yes	Yes	No
Lifespan	3-5 years	5-15 years	5-10 years	20-25 years
Cycle life[15]	1000	3500	2000-4000	>10000
Advantages	Mature and low cost technology Low self-discharge Modular scalability	High energy density and high efficiency High DoD Sodium is a non-toxic, low cost material Able to provide power for six hours or more Modular scalability	High energy density High efficiency Low self-discharge	Long duration technology Long life cycle Safe No degradation High DoD Design flexibility that allows independent sizing of power and energy Lack of degradation in performance over time Electrolyte is reusable and recyclable
Disadvantages	Low energy density Low DoD High maintenance Improper disposal leads to environmental risk	Safety is a big concern due to high temperature	Thermal runway Relatively short-life cycle compared to sulphur and flow batteries Transport restrictions Raw materials	High price of vanadium High capital cost VRFB supply chain is still fairly immature Low power and energy

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[15] Cycle life of a battery can be affected by factors such as aging, usage patterns, and environmental conditions.

	CONVENTIONAL LEAD-ACID BATTERY	SODIUM SULPHUR BATTERY	LITHIUM-ION BATTERY (IRON PHOSPHATE)	FLOW BATTERY (VANADIUM)
			subject to supply availability and socio-environmental challenges Higher profit margins for NEVs could potentially side line grid systems in the LIB supply chain	density compared to LIB
Application	UPS, black start and frequency regulation	Energy shifting, peak shaving, frequency regulation and emergency back-up supply	UPS, load levelling, frequency regulation, voltage support, black start and energy arbitrage	Load levelling, UPS, back-up power supply and NEV charging

Source: BloombergNEF, 2019; Oldacre, 2018.

LIBs, sodium sulphur batteries and VRFBs are all important battery technologies in the storage market as power generation evolves and the technologies can compete side-by-side – and are highly complementary in providing clean and sustainable solutions towards decarbonisation. The raw materials used in both VRFBs and LIBs involve the use of potentially toxic substances, with LIBs also being susceptible to unethical sourcing practices.[16] However, both battery technologies can contribute to circularity and sustainability by supporting the recycling and reuse of their components. Vanadium batteries can recycle and reuse the vanadium electrolyte, while key materials used in LIBs can also be recycled and recovered (but at present, the recycling of LIBs is significantly expensive compared to VRFBs or lead acid). In addition, sodium sulphur batteries are often considered sustainable due to the non-toxic and readily available nature of sodium, which can also be recycled.

A detailed overview of the three technologies and their roles in the grid market, along with examples of their deployments, is provided in the following subsections. Their respective advantages and disadvantages are also analysed.

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[16] There is a strong link between mining of lithium and cobalt and violations of environmental practices and human rights. Approximately 60% of the world's supply of LIBs (containing cobalt) comes from the Democratic Republic of the Congo, where numerous unregulated mines employ child labour. Furthermore, the mining of lithium has resulted in water loss, loss of biodiversity, increased salinity of rivers, soil contamination, and toxic waste.

3.2.1. Lithium-ion battery technology

LIBs retain a range of advantages, including high power and energy densities and high cell voltage. However, they also have a limited life cycle and are sensitive to thermal runaway (Zheng et al., 2018). Even though LIBs are commonly used for mobility applications, LIBs are well-suited for grid applications due to their high RTE, high-energy density and low self-discharge rates. Moreover, as LIBs are widely adopted, they benefit from economies of scale. Therefore, LIBs are expected to remain the dominant electrochemical technology in the short term due to their good overall performance and widespread deployment in several sectors. Major producers and OEMs of LIBs include Panasonic, LG Chem, Samsung, Contemporary Amperex Technology Co. Ltd. and BYD Company.

In grid storage, LIBs can be used for various applications, such as load levelling, peak shaving, voltage support, renewable energy integration and black start. They are also gaining popularity in micro-grid and residential applications because they are relatively cost-competitive when compared to lead-acid batteries and offer better efficiency and performance in these market segments.

LIBs have been deployed in various parts of the world for different applications. For instance, BYD completed a hybrid solar PV installation in 2012 that used a 250kW/500kWh iron-phosphate battery at the Qatar Science and Technology Park. The battery system provided electricity for both on and off-grid applications, including voltage/reactive power support, frequency regulation and black start capabilities (IRENA, 2020). Another example is the installation of a 32MW/8MWh LIB by AES Corporation in the US to support a 98MW wind generation plant. The LIB system enabled Laurel Mountain to provide frequency regulation and peak shaving services to the power grid (Chen et al., 2022; IRENA, 2021). The coupling of renewable energy sources with storage, such as LIBs paired with solar and wind, can increase the value of the system. It allows excess energy from wind or solar to be stored for future use, as demonstrated by the two examples of LIB deployments described above.

3.2.2. Sodium sulphur battery technology

Although sodium sulphur batteries have potential for market share gains, their deployment is currently limited to a few countries such as Japan, Germany and the United States (US), mainly due to their advanced technical performance parameters. According to Fourie (2018), commercially available utility-scale sodium sulphur batteries are produced by only one manufacturer, which is NGK Insulators from Japan. As technology deployment increases and NGK Insulators' patent on sodium sulphur batteries expires, there is an opportunity for heightened competition, commercial production, innovation, and accelerated cost reductions for these batteries (Fourie, 2018).

Sodium sulphur batteries retain high roundtrip efficiencies, fast response time and are suitable for utility-scale applications ranging between 10MW and 100MW or more. These qualities make this battery technology ideal for renewable energy integration, time shifting, peak shaving, grid frequency control, transmission and distribution, ancillary services and emergency back-up (Fourie, 2018). At least a total of 316MW sodium sulphur battery capacity has been installed globally (Chen, et al., 2022). However, the safety concerns associated with thermal runway, explosiveness and energy loss caused by high temperature, greatly inhibit their widespread adoption (Xu et al., 2018). In 2018, the largest sodium sulphur system installation with a capacity of 200kW/1 200kWh was commissioned. The battery system is connected to a 51MW wind farm in Rokkasho, Japan, and used for renewable energy integration (IRENA, 2021). The storage installation enhances wind integration by storing electricity produced at night during periods of low demand. In addition to renewable energy integration, the batteries can be used for ancillary services such as frequency response to maintain system stability (Kempener and Borden, 2015).

Although sodium sulphur batteries may not be a feasible energy storage option for widespread implementation in the South African market due to their limited global presence and technical complexities, Eskom identified them as one of the three potential technologies suitable for use at the Melkhout BESS site in the Eastern Cape in 2019 (SRK Consulting, 2019).

3.2.3. Vanadium redox flow battery technology

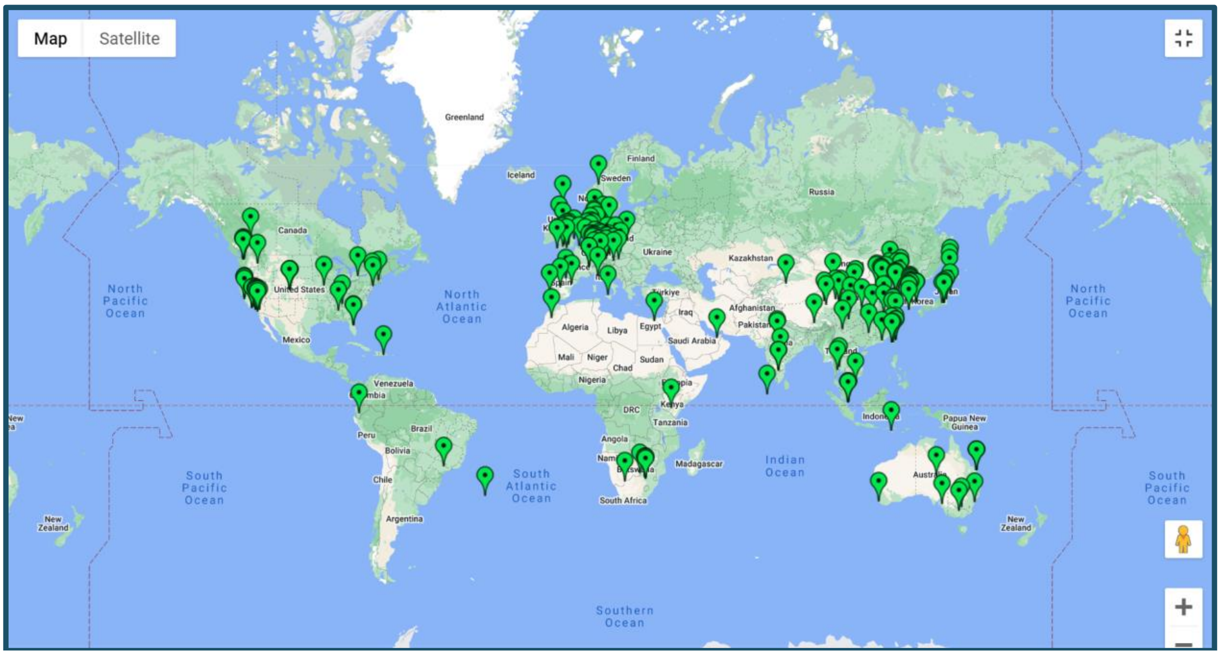
VRFBs stand out for their safety features, scalability, flexibility, and extended lifespan. They offer a unique separation of power output and energy capacity, granting greater design flexibility to tailor power and energy increases to specific consumer demands. Furthermore, this flexibility leads to 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 period in terms of TCO, VRFBs are more economical than LIBs. LIBs and lead-acid batteries do not have this flexibility in design, since both technologies are assembled using modules with a rated storage capacity and power output.

In power network operations, VRFBs can function as effective operating reserves, capable of restoring grid frequency after disturbances in the grid. They are also ideal for energy shifting, load levelling, peaking shaving, and renewable energy integration. Unlike other types of batteries, VRFBs have proven successful for bulk storage applications of up to 20 hours of continuous discharge. While lithium-ion and lead-acid batteries can also perform similar functions, they are better suited for events that last only a few minutes and/or hours (Fourie, 2018).

VRFB manufacturing is dominated by major players such as H2 Inc., VRB Energy, E22 Energy Storage Solutions, Invinity Energy Systems, 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).

Based on the Vanitec database, there are currently more than 290 VRFB projects globally (Figure 7). 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 Eskom, Thaba Eco Hotel, and various telecom locations in Gaborone and Johannesburg. China leads VRFB installations with a notable 42 operational VRFB projects.

Figure 7. Operational VRFB projects globally



Source: Gunjan et al., 2022.

The following are examples of VRFB projects:

- VRB Energy formed a partnership with the China Electric Power Research Institute in 2011 to commission a VRFB system. VRB Energy delivered a 500kW/1MWh VRFB to Wind Power Research and Testing Centre, a pivotal component in integrating the centre's 78MW wind and 640kW solar PV (IRENA, 2021).
- VRFB OEM Sumitomo has undertaken several VRFB initiatives. These include one of the world's largest operational VRFB systems located in Hokkaido, Japan, with a capacity of 15MW/60MWh. Sumitomo has also collaborated with Obayashi Corporation on a project with a capacity of 500kW/30 000kWh. In addition, Sumitomo has installed a 3000kW/800kWh battery at the Sumitomo Densetsu Office in Osaka, Japan.
- CellCube/Enerox installed a 2MW/8MWh VRFB in Illinois for a BTM industrial micro-grid application storing solar generated energy overnight and providing protection from variable electricity supply. Enerox/Cellcube has deployed more than 130 VRFB globally totalling 9.3MW/42.9MWh.
- Spanish storage company E22, in collaboration with gas and power supplier Naturgy, installed a VRFB for Naturgy in its Vega I and II wind farm in Zamora, Spain.
- StorEn Technologies installed a 5kW/30kWh VRFB at the Queensland University of Technology for application in a renewable hydrogen plant.

VRFBs have a wide range of applications in utility services, mini-grids and NEV charging, offering sustainable peak load shaving and grid services, supporting renewable energy integration and serving as backup power systems. In addition, the installation can provide load levelling and voltage support services (IRENA, 2021). These applications highlight VRFBs' versatility and potential in sustainable energy systems (Peycheva, 2020; Siecap, n.d.).

Summary

This analysis examined three different battery storage technologies in the energy sector. The analysis and table comparing various battery technologies indicate that VRFBs are an efficient choice for large-scale projects as they can stabilise power networks for several hours, balancing high-demand periods with times of surplus generation. VRFBs have a singular advantage as they can recharge while simultaneously providing power, which makes them ideal for mini-grid projects and remote areas where energy generation and consumption may be unpredictable. In contrast, LIBs are better suited for managing short-term events that may disrupt grid voltage and frequency in grid applications, and their lightweight design makes them well-suited for mobility purposes. It is worth noting that sodium sulphur batteries have geographical limitations to date, but they also have potential in the storage market, particularly for long-duration storage.

Given South Africa’s energy crisis and the need for energy storage to complement the adoption of renewable energy sources, both lithium- and vanadium-based batteries have the potential to support the country’s efforts. However, for large-scale projects that require long-duration storage, vanadium batteries can offer significant benefits to the South African market, particularly for Eskom and the mining industry. An advantage for South Africa is that it is a major producer of vanadium and, with the right support, can develop a local battery industry that uses domestically sourced vanadium. Nonetheless, the high capital cost of vanadium batteries, influenced by both supply and demand factors, is a significant disadvantage to their widespread adoption. Before determining the cost competitiveness of vanadium batteries relative to alternative technologies, it is necessary to establish whether there is a viable market for vanadium batteries in South Africa, as market conditions will play a crucial role in the success of localisation efforts.

4. VRFBS AND MARKET DEMAND: A KEY DRIVER FOR ADOPTION

It is essential to establish local demand for VRFBs, especially given South Africa's potential for localisation. Local demand can provide a stable customer base for local battery suppliers and manufacturers, promoting local production and investment. This, in turn, can create jobs and contribute to local economic development. Collaboration between battery suppliers, manufacturers and local research institutions, both local and internationally can foster innovation and product development. Building a resilient value chain can be achieved by reducing reliance on imported products, which can be susceptible to supply chain disruptions or geopolitical risks. Recent events have shown that global supply chains are vulnerable to disruptions, and countries that depend heavily on imports can be particularly susceptible to these risks. Local demand also contributes to environmental sustainability by reducing the carbon footprint associated with long-distance transportation of goods. Overall, a sustainable and thriving local battery industry is crucial for the widespread adoption of renewable energy and achieving a low-carbon economy.

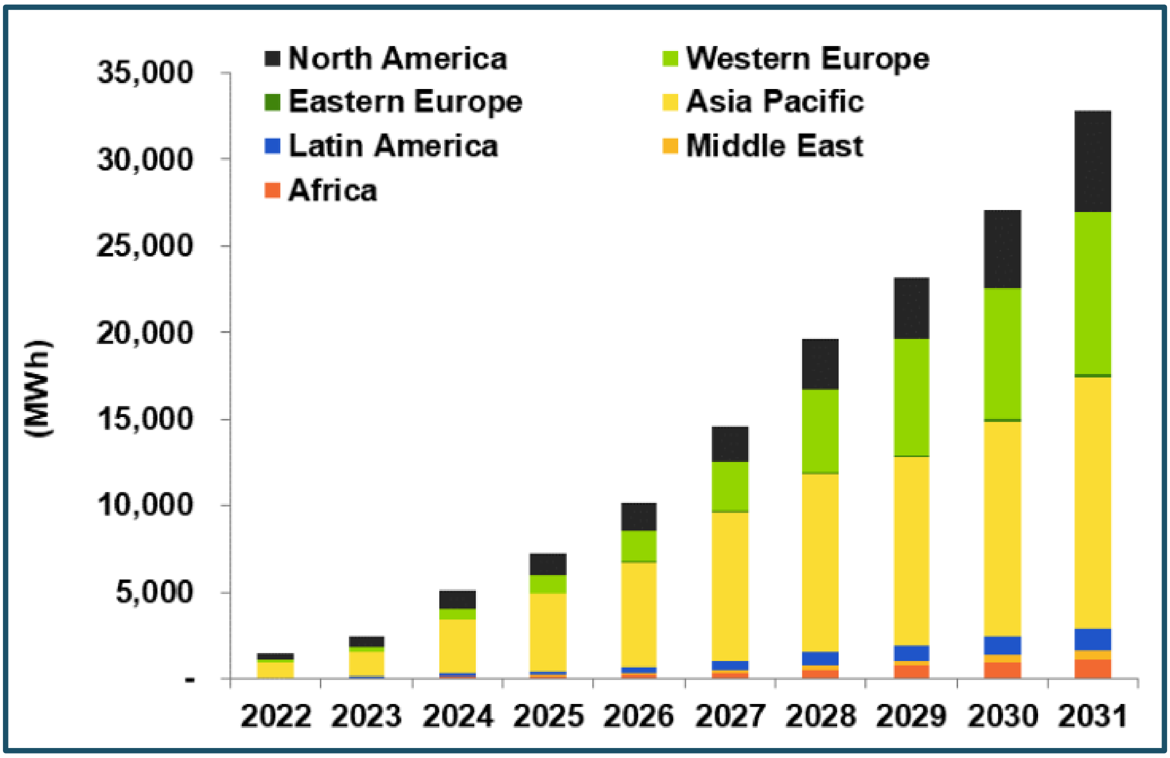
As previously highlighted, LIBs will primarily be used for short-term storage in high-power applications with storage times ranging from one to four hours, although there may be potential for expansion into other applications in the future.

Redox flow batteries (RFBs), including vanadium batteries, are experiencing increased market value, installed capacity, and cumulative deployment due to the growing adoption of renewable energy and the need for grid stabilisation. Despite the high manufacturing costs of VRFBs, IDTechEx (2021) predicts that they will become the market leaders in the RFB sector in the years to come, given their significant commercialisation. The Asia Pacific region, particularly China, Japan and South Korea, is the largest market for VRFBs, with Europe and the US following closely behind, while the Middle East, Australia and Africa are also anticipated to contribute to the growing demand for VRFBs.

As battery prices continue to fall, flow batteries are becoming more prevalent and, as a result, they are anticipated to follow a similar trend of increased market demand and market value as seen with the growth trajectory of LIBs. Flow batteries are currently in a similar position on the technological demand curve as LIBs were two decades ago. While the technology has been demonstrated to be effective, it is expected that installed capacity for flow batteries will rise over time. This means that with each doubling of the installed cumulative capacity, the price of VRFBs could decline.

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. Figure 8 suggests that the cumulative installed capacity and number of projects for VRFBs is projected to rise. Asia Pacific, Western Europe and North America are leaders for VRFB deployments globally. By 2021, it is estimated that 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. 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).

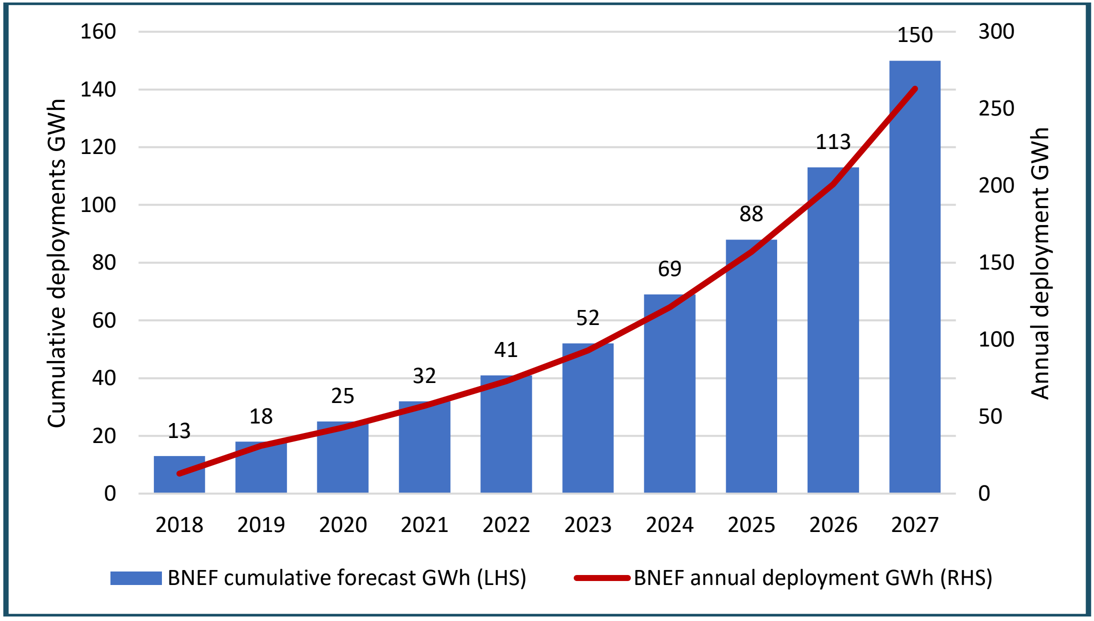
Figure 8: Annual installed VRFB utility-scale and commercial and industrial battery deployment energy capacity by region=: 2022-2031



Source: Gunjan, et al., 2022 (Commissioned by Vanitec).

Figure 9 shows the global count of installed VRFB projects will reach about 150 deployments by 2027.

Figure 9: Global cumulative and annual storage deployment in GWh 2018-2027



Source: Bushveld Minerals, 2018.

According to Harris (2022), harnessing the most efficient and affordable battery technologies to store and distribute energy generated from renewable energy sources presents numerous benefits for South Africa. The advantages of batteries for grid markets outlined in previous sections, will propel demand for batteries in the South African market. Emerging market demand for battery technologies in South Africa.

There is an emerging market demand for battery technologies in South Africa due to the country's energy crisis, and it is likely that the demand for BESS will grow stronger in future. Looking ahead, there are several signs of strong local demand in the country, including but not limited to the state's procurement programmes and the growing interest in own power generation. Currently, Eskom, residential households and the private sector drive the market for battery storage systems in South Africa. 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 the region to implement battery storage technologies as a means to improve energy access in the region. South Africa's 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 supported/aligned to the IRP2019 framework, such as Eskom's BESS programme, REIPPPP, RMIPPPP, the Repowering and Repurposing programme 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), seek to procure new energy technologies, including liquid and natural gas and electrochemical battery technologies, with the aim "to enhance power supply and energy security in an efficient and sustainable manner" (World Bank, 2010). All four procurement programmes outlined above 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 that are evaluated based 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.

4.1.1. Eskom's battery energy storage programme

Eskom's BESS programme is implemented in two phases, with the first phase involving the installation of 199MW/832MWh of BESS power at multiple sites near the existing grid to support the integration of renewable energy into the national grid. The initial phase aimed to achieve a distributed battery storage capacity of 200/MW800MWh by December 2020 (Eskom and African Development Bank, 2018; Chutel, 2018; Scotto and Fontana, 2019). However, the deadlines were shifted to June 2023, and there is a potential further delay until December 2023. Phase 1 sites include (Creamer, 2022b):

- 80MW/320MWh at Skaapvlei, 20MW/100MWh at Hex, 9.5MW/45MWh at Paleisheuwel, in addition to 5MW/30MWh at Graafwater, all located in the Western Cape;
- 35MW/140MWh at Melkhout, situated in the Eastern Cape;
- 40MW/160MWh at Pongola and 8MW at Elandskop, in KwaZulu-Natal; and
- 1.54MW/6.16 in addition to 2.04 MW of solar PV at Rietfontein, in the Northern Cape.

In the first phase of Eskom's BESS programme, a minimum 20% local content requirement is expected, which involves subcontracting to local suppliers and offering skill development programmes for local workers.

In Phase 2 of the BESS programme, Eskom plans to install 160MW/640MWh of distributed battery storage and 60MW of solar PV power. Sites would be selected to maximise the integration of renewable energy into the national and regional grids. The main use of the BESS will be for national peak shaving for four hours a day, with additional use for emergencies and local network backup (Creamer, 2022b).

In December 2022, Eskom announced the commencement of construction of the initial energy storage facility under its flagship BESS project's Phase 1 at the Elandskop site in KwaZulu-Natal (Hako, 2022). The facility will have 8MW capacity, which is equivalent to 32MWh of distributed electricity, providing sufficient power to a small town for a minimum of four hours (Hako, 2022).

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. The BESS system will be used to provide load capacity for four hours each day in the evening, which is generally the time when demand is highest and solar PV is minimal.

Nevertheless, the lack of financial support from the government for local assemblers in the LIB industry has constrained businesses, hindering their ability to expand their operations in the region and enter new markets. While many local LIBs manufacturers currently produce batteries for niche markets, only a limited number of local companies are producing LIB batteries for utility storage applications. Given the local manufacturing capacity and expertise, with the right support, more manufacturers and assemblers could produce LIBs for utility-scale applications for the local market. Although it may be necessary to import batteries in times of crisis, there is demonstrated local capacity and capabilities that should be utilised in the medium to long run to support the local market with locally assembled batteries.

LIBs have demonstrated the profitability of energy storage in the market, and VRFBs have benefited from their advancements. VRFBs excel in utility-scale applications requiring long-duration storage of up to 12 hours, where energy is needed daily (Gordon, 2022; Rapier, 2020). Despite the prevalence of LIBs, concerns have been raised about their potential to cause fires, such as in the case of the 2021 explosion of a battery pack at the 300MW/450MWh Victorian Big Battery facility in Australia (Toscano, 2021). This event has renewed attention to the risks of LIBs in grid-scale energy storage applications.[17] In contrast, VRFBs are considered among the safest batteries for energy storage, as previously noted.

For applications that demand energy storage duration of four hours or less, as outlined in some of the BESS projects, LIBs are the preferred or default option due to their performance and cost-effectiveness. As a result, most initial Eskom projects are expected to adopt LIB technology (this includes all Phase 1 projects, except for the two that have been subjected to re-tendering). However, as the BESS programme expands and more projects are commissioned, VRFBs could also be a viable option for bulk and large-scale projects that require longer storage periods and have adequate capital investment.

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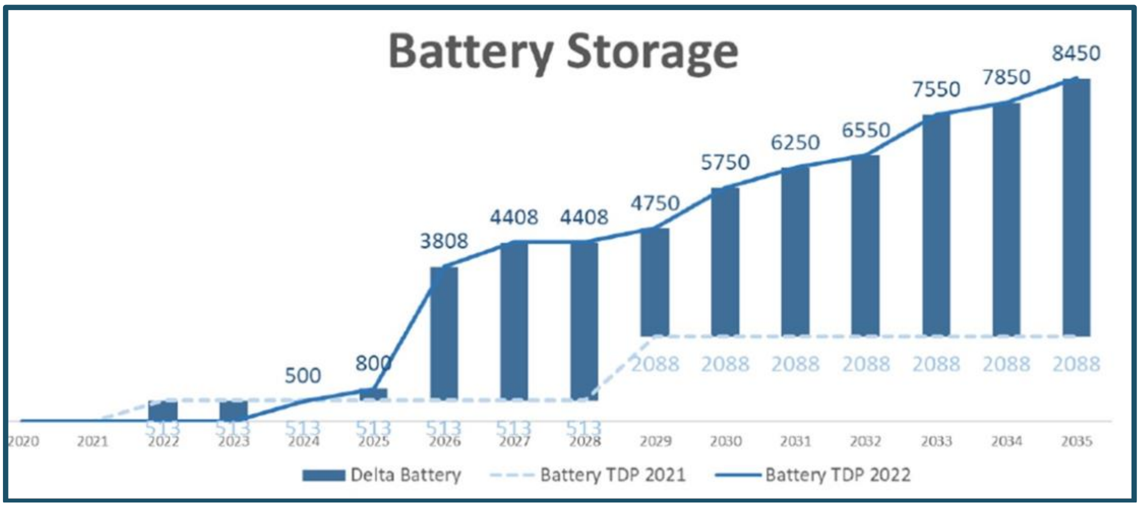
[17] The release of gases adds a level of complexity to dealing with these types of fires, which produce oxygen as they burn and cannot be extinguished with water. It is not mentioned which LIB chemistry was used because for example LFP batteries are meant to be a safer technology when compared to other chemistries.

Figure 10: Eskom's generation using battery energy storage



Source: Eskom, 2022b.

4.1.2. Leveraging battery storage for effective renewable integration

The REIPPPP, ESIPPPP and RMIPPPP play crucial roles in acquiring new generation capacity from alternative and renewable energy sources.

4.1.2.1. REIPPPP and ESIPPPP

Between 2013 and 2022, South Africa installed a total of 3 443MW of wind power, 2 287MW of large-scale solar PV, and 500MW of concentrated solar power (CSP), increasing total installed capacity from 467 MW in 2013 to 6230 MW in 2022, according to a 2022 report by CSIR. The REIPPPP has facilitated an increase in the contribution of renewable energy technologies, including wind, solar PV, and CSP. In 2021, a total of 5.7GW renewable energy capacity was installed, providing 6.6% of the total energy mix in South Africa. By 2022, the installed capacity of renewable energy technologies (wind, solar PV, and CSP) reached 6.2GW, representing a significant increase. Furthermore, these renewable sources contributed 7.3% to South Africa's overall capacity of electricity supplied (CSIR, 2022a). However, since 2011, South Africa has experienced a decline in electricity production, with output decreasing from 250TWh to 233TWh in 2022. The sixth bid window of the REIPPPP aims to secure 4200MW of renewable energy, with onshore wind farms contributing 3 200MW and solar PV plants contributing 1 000MW. Unfortunately, the DMRE could not allocate any of the wind projects within the specified 3 200MW designated for this particular bidding window. By 2031, South Africa is expected to add 30GW of new generation capacity, primarily from renewable energy sources, which would increase the share of renewable energy in the country's generation capacity to more than 40%. The use of batteries can optimise the utilisation of renewable sources and increase investment in storage technologies.

Meeting its net-zero goal by 2050 will require South Africa to heavily rely on renewable energy sources and storage solutions, as outlined in the country's IRP roadmap. However, since renewable energy sources are inherently variable, they cannot guarantee a consistent and dependable power supply on their own, hence the crucial need for energy storage. Currently, traditional fossil-fuel based generators are used to balance supply and demand for grids with minimal wind and solar sources. However, as renewable sources account for a larger share of the energy mix, the need for storage capacity increases.

The ESIPPPP Bid Window 1 was announced by the DMRE in March 2023. 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 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 round is focused on promoting the advancement and deployment of battery technologies that can mitigate the variability of renewable energy sources, while also enhancing grid stability and reliability. The BESS round offers both the public and private sectors an opportunity to invest in battery technologies and support the country's transition to sustainable energy. Battery storage, in this case VRFBs, will become key to managing rapid intermittency in both generation (renewable energy) and demand (rapid changes in use throughout the day) with long duration energy storage. It is important to highlight that although generation from wind and solar exhibits variability, this variability can be predictable with forecasts available up to one day in advance.

4.1.2.2. RMIPPPP

Under the RMIPPPP, Scatec ASA, a leading renewable energy solutions provider, signed a 20-year power purchase agreement for three co-located Kenhardt projects pairing 540MW of solar PV with 225MW/1140MWh of BESS capacity (Scatec, 2022). According to Creamer (2022a), Scatec revealed its plan to use LIBs to support its hybrid project. However, considering the project's size and duration, VRFBs may offer better cost competitiveness than LIBs when assessed over the 20-year life cycle. VRFBs exhibit high potential in utility-scale for several reasons compared to LIBs, notably because VRFBs demonstrate potential as an energy storage solution for extended periods of several hours, their independent sizing of power and energy, durability, and low operating and maintenance costs (Gordon, 2022). A thorough evaluation of vanadium-based batteries should consider their long-term investment potential, as the high upfront cost can be justified by their extended service life.

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. Government procurement programmes are an important tool for supporting demand for products and promoting economic development, particularly in the case of emerging industries or technologies. They provide a stable customer base, establish quality and safety standards, encourage competition and innovation, and can be used to support specific policy objectives, given technological uncertainties surrounding batteries

4.1.3. Repurposing of Eskom plants using VRFBs

Globally, power utilities are facing challenges such as declining profitability, environmental concerns, and outdated power stations. In South Africa, most power plants were established between the 1960s and 1980s when coal was the leading technology. However, as highlighted by Glossop and Johnsson (2021), there is now a shift towards a low-carbon economy, which has rendered the rejuvenation of coal-fired plants unfeasible. The decommissioning of coal-fired power plants incur significant costs, including dissolution, remediation and recovery to make the site suitable for reuse (ESMAP, 2021).

Several options could be considered for the repurposing of South Africa's existing coal power stations. Some of the options include energy generation, and using sites for non-energy activities, such as conversion into industrial parks or special economic zones, learning development centres, or for the recycling of fly ash into cement (Chaudhary and Harji, 2021; CSIR, 2022b).

According to Glossop and Johnsson (2021), repurposing coal-fired plants is a better alternative to decommissioning them and aligns with the circular economy's reuse and recycling principles. Repurposing can be done in several ways, as stated in the World Bank's technical report on *Coal Plant Repurposing for Ageing Coal Fleets in Developing Countries* (ESMAP, 2021). The report includes a cost-benefit analysis (CBA) framework for repurposing a coal plant, using India's decommissioning process as a case study. The findings indicate that repurposing power stations for repowering, i.e. for energy storage or generation, along with substantial investment in renewable energy, could be an effective strategy for developing countries such as South Africa, Chile, and India (ESMAP, 2021:3).

Repurposing could also allow for the installation of energy storage systems, ranging from battery or for the conversion of existing generators into a synchronous condenser (SynCON) to provide ancillary services to the electricity grid, including stability and voltage support (Chaudhary and Harji, 2021; Office of Gas and Electricity Markets, 2021) Other available renewable energy technologies for coal repurposing can also include CSP systems coupled with thermal storage.

The World Bank conducted a study to determine the advantages of repurposing coal-fired plants when combined with renewable energy technologies. The study included three scenarios: business as usual; decommissioning the coal-fired plant and building a new hybrid plant with a combination of solar, battery energy storage; and a SynCON. Scenario 1 becomes relevant when discussing life extension or the closure of a plant at the end of its lifespan. However, if the decision is to shut down the plant when it reaches its intended lifespan, then only options 2 and 3 are applicable. However, if the rationale supports an earlier closure, then all three scenarios can be employed.

The CBA showed that repurposing the coal-fired plant was more advantageous than decommissioning it. Repurposing coal power stations into brownfield sites for energy generation offers advantages over restoring land to greenfield redevelopment. Repowering can make use of existing infrastructure, maintain part of the workforce employed in the retired coal plants, increase the share of renewable energy, and deliver emission mitigation. However, repurposing requires consideration of plant characteristics such as age of plant, physical location, assets and liabilities and related value chain implications for coal communities and other stakeholders (Chaudhary and Harji, 2021). Repowered projects can be faster to implement and cheaper than greenfield solutions due to the reuse of permits, materials and infrastructure, and can offer further cost-saving advantages.

Many countries tend to choose an energy-related path for their repurposing solutions (see Table 3). According to Chaudhary and Harji (2021), key factors to consider for repowering are access to ports and road networks, the reuse of existing BOP equipment, operating flexibility, operations and maintenance costs and technical risk mitigation.

Table 3: Three scenarios for coal plant operation, decommissioning, and repurposing

SCENARIO 1: BUSINESS AS USUAL		SCENARIO 2: DECOMMISSIONING COAL-PLANT		SCENARIO 3: REPURPOSING COAL-FIRED PLANT WITH HYBRID SOLUTION	
Costs	**Benefits**	**Costs**	**Benefits**	**Costs**	**Benefits**
Water intensive	System balancing benefits	Restoration costs	Carbon benefits	Repurposing costs	Retention of ancillary services
Increased energy costs		Foreclosure sale of assets (scrap sale)	Health benefits	Solar costs Battery costs	Re-employment benefits
Heightened renewable energy costs		System balancing costs			Carbon benefits
Costs outweigh Benefits		Decommissioning costs			Health benefits
		Heightened renewable energy costs			Lower energy costs
		Costly retirement			Reutilisation of assets (resulting in lower initial renewable energy investment)
					Considerable circumvention of restoration costs
				Benefits outweigh Costs	

Source: Adapted from ESMAP, 2021:10.

Based on the available information, it appears that South Africa's approach to decommissioning Komati aligns with Scenario 3 from the World Bank study, which involves repurposing the plant with a combination of renewable energy sources and storage systems, including a SynCON.

As part of Eskom's Just Energy Transition (JET) Strategy for the Repowering and Repurposing of Komati, Eskom shut down its Komati coal power station in Mpumalanga in October 2022 due to the plant being past its useful production life (Eskom 2022a). (Eskom, 2022). Eskom's Komati plant will be repurposed using 150MW of solar PV, 70MW of wind energy, 150MW/300MWh battery storage and a SynCON, while the existing transmission infrastructure will be utilised. 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 micro-grids tailored for local use (Eskom, 2022a).

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. Their viability will depend on various factors like use-case, applications, services, and Eskom's technology preferences. However, unless vanadium battery costs decrease, or the recognition of their increased value-add becomes realised, 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.

4.2. Enhancing energy resilience through micro and off grid systems for C&I and remote projects

According to the World Bank, the deployment of micro-grids and other off-grid systems powered by solar PV and wind energy has contributed to the improvement of electrification in small, remote communities in Africa. These systems have played a significant role in the residential and C&I sectors, providing secure and stable electricity to small and isolated areas, and critical facilities. Solar-powered micro-grids are becoming cost-competitive with conventional-powered grids, offering governments and businesses an opportunity to scale-up electrification while reducing greenhouse gas (GHG) emissions. Micro-grids are effective in reducing vulnerability to grid outages caused by physical infrastructure damage and natural disasters.

Micro-grids can run purely on renewable energy, but storage is needed if solar and wind are used. Batteries not only enable the use of decentralised energy technologies but also improve grid reliability. However, the high upfront infrastructure and installation costs associated with micro-grids pose significant challenges to their widespread adoption, resulting in high risk for investors.

Battery storage technologies can revolutionise the deployment of renewable power by facilitating the management of variable generation, demand response services and stable power distribution. This creates an opportunity for utilities to compete with conventional electricity power plants on a level playing field. Although lead-acid batteries are commonly used for micro-grids, VRFBS can be an asset for micro-grid initiatives, remote grids, and off grid communities in rural areas or islands.

The US Energy Department has pointed out that VRFBs offer various benefits over LIBs for deployment alongside micro-grids. These advantages include the potential to store a significant amount of power in uncomplicated designs, discharge power for up to 12 hours continuously, and the absence of thermal runway issues. However, VRFBs do have some drawbacks in the micro-grid market segment, as the technology's narrow operating temperature range necessitates the use of air conditioning systems, which can lead to significant energy losses. It is important to note that both VRFBs and LIBs have a role to play in supporting micro-grids and integrating renewable energy with energy storage.

Micro-grids generally supply electricity within the range of 100kW to several MW. Based on a study by the Microgrid Partnership (FAIST, 2020), lead-acid batteries were used in 66% of micro-grid systems with battery storage in 2019, while 32% used LIBs. According to a study by Posséme (2020), the need for a more reliable battery technology that can lower the TCO for micro-grids is growing, but only a few developers are willing to take on the risk. The use of LIBs is increasing due to their high energy and power density and their suitability for micro-grids. Although VRFBs and sodium sulphur batteries are promising alternatives for micro-grid projects, they are restricted by their size and feasibility for small-scale deployment (Davis, 2022). Mini grids, which are slightly larger in scale than micro-grids, have demonstrated potential for extended duration storage. According to Figure 4, battery storage is likely to be predominantly applied for the use of mini grids across Africa.

Beyond the advantages and disadvantages previously stated, there may be additional factors to consider when assessing the viability of VRFBs in micro and mini grids, such as improved grid reliability, longer backup power system lifespan, and faster charging and discharging capabilities. Unlike other batteries, VRFBs do not suffer from capacity loss even after numerous charge and discharge cycles (Davis, 2022).

4.2.1. Micro-grid solutions for South Africa’s mining industry

Commercial and industrial businesses are significant consumers of electricity in South Africa. The use of micro-grids in C&I enables these entities to generate on-site energy, thus enhancing their grid sustainability, reliability and resilience. The mining industry consumes a substantial proportion, up to 30%, of Eskom’s annual power supply (Milovanovic, 2022).

South Africa’s load shedding crisis, increasing electricity tariffs, the Carbon Border Adjustment Mechanism (CBAM), climate policies, including the Carbon Tax Act No. 15 of 2019, and fuel price volatility are among some of the factors driving the mining industry to seek reliable, cost-effective and clean alternative solutions to ensure operations run optimally, while improving their environmental, social and governance (ESG) position (Milovanovic, 2022). According to Votteler and Brent (2017), some of the dynamics faced by mining companies heightened the operational expenditure of large mining companies from 8% to 20% of total operating costs between 2008 to 2015. While the focus on a stable grid remains crucial, the significance of coal as a power source remains important to the mining sector’s energy mix. Mining companies are actively pursuing the goal of decarbonising their operations by implementing various strategies. The ultimate objective of these efforts is to achieve energy security, reduce GHG emissions and achieve net-zero operations (Du Toit, 2021).

The mining industry in South Africa has traditionally relied on coal-based power plants and diesel generators due to power availability and grid instability issues. However, in response to these challenges and changing global dynamics, many companies in the mining sector have recently begun investing in renewable energy technologies to secure energy supply. According to Minerals Council South Africa, the industry aims to create 89 generation projects from 29 mining companies, generating 6.5GW of power by 2050 and valued at more than R100 billion of total investment (BusinessTech, 2022b; TimesLIVE, 2022; Creamer, 2022a). These projects include solar and wind power, as well as hydropower, hydrogen, gas and battery storage. While mining companies would still require Eskom’s grid in the short run, the planned renewable energy projects have the potential to lower long-term electricity costs, diversify energy supply, reduce GHG emissions, replace diesel generators with storage batteries, and demonstrate leadership in the transition towards a clean energy economy (Votteler and Brent, 2017).

Following the recent revision of Schedule 2 in the Electricity Regulation Act No. 4 of 2006 in South Africa, the National Energy Regulator of South Africa (NERSA) granted an exemption to generation projects over 100MW. However, it is important to note that these projects are still obligated to register and adhere to grid codes and other relevant laws and compliance (Mackay, 2023). As a result, IPPs and private companies have proposed ambitious plans for implementing renewable energy-based generation facilities, with the aim of generating about 13GW (5GW of wind and 8.3GW of solar PV) of private installed capacity by energy-intensive users, primarily in the mining industry (Mackay, 2023; SAREM, 2023). These projects will mainly involve solar and wind power, but will also require various 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. These projects may involve standalone energy storage facilities or a combination of renewable technologies with energy storage.

Mining companies are currently exploring the use of batteries, with VRFBs appearing to be a favourable and worthwhile investment due to the advantages previously stated. With their long duration discharge, VRFBs can ensure that mining operations run 24/7, increasing efficiency and productivity. In contrast, LIBs may not have the capacity to operate for such extended periods, making them less suitable for long-term mining operations.

Furthermore, VRFBs as an ideal solution for renewable energy integration are significantly advantageous for mining companies, which are increasingly investing in generation projects using renewable energy sources to reduce their carbon footprint and energy costs. The mining industry is prioritising the adoption of clean energy technologies to decarbonise their operations, and the implementation of VRFBs could play a vital role in achieving this goal.

4.2.1.1. VRFBs for mini grid support: A case study of Bushveld Minerals flagship project in South Africa

VRFBs are increasingly being used in projects, both ongoing and completed, to support off grid applications. This study explores two specific examples, one in South Africa and the other in the US. Despite the significant cost of VRFBs, the success of these projects demonstrates the feasibility of using these batteries to support micro and mini grid systems.

VRFBs can play a role in supporting mini grid systems, enabling the use of small-scale and decentralised energy systems for the mining sector. A noteworthy case study is Bushveld Energy's flagship project for VRFBs in South Africa. South Africa's vanadium producer Bushveld Vanadium plans to install a hybrid mini grid system in the North West, using VRFBs. This project involves a 3.5MW solar plus 1MW/4MWh VRFB storage at an alloy mine. It is an important flagship project for VRFBs in Africa as, on successful deployment, this project should showcase the technical feasibility of VRFBs in supporting power generation. It will also demonstrate how flow batteries could compete with LIBs in grid applications for the mining sector, where the demand for storage is expected to increase. In addition, Bushveld Energy, supported by the Industrial Development Corporation (IDC), is building an electrolyte facility which would support the anticipated growth of VRFBs. The vanadium feedstock for the facility will be sourced locally from the Vanchem vanadium mine (Bushveld Minerals, 2018). Developing local capacity to support local demand for VRFBs remains essential and has implications for reducing the high costs of VRFB systems.

Another illustration of the viability of VRFBs can be observed at Esko's testing site, which is dedicated to identifying technological solutions primarily applicable within Eskom. In collaboration with the IDC, Eskom installed a 120kW/450kWh VRFB supplied by VRFB OEM UniEnergy Technologies at the Eskom Research, Technology & Development site in 2019. The primary objective was to conduct an extensive 18-month testing phase to verify the VRFB system's operational efficiency in local conditions and to demonstrate the viability of the VRFB technology for wider commercial use and adoption in South Africa and across the African continent (Customized Energy Solutions, 2023).

4.2.2. KIBO Energy and Enerox/Cellcube collaboration on VRFB deployment in Southern Africa

Kibo Energy recognises the potential of VRFBs in micro-grid systems in Southern Africa as a means to address the power deficit in Sub-Saharan Africa and the United Kingdom (Kibo Energy, 2022). The company intends to offer long duration and clean energy to these markets. The company has signed a five-year partnership agreement with VRFB OEM Enerox/Cellcube, in which Bushveld Energy is a shareholder, to deploy 1000MW of electricity using VRFBs in the Southern African Development Community (SADC) (Kibo Energy, 2022; Takouleu, 2022). This move is a significant step for Kibo Energy to integrate long duration energy storage projects into its commercial project pipeline. At present, the partnership between Kibo Energy and Enerox/Cellcube is oriented towards the micro-grid sector rather than large-scale utility projects, citing the lack of maturity in the VRFB value chain as the reason (KIBO Energy, 2022). The projects deployed by Kibo Energy will service select business and industry sectors in South Africa that are currently facing loadshedding (Takouleu, 2022; Energy Capital and Power, 2022). This project presents another opportunity to demonstrate the potential of South Africa's VRFB manufacturing industry in meeting the demand across Africa.

4.2.3. A US case study of a decentralised approach to energy security

Micro-grids using VRFB systems have been installed in the US to provide backup power during emergencies, particularly in areas such as California that have experienced increased occurrences of extreme weather and wildfires (Fischer, 2022).

In February 2022, Sumitomo Electric and San Diego Gas & Electric (SDG&E) completed a five-year pilot project in San Diego, California, using a 2MW/8MWh VRFB system and solar PV to power utility customers in the Bonita community (Fischer, 2022). The VRFB system has the capacity to store 8MWh of energy, which can potentially provide electricity to around 1 000 households for up to four hours. During the initial test conducted by SDG&E and Sumitomo, the VRFB system was able to power 66 residential and commercial customers for almost five hours (Fischer, 2022). In another VRFB deployment in the US, Minnesota's primary member-owned energy cooperative, Connexus Energy, which provides service to more than 33 0000 people, has partnered with StorEn Technologies, a VRFB manufacturer, to deploy a 20kW/100kWh VRFB system at its New York headquarters (Connexus Energy, 2022; Davis, 2022). These initiatives demonstrate the value of testing vanadium batteries and their potential for providing long-term power storage, albeit on a smaller scale.

4.3. VRFBs for small-scale BTM applications: A case of shopping centres, office parks and residential markets

In South Africa, as in the mining industry, shopping centres, office parks and residential areas that use generators, lead-acid and LIBs present opportunities for VRFB demand. As previously mentioned, LIBs and lead-acid batteries are more cost-effective and have a lower levelized cost of storage (LCOS) than VRFBs in the market segment for office parks, malls and residential areas. Nevertheless, some VRFB OEMs still target these markets and see them as potential demand areas for VRFBs.

During loadshedding, South African malls and individual stores continue to operate, although they rely mainly on generators that can only provide minimal electricity for essential services. However, companies are increasingly looking to lower their carbon emissions by adding rooftop solar panels and batteries to supplement their grid consumption, enhance their energy security and combat rising electricity prices and power cuts, which have a negative impact on businesses, especially on small micro and medium enterprises (SMMEs). More and more retail shopping malls and businesses are turning to solar power to provide affordable and reliable electricity.

Shopping malls, centres and office parks are promising candidates for grid-connected solar power and battery energy storage. Renewable energy combined with storage provides various advantages for shopping centres and office parks, including improved sustainability, emergency backup, peak shaving, and the ability to operate independently from the national grid. By enabling retailers, restaurants, and hotels in office parks and shopping centres to continue trading normally during loadshedding, businesses can maintain a competitive edge and minimise economic losses.

It is worth reiterating that, despite being a relatively novel technology, VRFBs have already been successfully deployed worldwide for various applications. Yet, a strong business case is still necessary to attract investment in the technology and enhance its prospects for large-scale commercialisation. The demand for energy storage in South Africa has prompted several initiatives by commercial and industrial businesses, the government, and private entities to implement batteries to support energy demands. The local need for battery storage in South Africa and surrounding regions is apparent. The use of VRFBs with solar or wind generation as a cleaner technology compared to traditional generators, has the potential to significantly reduce the country's reliance on generators and the amount of money spent on fossil fuels to power them.

Despite the arguments presented in this paper for the expansion of VRFBs, whether they are residential, commercial or industrial customers, it is essential for individuals and organisations to evaluate their specific requirements and select the most competitive and appropriate option (Harris, 2022). By showcasing projects that use VRFB technology, this analysis provides insights into the potential of these systems in shaping South Africa's electricity landscape during its transition to cleaner energy sources. As VRFBs gain momentum, they could become a fundamental component of the country's sustainable energy strategy and there is a large opportunity for them to fill some of the energy storage needs generated by all the new wind and solar capacity.

4.4. Exploring successful VRFB implementation and market adoption: Examples from the US, Japan, China and Australia

The establishment of sizeable VRFB markets is not only dependent on local manufacturing but also on supportive procurement policies and investments in VRFB technology. The development of ESS policies that focus on regional electrification, energy diversification and increased regional self-sufficiency is evident in jurisdictions, such as the US, Japan, Europe, South Korea and China. VRFBs have already been commercialised in large-scale projects for various applications in these countries.

In recent years, VRFB systems have gained significant traction globally, with a notable adoption in Asia, Europe, and North America. According to Vanitec's projections (Figure 8), annual capacity of VRFB energy storage deployments is expected to reach 14.5GWh in Asia by 2031, along with 9.3GWh in Europe and 5.8GWh in North America. In this analysis, we explore the countries that have successfully implemented VRFBs and the strategies employed to foster the growth of VRFBs in these markets. Australia is also looking to actively pursue the development of a vanadium battery value chain with significant government support, indicating their commitment to fostering the growth of this industry.

In 2022, the California Energy Commission (CEC), a US energy planning agency, approved US$20 million in funding for research projects focusing on green hydrogen and long-duration energy storage of more than 10 hours (Rapier, 2020). Interestingly, the funding excludes LIBs, indicating an opportunity for VRFBs, sodium sulphur batteries, PSH and other long-duration storage technologies to compete in this market segment. The CEC's main objective is to meet California's mandate to decarbonise the electricity sector by 2045 and provide uninterrupted power supply to C&I facilities during grid outages (Rapier, 2020) (California Energy Commission, 2022). VRFBs can fulfil these criteria and become cost-competitive in long-duration storage and utility-scale applications as demand increases and economies of scale are achieved. Over their lifetime, VRFBs offer a lower cost per kWh and lower cost of ownership (Rapier, 2020). However, it is uncertain whether flow batteries can keep up with the rapidly declining costs of LIBs.

In addition to the CEC funding, the US has a LIB project that may have potential benefits for VRFBs. The US National Blueprint for LIBs presents three objectives for the battery industry: promoting economic competitiveness, decarbonisation, and meeting national security demands (CSIS, 2021). Despite lagging behind other major players such as Europe and China, the US has developed this strategy to narrow the gap and ultimately dominate the battery industry. This strategy involves both supply-side and demand-side measures aimed at reconstructing the US battery industry over time (CSIS, 2021). On the demand side, the Biden administration aims to promote the adoption of NEVs and utility-scale energy storage. On the supply side, the government is providing incentives and support to manufacturers while increasing funding for battery research and development, particularly in emerging technologies to reduce dependence on essential minerals, which are mainly produced by China (CSIS, 2021).

4.4.1. Japan’s successful implementation of VRFB technology

The launch of Japan’s Fourth Strategic Energy Plan in 2014 following the Fukushima disaster aimed to establish a sustainable energy supply system with energy security, economic efficiency, and environment and safety policy, also known as S+3E (METI, 2014:17). The primary policy objectives, due to Japan’s vulnerable energy supply-demand structure, included ensuring energy security, achieving cost-effective energy supply and promoting environmental sustainability. Japan is a major player in the global energy and renewable energy markets and is currently the world leader in smart-grid and energy storage technology. This, in turn, has created a strong demand for energy storage. Japan’s current legal and regulatory framework is more focused on large capacity energy storage systems (Berre, 2016:38).

Japanese VRFB manufacturer Sumitomo Electric Industries conducted a 4MW/6MWh VRFB installation aimed at mitigating fluctuations in power output at the Subaru Wind Villa Power Plant in Japan. The system was in operation over a three-year period, reporting a RTE of approximately 80% and cycle life of over 270 000 cycles over the period[18], effectively demonstrating the reliability and efficiency of VRFB technology (Crompton, 2016). Japan’s Ministry of Economy, Trade and Industry (METI) provided funding for the project as part of its Emergency Verification Project for Large-Scale Storage Battery System in 2012 programme (Crompton, 2016). In collaboration with Hokkaido Electric, Sumitomo Electric Industries undertook a 15MW/60MWh VRFB project in Hokkaido in 2015. In 2015, electricity utility companies and operators in the Hokkaido region implemented regulations requiring new renewable energy installations to be accompanied by energy storage. As a result, several battery storage projects emerged in Hokkaido, including a Tesla Megapack BESS project (Colthorpe, 2022).

4.4.2. China’s energy storage capacity and supporting policies towards a greener future

China’s National Development and Reform Commission, in partnership with the National Energy Administration, jointly released the Implementation Plan for the Development of New Energy Storage Technologies during the Five-Year Plan Period, also known as the 1^{4t}h FYP for Energy Storage, on 21 March 2022 (Wu, 2022). The plan advocates for the involvement of various entities, including government and private sectors, generation utilities, and IPPs, in energy storage projects. It also promotes the development of new technologies and the growth of the energy storage industry through market-driven initiatives, enabling large-scale distribution of energy storage in the power industry (Wu, 2022).

China is heavily investing in battery storage and has set a target of achieving 100gWof storage capacity by 2030, up from 3GW in 2022 (Maisch, 2022). However, according to BloombergNEF’s projections (BloombergNEF, 2019) , the total installed capacity of BESS in China is expected to reach approximately 96GW by 2030 (Maisch, 2022). To support this goal, China’s National Development and Reform Commission has released a policy document calling for several pilot projects using multiple 100MW/400MWh VRFB systems to be completed by the end of 2020, but unfortunately project completion was delayed by the COVID-19 pandemic.

The Dalian city in China commissioned a 100MW/400MWh VRFB system to the grid in 2022, currently the largest VRFB system in the world. The battery system is designed to be scaled up in Phase 2, with an eventual output of 200MW/800MWh capacity, thereby increasing the country’s

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[18] The data included shallow-cycling for grid firming as well as deep-cycling for load shifting: https://www.aemc.gov.au/sites/default/files/content/d50e5d51-e68b-4563-a1fd-aa86fd717b55/SWS-Australia-Pty-151105.pdf

grid connected battery storage capacity (Santos, 2022). According to Capital 10X (2023), the installation of this battery system was roughly 4% of the world's annual vanadium production, which equates to around 8 000 tonnes of vanadium pentoxide. The Dalian Flow Battery Energy Storage Peak-Shaving Power Station was installed by Chinese manufacturer Dalian Rongke Power using local vanadium resources from Dalian Bolong New Materials, a leading producer of vanadium chemicals over the world and a sister company of Dalian Ronkge Power.

The station is intended to provide peak shaving and auxiliary services to offset the variability of the city's solar and wind energy supply. At peak grid load, the stored chemical energy will be converted back into electrical energy and transmitted to users (Santos, 2022). The Dalian battery is operational, as reported by Todorović (2022) in November 2022. The Dalian project is a component of a long-term Chinese strategy to reduce energy consumption, boost the market for renewable energy and energy storage technologies and attain carbon neutrality by 2060 (Capital10X, 2023).

In addition to these projects, there has been significant activity in China recently on the VRFB supply chain, which includes the following projects (Van Wyk, 2022):

- China initiated the construction of its first VRFB gigawatt-hour power station in Qapqal Xibe, Xinjiang, with a total installed capacity of one million kW. The project is expected to be fully connected to the grid before the end of 2023.
- A contract was signed in Jishou, Hunan Province in September 2022, for the construction of a 100MW/400MW VRFB power station with a total investment of 680 million yuan (US$94.46 million). The project is expected to be completed and connected to the grid at full capacity by the end of June 2023.
- Pangang Group Vanadium & Titanium Resources will form a joint venture (JV) with Dalian Rongke Power to develop electrolyte production and VRFBs. The venture will build the first phase of a vanadium electrolyte facility in Panzhihua, Sichuan province. The facility will begin operations by the end of the year with an initial capacity of 2 000m^3. The JV is planning a second phase to begin construction in 2023-2024 and to raise capacity to 60 000m3, depending on market conditions.

4.4.2 Australia

Australia's growing renewable energy sector requires investment in flexible energy storage to manage variable generation. By 2050, the country's demand for medium and long duration storage is projected to exceed 180GWh. The Australian government has provided financing to several vanadium projects in the country with the aim of establishing a domestic value chain to support energy storage. The government has provided support for multiple VRFB projects, including the Australian Vanadium Limited (AVL) project, the Australian Renewable Energy Agency (ARENA) project and the Townsville project.

- As part of the Modern Manufacturing Initiative, Australia is providing AU$243.6 million (US$177.47 million) in funding for technology manufacturing projects, including establishing a vanadium processing plant. AVL received an AUS$3.69 million (US$49 million) federal government manufacturing grant to build a commercial vanadium battery electrolyte plant and support the rollout of VRFBs in Western Australia (George, 2021). The grant covers the entire vanadium production value chain, from mining to electrolyte processing. The project aims to produce vanadium electrolyte for VRFB projects in Australia and the Asia Pacific region. AVL is also developing VRFB prototypes for various applications. AVL's subsidiary, VSUN Energy, focuses on battery storage manufacturing, while AVL develops vanadium extraction resources for steel and battery markets in Australia. In addition, VSUN Energy plans to collaborate with V-Flow Tech for VRFB manufacture in Australia, with key elements such as the cell stacks being imported from Singapore (George, 2021, V-Flow Tech, 2021).

- AU$20.3 million (US$15.36 million) vanadium project in South Australia, supported by ARENA, will combine a 2MW/8MWh VRFB with a 6MW solar PV system. The project aims to provide energy to the wholesale market, offer frequency control ancillary services, and supply power to the local grid. ARENA granted AU$5.7 million to support the battery installation, supplied by Invinity Energy Systems (Invinity Energy Systems, 2023; Vorrath, 2020).
- The Queensland Government's Energy and Jobs Plan aims to increase renewable energy to 80% by 2035 and create a battery industry supply chain in North Queensland (Idemitsu, 2022). As part of this plan, a VRFB facility is being constructed in Townsville. The AU$75 million (US$53.38 million) facility, located in the North West Minerals Province, will establish a local value chain for vanadium production, supporting Queensland's renewable energy targets (Iannucci, 2023; Peacock, 2023). It will have an initial electrolyte production capacity of nine megalitres per year, using locally sourced vanadium. The Vecco Group will rely on imported vanadium to manufacture high-grade vanadium electrolyte at its Townsville facility until the Debella Project is operational (Iannucci, 2023). In addition to the new facilities, a Queensland Battery Industry Strategy is also under development to help grow local industry and supply chains (Gameng, 2023).

Summary

The case study examples shed light on two key trends in the development of a local VRFB industry, being the provision of incentives on both the supply and demand sides. The two largest VRFB markets, Japan and China, successfully deployed VRFBs using batteries manufactured by local companies. Both countries used policies targeting long-duration storage to support the market for VRFBs. Local battery manufacturing capacity with government support is key to developing the battery storage market. This strategy presents many learnings for South Africa, a country also endowed with vanadium resource and battery manufacturing and assembly expertise from lead-acid and LIB industries.

The high capital cost of VRFBs has hindered their widespread adoption on a global scale and more specifically in South Africa. Although South Africa's electricity crisis has increased the demand for VRFBs in long-duration storage, the high cost of vanadium batteries limits their commercial viability and expansion into the energy market, with LIBs being the preferred technology for BTM and some large-scale grid applications.

To promote the technology, it is necessary to address the cost issue, which can be achieved by examining the LCOS and identifying potential policy tools and mechanisms to reduce costs, while also emphasising the value-add of VRFB in renewable energy value chains. Lowering the cost of VRFBs is essential to stimulate demand for the technology, as cost is one of the most significant factor impacting a product's demand. If VRFBs remain more expensive than alternative technologies, demand for them may be lower, despite their suitability for some applications over LIBs for FTM and micro-grid projects. While cost plays a crucial role, it is equally essential to explore methods of enhancing the value proposition of VRFBs, which would 'allow' their deployment at higher costs. Another aspect of value is the emphasis on VRFBs long lifespan.

5. LEVELISED COST OF STORAGE FOR LIBS AND VRFBS

Table 2 compared the performance characteristics of battery technologies; however, to appropriately compare and evaluate the costs and economic feasibility of energy storage technologies, the LCOS of each technology can be estimated. Understanding the LCOS for a specific project is essential regardless of whether it involves a microgrid, mini grid or utility plant. 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 CBA and to be able to evaluate costs for different storage solutions with different performance attributes, in both BTM and FTM use cases.

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[19] is calculated as the lifetime cost of energy storage technology divided by the cumulative electricity delivered, using a discount rate,[20] while accounting for all technical performance parameters associated with installation through to termination of the storage technology (Schmidt et al., 2019; Fourie, 2015. The costs of LCOS are determined by several factors that are interconnected. Table 4 highlights the primary driving factors that impact LCOS. Lazard (2017) and Invinity Energy Systems (n.d.) serve as a key point of reference for this analysis.

Table 4: Drivers of LCOS

DRIVER	LOWER LCOS	HIGHER LCOS
Duty cycle	Higher throughput	Lower throughput
Battery costs	Lower capital cost	More ancillary systems
Asset lifetime	Longer lifespan	Shorter lifespan
Degradation	Minimal degradation	Faster degradation
Round trip efficiency	Higher RTE	Lower RTE
Charge price	Lower charge price	Higher charge price
Discount rate	Lower discount rate	Higher discount rate

Source: Invinity Energy Systems, 2023.

According to Lazard (2017), Schmidt et al. (2019) and Invinity Energy Systems (2023), the components of the LCOS considers technical and economic parameters affecting the lifetime costs of storage technologies with the inclusion of capital expenditure (CAPEX), operating and maintenance (O&M) expenditure, efficiency, replacement cost and end-of-life costs, as shown in Figure 11.

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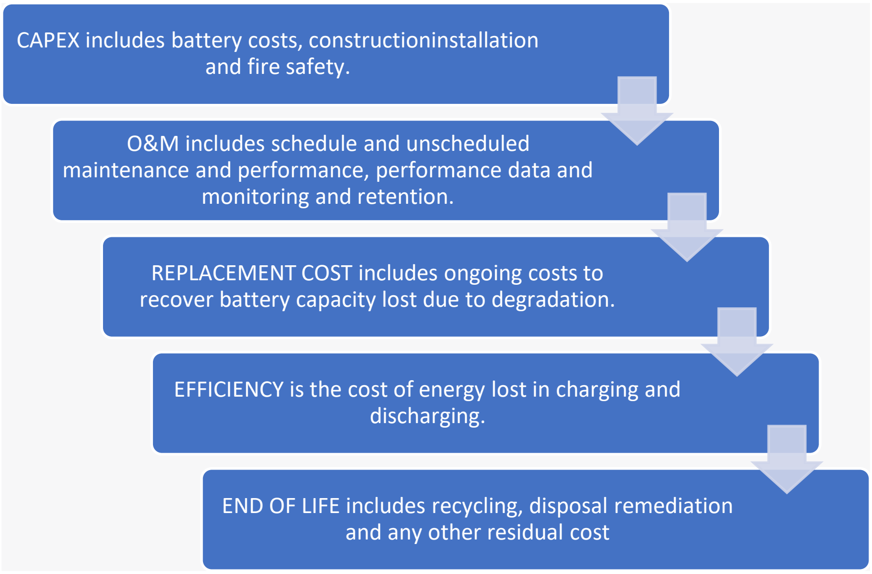
[19] LCOS is measured in currency per unit of stored energy discharged (e.g. US$/MWh or £/MWh).

[20] 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. The Lazard LCOS calculation methodology has many assumptions (cost, geography, system size) which have raised concerns but, as mentioned, there is no unified LCOS methodology.

Figure 11: Components of the LCOS



Source: Invinity Energy Systems, 2023.

Lazard's 2017 report offers a cost analysis of storage on a levelized basis for a range of use cases in both BTM and FTM applications using three types of batteries: lead-acid, LIBs and VRFBs. Notably, the analysis excludes the LCOS for sodium sulphur batteries, as it was not considered in either Lazard's 2017 report, the 2019 Schmidt et al. study or the Invinity Energy System analysis, and is therefore omitted from this analysis.

Lead-acid batteries tend to have a low LCOS for BTM applications, mainly in the residential, due to their low initial investment and ease of maintenance and recycling (Xu et al., 2022; Schmidt, 2019) – see Table 5. However, recently LIBs have become cost-competitive with lead-acid batteries in BTM applications, in residential and microgrid markets for example. It is worth noting that the Lazard analysis is based on data from 2017 and, since then, there have been significant advancements in battery technology, for both LIBs and VRFBs. Therefore, the difference in results will vary when current factors are taken into account. Lazard released a publication on LCOS and LCOE recently (Lazard, 2023), but it does not include LCOS values for the three battery technologies evaluated in Table 5. Schmidt et al. (2019) considers that, by 2050, LIBs will dominate in almost all applications. The exception is long-duration systems, for which PSH has the potential to emerge as the preferred solution, specifically in areas where geographical conditions permit. The LCOS varies can vary with different application scenarios, different storage technology comparisons, region and data sources.

Table 5: Levelised cost of storage for FTM and BTM applications in 2017

	LEAD-ACID BATTERY	LIB	VRFB
Front-of-the-meter		30 USDc/kWh	34 USDc/kWh
Behind-the-meter	41 USD/kWh	43 USD/kWh	

Data source: Schmidt et al., 2019.

LIBs have a lower LCOS compared to VRFBs because of LIBs benefits of high efficiency and low charging costs, even though their end-of-life cost is shorter than VRFBs. Taking these factors into consideration, the LCOS value of the VRFBs is 12.5% higher than that of LIBs resulting from several factors.

VRFBs have some shortcomings notably a higher CAPEX, relatively lower efficiency (which affects the charging price and discharged electricity) and the technology is still in its early maturity of development, which means that it lacks economies of scale. 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 their relatively high LCOS in FTM applications currently, Fourie (2018) states that VRFBs will replace LIBs by 2030 as a competitive storage alternative, specifically for long-duration storage. The analysis conducted by Invinity Energy Systems supports the views expressed by Fourie (2018), indicating that VRFBs demonstrate a more competitive LCOS compared to LIBs over a 20-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, 2023). This approach allowed the battery to undertake valuable tasks such as time shifting and energy arbitrage, which increased its revenue potential (Invinity, 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. A 40-year project lifespan is determined by a range of factors and taking this into account, committing to a 40-year agreement might pose difficulties given the changing landscape of storage and battery technologies, in particular. However, policies might potentially provide a safeguard for these agreements against political fluctuations and enhance investment security.

The LCOS for both systems indicates a value of US$111/kWh for VRFB and US$131/kWh for the LIB.

Figure 12: The LCOS for VRFB modelled over a 40 year lifecycle US$111/kWh

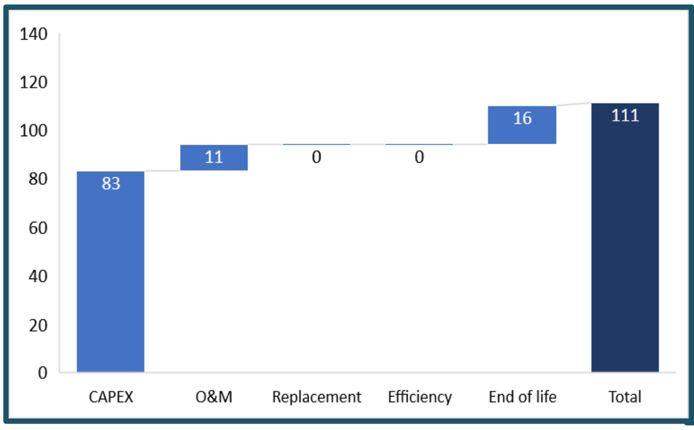
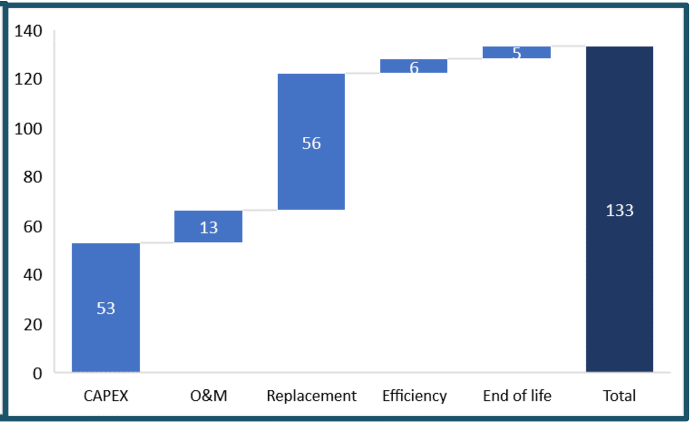


Figure 13: The LCOS for LIB (LFP) modelled over a 40 year lifecycle US$131/kWh



Source: Invinity Energy Systems, 2023.

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.

For O&M costs, 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, 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% per 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 reusability and recyclability vanadium electrolyte in VRFBs reduces end-of-life costs. The initial RTE of the LIB is higher, but degrades over time and is only marginally recovered through augmentation (Invinity Energy Systems, 2023). As a result, both batteries have efficiency losses, with the VRFB costing US$16/MWh of throughput over its lifespan, compared to US$5/MWh for the LIB.

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 enables one to make informed decisions, leading to better performance and return on investment for battery storage projects.

6. BUILDING A LOCAL VRFB INDUSTRY: EXPLORING OPPORTUNITIES FOR LOCALISATION

In the context of battery markets, the availability of local supply plays a vital role in determining the demand for batteries. Thus, the availability of a local supply of batteries ensures that the energy demands of the region can be met without relying (extensively) on imports. This is especially important in cases when the cost of importing batteries from outside the region is high, or where battery deliveries have experienced longer lead-times due to the impacts of COVID-19 and supply chain disruptions.

As noted, South Africa possesses vanadium deposits and plays a significant role in vanadium global production. In 2021, it ranked as the third largest producer of vanadium, responsible for 7% of the world's supply. The presence of this mineral provides South Africa with a comparative advantage and motivates the country to exploit localisation opportunities along the VRFB value chain (Rebel Group and TIPS, 2021. If South Africa can capitalise on this and establish a VRFB industry, it could supply batteries and offer clean energy solutions to both BTM (in microgrids) and FTM customers in local and regional markets. Establishing local battery manufacturing can assist in fulfilling local content requirements specified in storage procurement programmes. South Africa's localisation policy could help facilitate this.

There are numerous justifications for pursuing local production of VRFBs, such as increased value addition to vanadium mineral, employment creation, promoting economic growth, advancing investment in new technologies, developing high-value products for export, expanding and stabilising the energy system and securing energy supplies (Rebel Group and TIPS, 2022). For these and other reasons, there is a fundamental competitive rationale for investigating VRFB prospects. However, it is crucial to support localisation with demand, as it encourages investment in local manufacturing, and stimulates production in VRFBs. Strong domestic demand and local production often underpin significant vanadium markets. Therefore, if South Africa is to exploit localisation opportunities, demand must be a crucial factor to consider.

The following section focuses on the supply-side aspects of VRFB technology. In assessing VRFB supply, the study examines the vanadium battery value chain and identifies areas in which South Africa can participate in the production of the battery system and its associated components. The value chain analysis section draws on some of the insights from the Rebel Group and TIPS, commissioned by the IDC and Bushveld in 2022.

6.1. Vanadium supply: mining production, reserves and trade

This subsection examines the mining output, reserves and trade of vanadium. It highlights South Africa's critical role as a vanadium producer and explains why it is essential for the country to capitalise on its vanadium reserves and production. According to the United States Geological Survey (USGS), China, South Africa and Russia account for at least 92% of global vanadium production. Vanadium is marketed as vanadium pentoxide (V2O5) and, less frequently, as vanadium trioxide (V2O3) for non-steel applications and ferrovanadium (FeV) in the production of steel alloys (Summerfield, 2019). Vanadium pentoxide is a key ingredient in the VRFB electrolyte, and the cost of the vanadium is a significant factor in the overall cost of the electrolyte. Consequently, the price of vanadium has a direct impact on the expense of the electrolyte and, ultimately, on the cost of the battery system. The cost structure and pricing of vanadium is discussed in a subsequent section.

Vanadium does not occur in its metallic form in nature, but rather in around 65 minerals, with magnetite deposits, from which vanadium is extracted either directly (primary production[21]) or indirectly as a vanadium rich slag during steel-making or pig-iron production (co-production) (Bushveld Minerals, 2018; Summerfield, 2019). Fossil fuels such as crude oil and coal also contain vanadium (Summerfield, 2019). Vanadium is primarily used in the production of steel alloys, which are used in nuclear engineering and reactors, ceramics and electronics, and the manufacturing of vanadium batteries. Approximately 90% of vanadium production is used in steel production (Li, 2022; Bushveld Minerals, 2023). As a result, the price of vanadium is closely tied to the steel industry. This is further explored in the subsequent section on the vanadium price outlook and how steel affects the price elasticity of demand for vanadium batteries.

In 2018, global vanadium reserves were estimated to be 22 million tonnes, with China, Russia, South Africa and Brazil being the top producers, as shown in Figure 14. China holds the largest share of vanadium reserves globally, accounting for 37%, Australia holds 29% of the world's vanadium reserves, while South Africa's vanadium reserves account for 14%. Brazil and the US have small volumes of vanadium reserves. China is a significant player in the global vanadium industry as it holds the position of being both the largest producer and consumer of vanadium. In addition, it is one of the largest markets for VRFBs. China uses locally sourced vanadium and refines the material within the country, and this is crucial in supporting the local battery manufacturing industry. South Africa has an opportunity to emulate this strategy, especially given China's trade disruptions, which makes securing vanadium for local battery production more important.

According to Figure 15, South Africa is the third-largest vanadium producer worldwide, with Bushveld Minerals and Glencore being the major suppliers of the country's production.

Bushveld Minerals is a vertically integrated vanadium producer that operates a vanadium mine and owns two out of the four primary processing facilities of vanadium globally (Customized Energy Solutions, 2023). Apart from these two companies, smaller mines such as Sable Metals and Minerals are also involved in vanadium production. South Africa produced 9% of the world's vanadium feedstock in 2021. However, the country's vanadium production declined significantly, from 21 397 tonnes in 2013 to 8 163 tonnes in 2016, primarily due to the closure of Evraz Highveld Steel and Vanadium in Mpumalanga, which resulted in the loss of more than 11% of vanadium feedstock supply (Bushveld Minerals, 2023). The Evraz Highveld Steel and Vanadium mine had a capacity of producing 5 000 tonnes of vanadium a year and was one of South Africa's largest vanadium producers.

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[21] According to Bushveld Minerals (2022), primary source of vanadium supply is co-production, accounting for about 73% of production in 2021. Most of these steel slag producers are located in China. In contrast, primary production accounted for about 17% of global supply in 2021, with major producers including Bushveld Minerals and Glencore, and Largo Resources in Brazil.

Figure 14: Global reserves of vanadium (in metric tonnes of contained vanadium)

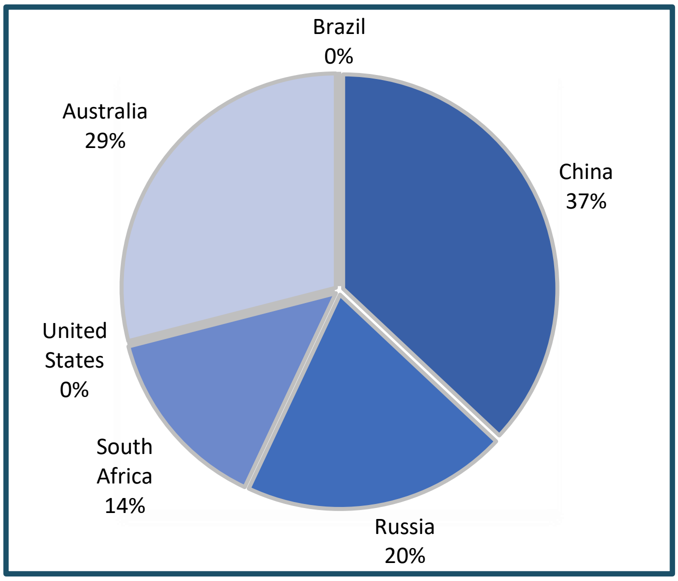
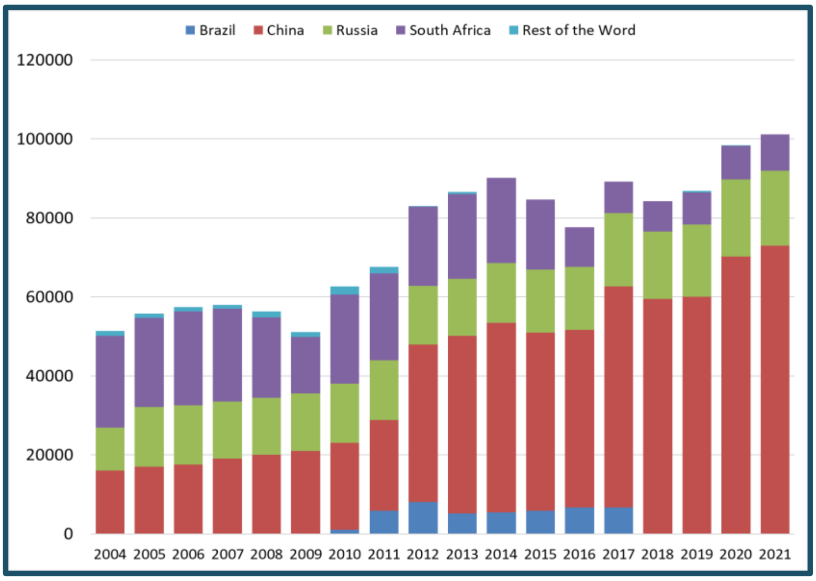


Figure 15: Global production of vanadium (in metric tonnes of contained vanadium)



Source: Authors, based on data from the US Geological Survey Minerals Yearbook, Series on vanadium, downloaded in October 2020 at https://www.usgs.gov.

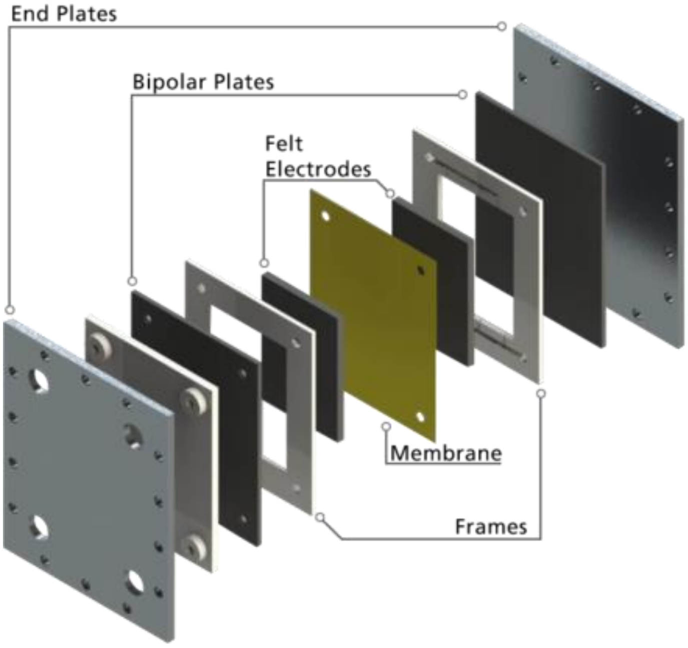
6.2. VRFB value chain analysis

This sub-section introduces VRFB components, including the price of vanadium, and discusses the proportion of vanadium cost in a VRFB.

6.3. Overview of Vanadium Redox Flow Battery Technology

The VRFB is the most advanced flow battery technology and has the largest share of the flow battery market (Sánchez-Díez, et al., 2021).

Figure 16: VRFB cell components



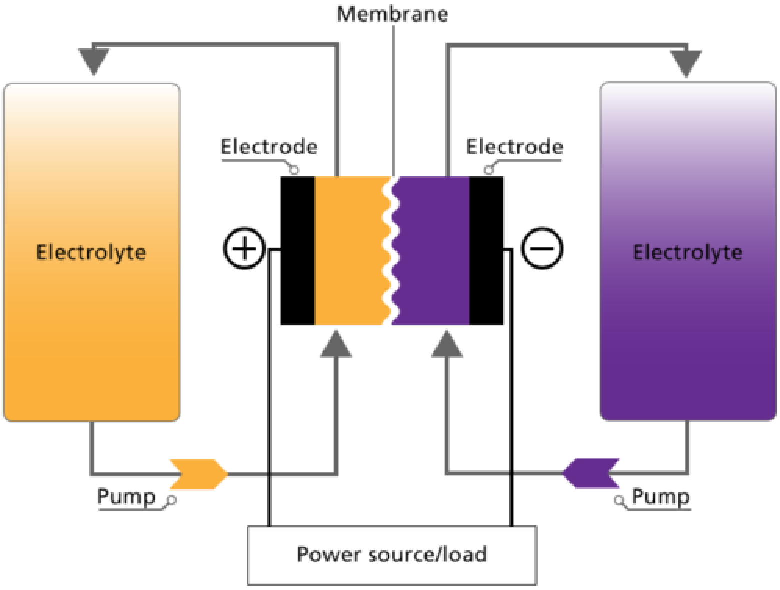
Source: FlowCamp, n.d.

Conventional redox flow battery technology relies on a reversible electrochemical reduction-oxidation (redox) reaction between two vanadium electrolytes (Haoyang, et al., 2020). Typically, flow batteries are made up of three core subsystems: the cell stack, electrolyte storage and the balance of plant. The cell stack is assembled from several cells made from a polypropylene plastic frame, a bipolar plate and a polymer membrane, see Figure 16 (Haoyang, et al., 2020).

Figure 17 shows the operation of a VRFB. During operation, the vanadium electrolytes are pumped through the spaces between the electrodes, where the redox reaction takes place. The electrolytes in the two tanks act as cathode (positive electrolyte) and anode (negative electrolyte). The cathode and anode consist of the same vanadium-solution in different chemical concentrations and oxidation states, both with high storage capacity (Haoyang et al., 2020). Charging of the battery converts electrical energy into chemical energy; and the discharge is the reverse where chemical energy stored in the tanks is converted into electric energy[22] (Haoyang et al., 2020; Chen et al., 2022).

The liquid electrolyte in the tanks is directly proportional to the stored energy, while the electrode surface area determines the output power of the battery. Power generation and energy storage are therefore independent of each other in a flow battery, one of the key advantages of flow battery technology (Al-Yasiri and Park, 2018). This separation of storage and generation makes VRFBs flexible. It also means that VRFBs are more suited to a broader range of applications in the electricity market (Al-Yasiri and Park, 2018). For that reason, flow battery technology is growing in popularity for utility-scale projects.

Figure 17: Schematic diagram of a VRFB with two tanks containing liquid electrolyte solution



Source: FlowCamp, n.d.

The materials associated with each component of a VRFB are comprised of carbon-based materials, a selection of various polymers, glass fibre and metal elements such as vanadium, copper and steel.

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[22] During discharging, reduction occurs at the cathode (+) and oxidation occurs at the anode (-).

6.4. VRFB cell stack components

The cell stack in a VRFB is comprised of active key components including the electrolyte, electrodes, membrane and the bipolar plate. The vanadium battery also has passive components made of the pumps, piping, endplates and gasket, current collectors and the cell frame found in the balance of plant system and cell stack (Lüth, et al., 2018) Each component has its own functionality, and all the different parts work together to store energy. These components are discussed in detail below.

Modularised battery systems for VRFBs are commonly housed within storage containers made of corrugated steel. These containers contain multiple battery cell stacks and have been designed to withstand external pressure while protecting the batteries from damage. However, due to their size and bulkiness, transporting VRFBs can be difficult, making them more suitable for local production and sales. Alternatively, VRFB systems can be built on-site by constructing a custom facility, if there is sufficient land available, or by integrating them into a building. Although the construction and assembly of a VRFB is alike across manufacturers, individual OEMs produce various types of battery sizes depending on product specification and use-case.

6.4.1. Cell membrane

The membrane or separator is a crucial element within the cell stack. The membrane separates the positive and negative electrolytes and prevents the two electrolyte solutions from cross-mixing,[23] while allowing ions through from the negative to the positive electrode (Prifti, et al., 2012). The ideal VRFB membrane should have high ion conductivity, low vanadium permeability, and high chemical stability (Prifti, et al., 2012). According to Prifti, et al., (2012), fuel cells and VRFBs use the same materials in their membrane component. The perfluorosulfonic acid (PFSA) polymer membrane, which is widely used in fuel cells, is currently the most common membrane material used in VRFBs, as they provide high conductivity and high stability (Merck, 2022); (Vrána, et al., 2018).

PFSA polymer, Nafion®, developed by US chemical company DuPont, is the most applied membrane material in VRFB (Haoyang, et al., 2020). Although perfluorinated membranes often possess desired characteristics in fuel cells and VRFBs, the main barrier to large-scale production is their high cost. Minke and Turek (2015) estimated that the Nafion membrane cost about ~500-800 US$/m or 100 US$/kg of the total raw material cost in a VRFB. An alternative to a membrane is to use separators (fuel cells also typically use separators). Recent advancements in material sciences and polymer chemistry have paved the way for further progress in developing alternative polymeric materials and composites as membranes or separators for VRFBs. This includes creating new types of membranes, including cation exchange membranes (excluding Nafion), anion exchange membranes, amphoteric ion-exchange membranes, and non-ionic porous materials. By employing cost-effective porous separators in flow batteries for example, it becomes possible to reduce the overall cost of VRFB systems. However, it is important to note that each type of material used in membranes or separators has its own set of advantages and limitations. For a significant breakthrough in commercial applications, it is imperative that new membranes or separators exhibit chemical stability, scalable fabrication process, and offer robust quality assurance. These factors are crucial in enabling high production volumes and minimising costs.

6.4.2 Bipolar plates

The bipolar plate or flow field plate is a key component of a flow battery cell. The main role of the bipolar plate is to distribute the electrolyte liquid inside battery cells and allow for the flow of electrons (Al-Yasiri and Park, 2018). The bipolar plate in a VRFB is made from graphite or carbon

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[23] VRFB electrolytes are identical which eliminate the cross-contamination caused by the diffusion of ions from the positive electrolyte to the negative electrolyte through the membrane.

composite materials (bipolar plates can also be made from metallic materials for non-VRFB applications) (Haoyang et al., 2020). Bipolar plates should have high electrical and thermal conductivity, as well as high resistance to corrosion (Pasupathi, et al., 2016).

Carbon-based composite materials used in bipolar plates are suitable for both fuel cells and VRFBs. EPRI (2007) notes that OEMs often contract the production of the conductive polymer of the bipolar plate to outside suppliers, rather than producing the plates in-house. Schunk, SGL Carbon and Dana rank among the leading manufacturers of graphite bipolar plates for fuel cells and flow batteries.

6.4.3. Electrodes

Within each cell, there are two electrodes. Electrodes provide reaction sites in each cell for the redox operation during the charge-discharge process (Jiang, et al., 2020). Electrode chemical and physical properties affect the performance of a VRFB, therefore selecting the right set of materials for the electrode is important to the overall capacity, durability and efficiency of redox flow technology (Maleki, et al., 2020). Electrodes are commonly made from carbon-based materials, including carbon cloth, carbon-polymer composite, graphite felt, carbon paper and graphene. Carbon is the preferred material for the electrodes because of advantages such as high electrical conductivity, strong mechanical properties and a large surface area (Maleki, et al., 2020). On the downside, carbon-based electrodes have low electrochemical activity which needs to be improved.

Specialist material suppliers based in the US, Europe and Asia supply the electrode material (EPRI, 2007[24]). OEMs can either purchase electrodes from suppliers tailored to the specification of the OEM design and manufacture their own electrodes using purchased material from specialist suppliers. Commonly, OEMs prefer to source their electrodes from specialist component manufacturers.

6.4.4. The vanadium electrolyte

The liquid electrolyte in the flow battery is predominantly vanadium pentoxide powder dissolved in a diluted sulphuric acid solution[25] and water to create the electrolyte solution made of different oxidation states of vanadium[26] (Wu, et al., 2014; Roznyatovskaya, et al., 2019). Since an acidic solution is used in the electrolyte, the cell stack materials (cell frame, bipolar plate, membrane) in contact with the electrolyte solution are resistant to acid (Daub et al., 2021; Haoyang et al., 2020). The electrolyte is produced through a complex, expensive series of chemical and electrochemical processes (EPRI, 2007). Because the electrolyte volume impacts on vanadium battery capacity, the supporting electrolyte used in the VRFB needs to have good chemical stability and solubility (Wu, et al., 2014). Compared to other battery technologies, the vanadium electrolyte used in VRFBs does not degrade, making it easier to recycle and reuse in other VRFBs without requiring replacement (Linquip Team, 2021; Doetsch and Pohlig, 2020). A sulphuric acid-based electrolyte is preferred over those based on halide salts, which can be highly toxic and release poisonous fumes during charge and discharge. Vanadium pentoxide is insoluble in hydrochloric acid, which makes other acids unsuitable for dissolving it (Cary and Costigan, 2005). Alternatively, a sulphate-chloride mixed based electrolyte can be used in a VRFB; however many OEMs are said to prefer a sulphate-based electrolyte.

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[24] Even though this reference is dated, companies manufacturing electrodes are still primarily situated in the United States, Europe, and Asia. e.g. GrafTech (US), Targray (Canada), Fangda Carbon (China), SEC Carbon (Japan), Tokai Carbon (Japan) and Nippon Carbon (Japan), among others.

[25] Sulphuric acid increases the ionic conductivity of the electrolyte, and also provides hydrogen or proton ions for the reduction of VO+2VO2+ ions (vanadium exhibits oxidation states of +2, +3, +4 and +5).Vanadium oxide (VO) is with vanadium in the +2 oxidation state

[26] All-vanadium redox flow batteries have V3+/V2+ redox reactions on the negative side (anolyte) and VO2+/VO2+ on the positive side (catholyte).

6.4.5. Electrolyte storage

The electrolyte storage includes the electrolytes and tanks. The electrolyte is stored in tanks outside the cell stack and is circulated through the electrodes by the pumps. The tanks must be composed of materials that are able to prevent corrosion (EPRI, 2007; Lüth et al., 2018). Carbon fibre, steel, and plastic materials are commonly used for the tanks; however, the choice of material depends on the specific requirements of the VRFB system (Haoyang, et al., 2022 EPRI, 2007). The electrolyte tanks are said to be like those used to store gasoline (EPRI, 2007). According to (EPRI, 2007), more innovative methods of electrolyte storage have also been proposed, such as flexible plastic bags contained in secondary containment units.

6.4.6. Balance of plant

The balance of plant includes several components that support the operation of the battery, including recirculation loops consisting of pumps and piping, valves, a power conditioning system (PCS) for current conversion[27], heat exchangers used for cooling the electrolyte, and other structural supporting accessories (Haoyang et al., 2020: 3). The accessories used in the cell stack and other supporting components included in the balance of plant vary for different flow batteries (modularised vs on-site assembly) and by application.

6.4.7. Pumps, piping and valves

Pumps, valves, pipes, and other supporting accessories and components must be corrosion resistant. For this reason, pumps, piping and valves made from plastic materials are commonly used in VRFB installations (EPRI, 2007). A key advantage of using plastic materials is that they are inexpensive and readily available (EPRI, 2007). OEMs can use prefabricated piping, which reduces the amount of piping required.

6.4.7. Battery management system (BMS) and Energy management system (EMS)

A BMS is essential for the reliability and efficiency of a battery system operation. The BMS in a VRFB is relatively different from a LIB due to the different battery structure and operating principles of the two batteries (Trovò, 2020). The BMS in a VRFB is designed specifically to monitor stack voltage and to ensure the optimal flow rate of the system, depending on flow battery state of charge, load current and electrolyte temperature (Trovò, 2020). The accuracy in the monitoring and innovative algorithm in the BMS guarantees the correct management of the electrolyte solution in each battery over its lifespan and in moments of inactivity (Knowledge Share, n.d.). Furthermore, the BMS leads to optimal operational parameters of the entire stack that aims to improve battery response time. There are numerous commercial hardware management systems available in the market for BESS technologies, but OEMs typically design and develop their own BMS software tailored to their specific battery product.

Given that VRFBs are usually integrated into grid-level systems, having an EMS and BMS is crucial for effectively operating the entire system (Wang, et al., 2023).

6.4.8. Cell frame and other stack components

A cell frame, made from PVC, provides a frame that seals the membrane, electrodes and bipolar plate to form a cell. Other components in a flow battery such as copper current collectors, gasket and the end plates provide support to the cell stack. VRFBs are sealed with a plastic gasket to prevent the loss of electrolytes; however, new technologies, such as welding or gluing the seal, could see a replacement for gaskets (Lüth et al., 2018).

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[27] The PCS converts the DC energy in the battery into AC electricity.

7. PROPORTION OF VANADIUM COST IN A VRFB

In the following subsection, the cost structure of these batteries will be examined to determine how this contributes to their high cost.

The costs of a VRFB system are divided roughly into the following:

- Cell stack component costs (including the BOP, PCS, electrolyte),
- Assembly costs, and
- Delivery and installation costs.

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.

With the system costs of a VRFB shown in Figure 18, the component costs of the battery account for the highest proportion, at approximately 67% of the cost of the battery. The vanadium electrolyte is the most expensive component in a VRFB, representing 30% of the total cost. This, however, varies depending on individual VRFB companies and on the energy vs power ratio (e.g. in an eight-hour battery, the electrolyte makes up nearly double the percentage of a four-hour battery).

The vanadium electrolyte accounts for 30% to 65% of a VRFB system, depending on the required energy storage capacity. Cell stack components also have a high value representing 17% of total cost, followed by power electronics accounting for 12% of costs and BOP components including pipes, tanks, BMS and EMS, accounting for 8%. Cost analysis estimates that vanadium comprises between US$81/kWh and US$182/kWh. According to Rodby et al. (2023), the current VRFB electrolyte price is at US$125 per kWh, which is the lowest it has been in the past five years, and there is potential for it to increase significantly in the future. Newer generation electrolytes may lower the vanadium cost. Overhead costs including delivery and installation[28] and assembly are also relatively important costs in VRFB manufacturing, contributing 24% to the overall cost of the battery. The cost of a VRFB is influenced by delivery expenses, which are primarily due to sourcing components from various regions or countries. For instance, the electrolyte might be produced in one country, whereas the system is manufactured and assembled in another (Gouveia, et al., 2020). Additional expenses incurred are energy costs, R&D expenses, and administrative costs. The costs breakdown in Figure 18 is indicative for the industry. The actual breakdown varies based on the materials, technologies and components used by individual companies and the power to energy ratio of a specific battery.

To reiterate, lowering the costs of battery components is critical for the widespread adoption of VRFBs in energy storage applications. Lüth et al., (2018) notes that the cost reduction on passive components 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 because most of the passive components are readily available and are manufactured in large quantities. Hence, if the cost of active materials declines as predicted, the share of the passive components is estimated to increase from 18% to 46% (Lüth et al., 2018).

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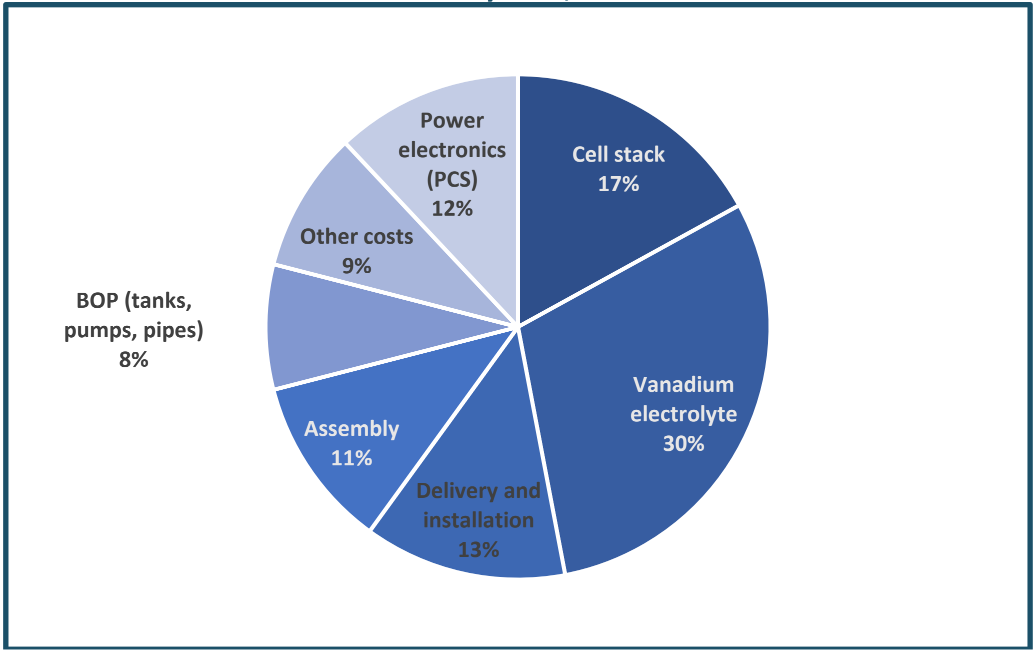
[28] The installation of VRFB systems can take place either on-site or off-site.

Figure 18: Average cost breakdown for a 250kW/1MWh, 4-hour VRFB system, AC installed



Source: Oldacre, 2018.

7.1. The price of vanadium (pentoxide)

The price of vanadium is highly volatile. The cost of vanadium is a significant factor in the overall cost of VRFBs, therefore lowering the cost of vanadium could potentially lead to a reduction in the overall cost of VRFBs. Despite South Africa's substantial vanadium production, the pricing of vanadium, along with other South African commodities, is determined by the import parity price. This price reflects the cost of importing a commodity into South Africa, including transport, insurance and taxes. Therefore, if the global price of a commodity is higher than the cost of producing it domestically, the local mineral prices could increase.

The demand for vanadium is mainly driven by the steel industry, which dominates the vanadium demand base (Ford, 2021). The global vanadium market is primarily guided by market fundamentals and government policies in China, which is the largest producer and consumer of vanadium (BloombergNEF, 2019). Vanadium reached a peak of US$26.3 per pound in 2005, driven by China's increasing demand for the mineral (Gunjan et al., 2022). In 2008, prices of vanadium reached US$17 per pound due to the loadshedding crisis in South Africa, which had a negative impact on the global production of vanadium (Figure 19).

In 2018, the price of vanadium reached a high of U$28.8 per pound due to the speculation surrounding Chinese rebar standards, which required the use of more vanadium (Energy Fuels, 2019; BloombergNEF, 2019). The price of vanadium was affected by COVID-19 in 2020. By January 2022, the price of vanadium had dropped to US$8.8 per pound. The price of vanadium went from US$12/lb in March 2022 to US$7/lb in September 2022, and US$10/lb in February 2023. After a surge in vanadium prices, it is common for the price to decrease as this stimulates China to increase its production, leading to a subsequent decline in price. (Energy Fuels, 2019).

In the near future, China's plans to develop 1 500MWh of VRFB projects that would require over 8 200 megatonne (mt) of vanadium (approximately 7% of global vanadium demand) is expected to increase the price of vanadium (Grech, 2021). Europe, South Africa, Australia, the US and Japan have all stated their plans to commence vanadium projects in the next few years.

Figure 19: Vanadium pentoxide price (2000-2022)

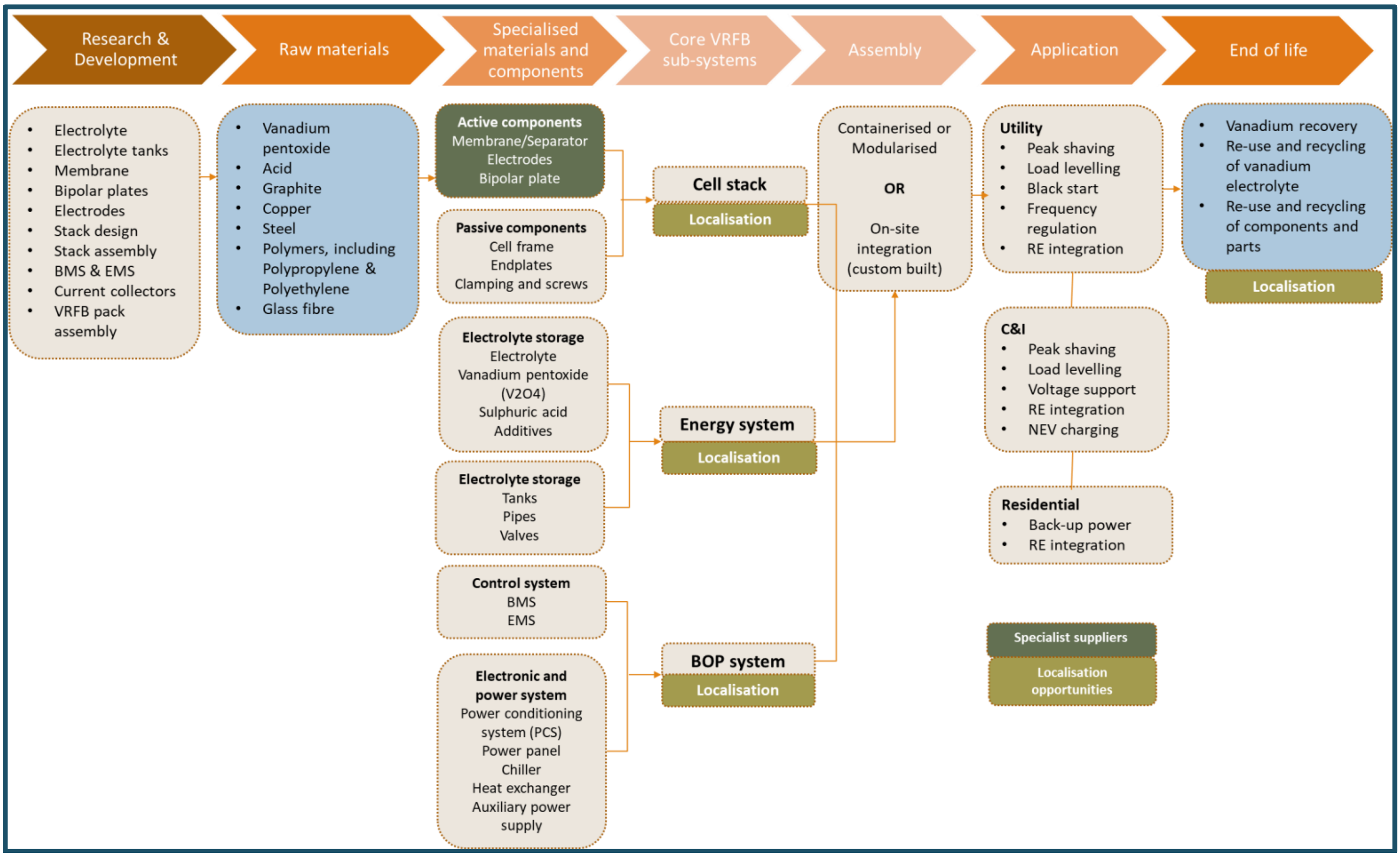
Source: Gunjan, et al., 2022 (Commissioned by Vanitec).

8. THE VRFB VALUE CHAIN ANALYSIS: CAPTURING VALUE ADD IN VRFB TECHNOLOGY

In this section, a value chain analysis of vanadium is conducted. The analysis covers the mining and processing of vanadium electrolyte, the involvement of OEMs in component manufacturing and assembly, and the potential benefits at the end of the VRFB lifespan. In addition, the significance of patents in the VRFB value chain is also discussed.

Figure 20 illustrates the production of a VRFB. The VRFB value chain is comprised of various stages including materials extraction, processing, manufacturing and assembly, and end of life phase, where the battery reaches the end of its lifespan, which includes either vanadium electrolyte recovery (recycling) or the re-use of the electrolyte into a new VRFB.

Figure 20: Vanadium redox flow battery value chain



Source: Rebel Group and TIPS, 2022, based on Lüth, et al.

8.1. Value chain analysis

The cell stack in a VRFB holds most of the value creation and opportunities for reducing battery cost. Most OEMs are involved in the design, fabrication and production of mainly active components, with the exception of the membrane, electrodes and bipolar plates. The membrane is a highly expensive and widely patented component, mostly produced by specialist upstream suppliers, and a few OEMs in some cases, however rare. The bipolar plates and electrodes are generally sourced from component suppliers and can be custom designed to suit OEM requirements. As stated, the electrolyte is an important component of a VRFB. OEMs are generally involved in the development of the electrolyte technology by incorporating additives and various acids to enhance the performance of the electrolyte.

OEMs typically handle the design, manufacturing, and in-house assembly of their own cell stacks. However, some OEMs rely on external manufacturers or suppliers to purchase cell stacks, as seen with of Volterion, which supplies VRFB applications with an integrated electronic stack monitoring system to ensure optimal operating conditions (Volterion, n.d.). External suppliers are often responsible for providing passive components in the BOP, including pipes, pumps, valves, gaskets, containers, and frames, which are used by multiple industries.

8.1.1. Mining and processing of the vanadium electrolyte

VRFB OEMs can expand their involvement in the vanadium battery value chain by integrating vertically with vanadium mining companies, which could supply them with vanadium for their batteries. For instance, Largo Clean Energy, a subsidiary of Largo Resources, relies on its vanadium supply from the Maracás Menchen mine in Brazil, which is owned by its parent company. VRFB OEM Enerox/CellCube, in partnership with Bushveld Energy, will source vanadium for its VRFB system from a Bushveld owned mine, for Bushveld's planned VRFB mini-grid pilot project. In addition, as mentioned, Dalian Bolong New Material Co. Ltd. has a stake in Ronkge Power, and the OEM could use this existing shareholding relationship with the mining company to make the sourcing of the vanadium more cost competitive. Although many OEMs stated that they mainly obtain their electrolyte solution from external suppliers, primarily in China, they could pull in vanadium mining companies through vertical integration to enhance their position in the vanadium battery value chain.

OEMs invest in electrolyte chemistries such as the sulphate-based electrolyte and in other electrolyte chemistries such as the PNNL electrolyte, a mixed-acid electrolyte compatible with VRFBs. The PNNL electrolyte is, however, not preferred by many OEMs for use in their batteries as the technology is "not mature enough nor used in commercially available units" (OEM Interviews, 2022). While OEMs typically do not produce their own electrolyte and rely on third-party electrolyte manufacturers, they conduct internal research and development to enhance the performance of the battery through the use of additives and improved manufacturing processes, as depicted in Figure 20.

8.1.2. Component manufacturing and assembly

The level of modularisation in VRFB technology affects the assembly and installation process. In the past, large battery systems were custom-built on-site. However, there is a shift towards containerisation to benefit from manufacturing scale economies and simplify the installation process. VRFBs are often characterised as bulky compared to other types of batteries, but the overall size and weight of the battery depends on the energy storage capacity needed.

The estimated lifespan of a VRFB is about 20 years. However, the majority of VRFB systems currently in operation have not been running for a significant length of time. The only OEM with a VRFB system that has been in operation for more than 10 years is Cellcube/Enerox, which installed a VRFB system in 2010. This highlights the technological uncertainties associated with VRFBs, as no VRFB system has yet reached the full 20-year lifespan.

Many OEMs involved in VRFB manufacturing and assembly have prioritised ensuring high-quality management in VRFB manufacturing and maintenance, expanding markets, and creating a successful product in their current manufacturing strategy. Despite this, economies of scale in VRFB manufacturing have yet to be established, particularly given that at present, VRFBs have a relatively high LCOS compared to other battery technologies. Due to the inability to take advantage of economies of scale in the production and assembly of VRFBs, OEMs expressed uncertainty about focusing on BTM applications until economics of scale in VRFB manufacturing can be realised. The deployment of VRFBs at a utility scale requires a well-established value chain, where companies can benefit from economies of scale and large investments in VRFB production volumes.

The production and assembly of VRFBs are mainly centred in Asia, Europe and North America, where various companies provide tailor-made VRFB products. In addition, several OEMs engage in the manufacturing and assembly of VRFB systems components such as cell stacks, and balance of plant components. OEMs often develop these core battery components in-house to fit them into their own battery design. Development of some key components such as the electrolyte requires significant R&D and advanced chemical engineering. Other battery components, such as power conditioning system (inverter) and related accessories BOP components (excluding BMS/EMS), do not require advanced R&D, but need to meet the battery producer’s specific design requirements. Component suppliers are the source of key components such as the membrane and electrodes, but the cell stack is typically assembled in-house. Companies take advantage of their engineering expertise and R&D knowledge to create value in VRFBs.

Many OEMs primarily focus on cell stack assembly and rely on specialised suppliers for components such as electrodes, bipolar plates, and membranes or separators. However, one VRFB OEM has designed and manufactured its own membrane. According to the OEM, it had previously designed and manufactured its own membrane and also outsourced the membrane manufacturing to suppliers in China and the US. In addition, the OEM has conducted R&D work on electrodes and bipolar plates, which are manufactured in China, similar to the common model used by other VRFB OEMs.

The approach used by numerous OEMs has implications for which components can be localised and which ones they prefer to procure from external global suppliers.

8.1.3. End of life

The vanadium electrolyte used in VRFBs can be recycled or reused, even after the battery has reached its lifespan of 20 years. It is possible to recover it from used batteries and recycle it into new batteries. VRFBs have an advantage over other types of batteries when it comes to recyclability and reuse. Vanadium batteries can be a part of the circular economy as they promote the reuse of the electrolyte, further reducing waste and promoting circularity. According to C-Tech Innovation (2021), “the process of recycling vanadium electrolyte is simple and involves reprocessing through a vanadium production facility, such as the plant that manufactured the original electrolyte, once rebalanced the liquid is then able to be used for another 20 years”.

The long lifespan of vanadium batteries also contributes to their circularity. As they can operate for more than two decades, they can be used in multiple applications over their lifetime, reducing the need for new batteries to be produced (Liang et al, 2022). Overall, the mining of vanadium can be toxic, and while there are still technological and economic challenges associated with implementing a circular economy for vanadium batteries, they do have the potential to be a key part of a sustainable and circular energy system (Mitterfellner and Winkler).

To address the high cost of vanadium and subsequently lower their LCOS, Invinity Energy Systems and Bushveld Minerals formed Vanadium Electrolyte Rental Limited (VERL), which offers a vanadium electrolyte rental option to Invinity’s customers (Slater, 2020). This approach provides a different model for companies to position themselves in the value chain. However, other components of a

VRFB, such as pumps, tanks, and power electronics, may degrade in performance over time and require replacement (EPRI, 2007). Due to their inexpensive and generic nature, the replacement cost of these components is expected to be low. Although the recycling potential of crucial stack components could be looked into, this aspect remains unexplored thus far.

8.2. The importance of IP in VRFB manufacturing and capturing value in the VRFB value chain

Patent information essentially informs where new players in the VRFB industry can compete. In BESS technologies, patents help protect new inventions and technical aspects through R&D efforts. BESS manufacturers use patents for technological inventions across all parts of the battery, including the battery cell stack and related components. IP can enable manufacturers to move up the value chain, advance their competitive advantage, and help position the manufacturer as a leader in the market (Nielson, 2021). Protection for specific aspects of a battery or cell enables manufacturers, particularly start-ups, to capitalise on their experience, knowledge and expertise (Nielson, 2021).

Growth in patenting activity in VRFBs signals strong growth in R&D and the increasing market for VRFBs. Categories of patentable IP in VRFBs include key battery materials, components, battery design and structures, methods of manufacturing as well as the mechanical, electrical, and thermal aspects of the battery (Nielson, 2021). Table 6 shows a list of IP sensitive and non-IP sensitive components in a VRFB.

The most patent sought after components in a VRFB are the electrolyte, the cell stack components and battery design and fabrication. The electrolyte component in a VRFB affects cell properties and the capital cost of the battery. The electrolyte can influence the energy density, operating temperature range and the applications of the VRFB (Cao et al*.,* 2018). As a critical component in VRFBs, the electrolyte has been the subject of significant patenting activity in developing VRFB technology. As such, to develop a high-performance VRFB with improved energy density, the VRFB electrolyte is continuously being developed. Accordingly, innovative patented developments include using selected additives in the electrolyte solution that would increase or widen the operating temperature range of the battery (Nguyen et al., 2020; Cao et al., 2018). The membrane and bipolar plates are also subject to significant patent activity.

Patent filings for materials are seen for copper, graphite, membrane materials and in materials for gaskets, and a variety of polymers for the bipolar plate and electrodes (Nielson, 2021). The battery management system (including both software and hardware features) is also considered IP sensitive. There are several BMS for VRFBs available on the market, but OEMs often design and manufacture their own BMS, specifically the software and the BMS hardware is usually sourced from an external supplier.

Despite large investments in R&D, OEMs do not control all patentable categories for VRFBs, instead there are a select few components and processes that OEMs dominate through IP and knowhow. Different companies, which specialise in different markets and research areas, drive R&D for active components. Specialist membrane companies that largely specialise in chemical and material processing drive R&D in the membrane component. Membrane developers and academia-based researchers often work together in developing appropriate membranes for use in VRFBs. Researchers look to develop VRFB membranes that use affordable material, while maintaining the desirable qualities of the membrane.

R&D for patentable material, that is material used for the electrodes, collectors and gaskets is carried by material specialists. OEMs appear to have limited involvement in the R&D of materials, but this could change should VRFB materials become rare or increase in demand. The electrolyte, which is one of the most patentable components in a VRFB, is highly researched. OEMs, research institutions and universities all have some involvement in the R&D of the electrolyte, with a particular focus on altering the formulation of the electrolyte solution to increase battery capacity while also reducing cost.

It is important to note pending patents as these further signals where R&D efforts are concentrated and allows for insight into IP sensitive components and processes in VRFBs.

Table 6: IP sensitive VRFB components

VRFB Component	IP Sensitive	Novel Claims
Single Cell Stack		
Cell stack	Yes	Module integration, manufacturing method and stack design
Electrolyte	Yes	Electrolyte formulation and the preparation method of the vanadium electrolyte using additives[29]
Electrolyte storage tanks	Yes	Leak-proof electrolyte tanks
Membrane	Yes	Material, method or process of forming a membrane.
Bipolar plate	Yes	Process and component sheets of a bipolar plate
Electrodes		Inventions related to electrode material, as well as various forms and structures – pertaining to either the thinness or thickness of the electrode, depending on the characteristics of electrolyte.
Cell frame	Yes	Cell frame material
Balance of Plant		
Pumps	No	• Low cost technologies • Use of generic/common materials • Not exclusive to VRFB
Tanks	No	
Valves	No	
Pipe	No	
End plate	Yes	
Gasket	Yes	
Current collectors	Yes	Arrangement and composition of the current collectors
Nuts and bolts	No	
Battery management system (BMS) Energy management system (EMS)	Yes	Hardware and software
Inverter	Yes	
Power conditioning system (PCS)	Yes	
Heat exchanger	Yes	

Source: Rebel Group and TIPS, 2022.

An IEA report (2021) revealed that out of 1 214 Intellectual Property Families (IPFs) for redox flow batteries, the majority (622 or 51.2%) belonged to VRFBs. Table 7 indicates that, between 2000 and 2018, the US had the most IPFs in redox flow batteries (33.2%), with VRFBs accounting for 28.4% of the patents. Japan followed closely with 24.1% IPFs in VRFBs, while the European Union accounted for 19.5% of patents in vanadium batteries. The competitive position of US, China and Japan, in terms of VRFB OEMs is supported by a strong patent portfolio. These findings support the geographic clustering trend where China, Europe and the US lead in VRFB R&D.

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[29] EPRI, 2007.

Table 7: Geographic distribution of IPFs for redox flow batteries and VRFBs, 2000-2018

	REDOX FLOW BATTERY	VANADIUM REDOX FLOW BATTERY
Japan	19,2%	24,1%
Korea	10,6%	12,4%
US	33,2%	28,4%
European Patent Convention	23,7%	19,5%
China	4,6%	6,5%
Total	**1214**	**622**

Source: IEA, 2021.

The landscape for manufacturing and assembling VRFBs is distinct from that of LIBs, with only a few dominant players in the market, each with varying levels of experience. While some startups have successfully developed VRFB technology, this required significant capital investment and collaboration with science councils, research institutions, and universities to enhance R&D capacity. VRFBs are a complex technology, with an IP-driven value chain, necessitating collaborations and partnerships between OEMs, suppliers, and other stakeholders to create a competitive battery system. For this reason, among others, if South Africa intends to establish a VRFB manufacturing industry, it will need to forge strong and strategic partnerships with OEMs, component suppliers, research councils, and other relevant stakeholders in the VRFB value chain. The section on component localisation will cover South Africa's R&D contributions and IP in battery manufacturing.

9. POTENTIAL FOR STRENGTHENING LOCAL CAPABILITIES IN THE VRFB VALUE CHAIN

This section focuses on the competitiveness of the supply of raw materials, cell stack and components. While vertical integration has been acknowledged as a means of building a competitive advantage, the majority of VRFB OEMs are knowledge-based firms, with only a few exceptions, such as Bushveld Minerals, Ronkge Power, and Largo Clean Energy (Rebel Group and TIPS, 2022) Competitive advantage is established through domain-specific knowledge and expertise, particularly with the IP on stack design and operation. Although leveraging vanadium may contribute to building a local competitive industry for batteries, there are other components that can also be localised by leveraging other similar industries and technologies, this may also aid in developing a competitive sector.

It is therefore important to identify local capabilities involved in the production and manufacturing of these components and whether they can support a local VRFB industry. Little competitive advantage can be gained through passive components, since countries such as China have significantly lower input costs for most commodities relative to South Africa (Rebel Group and TIPS, 2022). South Africa should not limit itself to being merely an assembly hub of BOP components, but rather employ its battery knowledge and skills to advance the local VRFB industry.

Opportunities for localisation in South Africa currently lie in electrolyte and BOP components such as containers, pumps, pipes, valves, containers and tanks. In addition, South Africa can potentially contribute to several other segments of the value chain; however, its relevance to the VRFB industry and competitiveness in these segments is yet to be confirmed.

This subsection focuses on VRFB components that can be localised in South Africa.

Localisation of numerous BOP components, as well as the core components of VRFBs such as the electrolyte, membrane and electrodes, could be feasible and supported by local industries, as shown in Table 8. There is potential for South Africa to also manufacture casings, gaskets and frames for VRFBs.

Table 8: Battery components manufactured in South Africa for battery and non-battery applications

VRFB INDUSTRY	LIB INDUSTRY	FUEL CELL INDUSTRY	MINING/MANUFACTURING INDUSTRIES
VRFB electrolyte	BMS and EMS	Membrane/separator	Pumps, valves and pipes
Acid	Current collectors	Electrodes	Containers
	Battery casing	Current collectors	Tanks
	Gaskets		Acid
	Electronics		Polymers
			Inverter[30]

Source: Authors.

9.1. Competitiveness of the supply for local materials

While South Africa and the surrounding region have access to materials such as copper, steel and graphite, which are essential components in vanadium batteries, vanadium remains the core

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[30] Although South Africa has inverter manufacturers for solar PV it does not locally manufacture inverters. These inverters can potentially be customised to suit VRFBs.

ingredient in these batteries. South Africa, Zambia, and the Democratic Republic of Congo are major copper producers, and Mozambique and Tanzania produce graphite, but simply having access to these materials is not sufficient for component battery production. Significant R&D investment, as well as refining capabilities, are necessary to convert these materials into battery components.

Polymers, including plastics such as polyethylene, play a vital role in the production of various components used in VRFBs, such as tanks and frames. In South Africa, the plastics industry has a well-established value chain that caters for diverse sectors such as pharmaceuticals, packaging, automotive and construction (the dtic, 2023). Polyethylene, for instance, finds use in a range of downstream applications, including blow moulding, rotational moulding, injection moulding, film, coatings, and pipe and sheet manufacturing. Among these applications, rotational moulding is particularly relevant to the manufacture of VRFB components.

9.1.1. Localising vanadium electrolyte production

For specialised components, South Africa has limited local production. However, this is not the case for chemical ingredients, especially for the electrolyte component. Several local suppliers provide sulfuric acid, which is necessary in preparing the electrolyte. In the environmental scoping draft report study for Bushveld commissioned by EOH Coastal & Environmental Services (2018), it was reported that Bushveld would carry out the preparation and purification procedures for the sulfuric acid required for its electrolyte on-site at the vanadium mine.

Some of the major local producers of sulphuric acid include Sasol, Omnia, Foskor, Protea Chemicals and Nyanza Light Metals. Most of these companies, with the exception of Protea Chemicals, produce sulphuric acid as a by-product in a number of industrial processes, such as oil refining, gas processing, and metal smelting (van Nieuwenhuyse, 2000) Davenport, et al., 2006). By producing sulphuric acid as a by-product of other industrial processes, companies can reduce waste and increase efficiency. However, the quality and purity of the sulphuric acid produced as a by-product may not always meet the standards required for certain applications, and additional purification may be required (Davenport, et al., 2006).

9.1.2. Vanadium electrolyte manufacturing plant in East London

In 2016, Bushveld Energy and the IDC formed a partnership to establish a vanadium electrolyte production facility in the East London Industrial Development Zone (ELIDZ). The production of vanadium electrolyte at the ELIDZ facility is expected to meet a significant portion of both the domestic and international markets' demands (EOH Coastal & Environmental Services, 2018). In May 2022, Bushveld Energy announced plans to invest approximately US$5.1 million in capital expenditure for the project until 2024, while the remaining required funding of approximately US$8.5 million will be financed through an equity and debt agreement with the IDC (Colthorpe, 2021).

The electrolyte plant is expected to support the rapidly growing long-duration energy storage market and produce up to 200MWh of VRFB energy storage annually. The plant will source its vanadium feedstock from Vanchem's existing mining and processing operations (from Bushveld Vanchem) (Bushveld Minerals, 2018). The facility has been specifically designed to produce various electrolyte products that meet the specifications of major global vanadium battery manufacturers. The vanadium is being converted into electrolyte component, in collaboration with international chemical companies. This development is supported by South Africa's metallurgical expertise and infrastructure. (Bushveld Minerals, 2018).

As mentioned, Bushveld Minerals has expanded into upstream activities, including project development and investment in VRFB companies, by offering a vanadium electrolyte leasing option. This allows Bushveld Energy or OEMs to lease the electrolyte to VRFB users or buyers while retaining ownership. Electrolyte rental provides a long-term pricing model that reduces the upfront capital cost of VRFBs and lowers their LCOS, making them a relatively cost-competitive storage technology for long-duration applications (Bushveld Minerals, 2018).

VRFB OEMs have expressed interest in procuring vanadium electrolyte locally to ensure supply security and reduce shipping costs. With the right support and favourable business arrangements, South Africa is well-positioned to supply vanadium electrolyte to VRFB OEMs both domestically and internationally, particularly given China's disruptive value chains.

9.2. Cell stack component manufacturing

Local expertise and capability in cell stack, component manufacturing and assembly for fuel cells and other types of batteries exist in South Africa, owing to the presence of lead-acid batteries, LIBs and fuel cell industries.

9.2.1. Membrane manufacturing supported by the fuel cell industry

South Africa has demonstrated interest in fuel cell technology and has undertaken various initiatives to support its development and adoption. The government has backed R&D in this field, and several universities and research institutions in the country are actively involved in fuel cell research through the Hydrogen South Africa (HySA) programme. The country has the potential to provide essential components for fuel cell production, including the membrane and electrodes, which are shared with the design of modular VRFBs. Further investigation is required to determine its relevance to OEM battery systems. Intellectual property concerning membrane selection and cost will be necessary for membrane supply in the local market (Rebel Group and TIPS, 2021)

A few companies in South Africa, such as HyPlat (Pty) Ltd, Isondo Precious Metals (IPM), Mitochondria Energy and Sasol, are involved in fuel cell production and commercialisation. There is a local value chain for the manufacturing and assembly of fuel cell membranes. For example, IPM, a fuel cell component manufacturer, intends to establish a platinum-containing membrane electrode assembly manufacturing facility using locally sourced platinum group metals (Makhafola, 2018). While the membrane is suitable for use in proton electrolyte membrane (PEM) fuel cells, it remains to be seen if it is compatible with VRFBs, and tests would be necessary to determine its suitability in this application.

As highlighted from the value chain analysis, OEMs currently favour the use of Nafion membrane, but ongoing R&D aimed at finding more affordable alternatives is necessary. There is potential for South Africa's fuel cell industry to develop cost-effective membranes with good chemical stability for VRFBs. However, it is important to bear in mind that membrane production requires extensive R&D investments.

9.2.2. Electrodes

To produce batteries, the manufacturing of electrodes is a critical component. In South Africa, several companies have invested in R&D to create high-quality electrodes for use in several industries. Electrode manufacturing companies operating in South Africa include GrafTech, I-CAT, Tiaano, Zest WEG Group, ArcelorMittal South Africa, and TFD Manufacturing. It is important to note that not all of these companies solely specialise in manufacturing electrodes.

GrafTech South Africa, which is a subsidiary of Graftech International, specialises in producing graphite electrodes and is the only manufacturer of this type of product in Africa. The company's main purpose is to manufacture graphite electrodes that facilitate the conversion of electricity into heat in electric arc furnaces, thereby enabling the melting of ferrous scrap to produce steel (GrafTech International, n.d.) In addition to graphite electrodes, the firm also produces a range of other carbon and graphite products. However, GrafTech currently does not manufacture products for the battery industry.

SGL Carbon, the German company known for manufacturing carbon-based electrodes for VRFBs, has a subsidiary in South Africa. This subsidiary specialises in producing graphite products. The company states that in order to obtain approval from the head office for local production of graphite electrodes for VRFBs, a business case would be necessary. This type of production also entails substantial investments in R&D as well as skilled expertise.

The value chain analysis highlighted the significance of R&D for key components of VRFB, and it is noteworthy to acknowledge the crucial contributions made by CSIR and South African Nuclear Energy Corporation (NECSA) in the R&D of electrodes and membranes in South Africa. The CSIR has conducted R&D for electrode materials used in the fuel cell industry (Pierce and Le Roux, 2023). This includes developing membrane electrolytes for fuel cells and electrolysers, as part of the HySA initiative (Pierce and Le Roux, 2023). NECSA, an organisation involved in various aspects of nuclear technology and its applications, has been engaged in developing electrode materials, specifically for use in nuclear reactors. These materials are used in the production of control rods that regulate the nuclear reaction and ensure safety in the reactor.

The R&D and commercialisation projects for electrodes by both organisations demonstrate that South Africa has comprehensive knowledge and expertise in electrodes for diverse applications. Therefore, players in this market could provide guidance and direction on adapting these components for vanadium batteries.

9.3. Balance of plant components in a VRFB system

Almost all BoP components can be manufactured locally. The analysis below focuses on tanks, containers and pumps, pipes and valves, but nuts and bolts, gaskets, electronics, inverters, casings and current collectors can be made locally.

9.3.1. Battery and energy management systems

VRFB OEMs have the ability to develop their own software and hardware for EMS and BMS, but they may also seek these components from local South African LIB manufacturers and assemblers who use locally sourced materials and expertise.

According to a previous study on the development of LIBs in South Africa by (Montmasson-Clair, et al., 2021), while local assembly of LIBs is still in its early stages, several small and medium-sized companies have formed partnerships to locally produce LIB packs for both domestic and international markets. Some of these companies, in collaboration with academic institutions, have developed IP and expertise in manufacturing specific components, parts, and systems, particularly BMS and EMS (Montmasson-Clair, et al., 2021). Some companies have their own in-house master BMS, while others import it from Chinese manufacturers. Balancell, BlueNova, and Maxwell and Spark are among the companies currently holding IP in BMS design. In addition, BlueNova engineers use local component suppliers to develop all the control electronics, displays and software in the LIB pack. These expertise and competencies in the local LIB industry can possibly be adopted for VRFB systems.

9.3.2. Tanks

As mentioned, there are various options for constructing electrolyte storage tanks, and EPRI (2007) has noted that the tanks for VRFB electrolytes can be similar to those used for fuel storage. In South Africa, there are numerous manufacturers of fuel tanks, such as Fuel Proof, SBS Tanks, and Redstar Africa Networks, among many others.

9.3.3. Containers

To reiterate, passive components are easier to localise due to their low manufacturing cost and applicability across various industries and markets. Based on the previous research conducted, VRFB system containers are the simplest item to source locally, as importing them would not be cost-effective for VRFB OEMs. Procuring these containers locally could also reduce shipping costs, especially considering the distance between South Africa and international-based OEMs.

Many companies in South Africa supply shipping containers for different industries, such as Seaco Global, Big Box Container, Container King, and Highveld Containers. However, the primary source of containers is China since importing them is more cost-effective than manufacturing them, and they are subsequently retrofitted locally. China leads the world in shipping container production, accounting for over 85% of the world's total production (xChange, 2022) (BizVibe, 2022). In addition, several of the world's top 10 largest shipping container manufacturers, including China International Marine Containers, Singamas Container, CXIC Group Containers Company Limited, and China Electronics Corporation are based in China. While containers can be modified and custom-made for specialised purposes such as VRFBs, it is not clear if local firms can modify containers for VRFBs and other battery technologies.

9.3.4. Pumps, pipes and valves

South Africa boasts of having established manufacturers and suppliers that distribute pumps, pipes, and valves to numerous industries in the local and regional markets. Table 9 lists local companies that supply pumps, pipes, and valves to South Africa. KSB Pumps and Valves, SAM Engineering, and Donnlee Pump Tech are some of the major suppliers of pumps in the mining, manufacturing, chemical and petrochemical, energy, and water and wastewater industries. The KSB Group, Rapid Allweiler, Ebara Pumps South Africa, Prochem Pump Manufacturing, and Roto Pumps are other suppliers of pumps. For valves and pipes, Thermal Value Manufacture (TVM), LVSA, MSV, Industrial Valve & Engineering Supplies, Guth, and RGR Technologies are the major suppliers catering to various industrial sectors such as petrochemical, mining, power generation, and paper and pulp industries. It is not clear if these companies can produce these components for the local VRFB industry and provide the support required from VRFB OEMs.

Table 9: Local pump, valve and pipe suppliers in South Africa

Supplier	Component	Description
KSB Pumps and Valves	Pumps and valves	KSB Pumps and Valves manufactures and supplies components across several industries such as mining (26%), manufacturing (18%), chemical and petrochemical (10%), energy (22%), water and wastewater (21%) and construction (3%).
SAM Engineering	Pumps	SAM Engineering is one of Africa's leading centrifugal pump manufacturers, primarily serving the demands of the mining and petrochemical industries as well as process applications such as food, chemical, and pulp and paper where chemical resistance and anti-corrosive properties are a high priority. The company offers customised pumping solutions for unlimited pump configurations to suit any application.
Donnlee Pump Tech	Pumps	Donnlee Pump Tech has served the mining industry for over 35 years. The company has developed its product range to cater to the specific requirements of the mining industry, throughout South Africa, it also exports to sub-Saharan Africa, Fiji and Ireland.
The KSB Group	Pumps and valves	KSB is a global company with more than 30 manufacturing sites in 19 countries serving water utilities, the energy and mining sectors. Each manufacturing site produces KSB pumps and valves to global quality standards. Valves come in a choice of designs, sizes and materials for a whole spread of applications.
Bray	Valve	Bray International supplies various valve products that are engineered to meet the needs and expectations of customers.
Thermal Valve Manufacture	Valve and pipes	TWM is an industrial valve distributor based in Cape Town. The company has partnered with LVSA, ROMOTAS, and PETREL to offer engineering pipes, valves, and fittings. The main markets this company serves include mining, power generation, petrochemical, pulp and paper, sugar, iron and steel as well as food and beverages.
LVSA	Valves	LVSA is a butterfly valve supplier in South Africa. The company provides industrial valves to several global brands. The market sectors LVSA valves are involved in include petrochemical, pulp & paper, iron and steel, power generation, mining, sugar, oil and gas and food and beverage industries.

Source: Various sources.

10. SCOPE OF VRFB MANUFACTURING AND ASSEMBLY IN SOUTH AFRICA

To achieve localisation opportunities, VRFB OEMs need to ensure that component suppliers meet specific requirements through evaluations of product quality, compliance, and other performance factors. Furthermore, assessments must determine if identified suppliers can competitively supply components for the local vanadium battery industry. Investing in R&D and skills development, and implementing demand policies are crucial to support localisation efforts. The global vanadium industry owes its success to robust R&D efforts and collaborations with a diverse range of stakeholders.

If South Africa commits to developing this industry, it should take a cue from these best practices. Investing in R&D can lead to the development of more efficient and cost-effective production processes for vanadium battery components and systems. Similarly, the option of component supply would only become an option once one or more OEMs pursue significant local storage projects. However, it remains to be seen whether these companies are capable of producing components for VRFBs, and further engagement with them may be necessary to determine their capacities.

To ensure that South Africa does not miss the opportunity to benefit from vanadium beneficiation and local battery production, it is necessary to invest in local manufacturing and supporting ecosystems for new industries. While it may take time to establish local production, demand take-off can help determine the timeframe for implementation, as demonstrated by international VRFB manufacturers.

Although working with universities, research institutions, or international organisations can speed up the process, this may not be feasible in the short run. Therefore, in the short run, it is probable that South Africa would need to import VRFB stacks and some other components to resolve its existing energy crisis, while simultaneously striving to establish local production to support storage demand in the medium to long run. To optimise the results, it is recommended to refrain from importing VRFBs as black boxes, and instead to prioritise the import of stacks and specific components while emphasising the localisation of available resources.

There is currently a small and developing VRFB industry in South Africa with limited options for a local assembler without an international partner that owns the VRFB technology. Bushveld Minerals, a major shareholder in VRFB OEM Enerox/CellCube, could explore how local production could be beneficial through vertical integration. Through a five-year agreement with an energy asset developer, Enerox/Cellcube hopes to install 1GW VRFBs in SADC countries. This creates a significant opening for South Africa to produce and supply locally produced batteries for the project. This level of magnitude of deployment is necessary to stimulate demand.

Pilot projects, such as the Bushveld Minerals one, are crucial for testing and validating new technologies on a small scale before scaling up for commercial production. This would allow for any issues to be identified and addressed before significant investments are made. Therefore, the provision of assistance from government is key to assisting the company in ensuring the success of the pilot project, as this would demonstrate the company’s production capabilities and pave the way for establishing a local VRFB value chain. It should be acknowledged that Bushveld Minerals stands to gain from a local vanadium industry, given its investments in upstream and downstream vanadium activities. However, establishing such a value chain would also aim to create employment opportunities and economic multiplier effects that generate benefits for South Africa’s industries and broader society.

10.1. Driving the local industry through strategic partnerships and collaborations

To overcome the challenges associated with establishing a new local battery industry and adapting to evolving energy technologies, customer requirements, and other global shifts, strategic partnerships and collaborations can often provide a more efficient solution. These collaborative efforts are of utmost importance in fostering the advancement of innovative technologies and expanding market presence, either by broadening product offerings or increasing market reach. Companies and countries are increasingly recognising the value of harnessing capabilities from multiple industries, leading to a rise in cross-sector acquisitions and collaborations. This approach involves adopting new business models and partnering with or acquiring companies that can collaboratively cultivate the necessary expertise, capabilities, resources and services, provided that the partners possess complementary competencies. A crucial aspect of this strategy involves establishing long-term partnerships that entail shared investments and a framework for developing future technologies, among other benefits. In building battery value chains, companies and countries alike can evaluate their capabilities to meet the demands of this emerging market and determine if they possess the necessary expertise. If they lack the expertise, they can still leverage any advantageous positions to participate by forming strategic partnerships, joint ventures or a combination of both.

Over the years, partnerships have demonstrated their importance as a vital means of establishing new competitive advantages and enhancing the resilience and diversity of value chains. The application of strategic partnerships and collaborations has proven successful across various industries such as automotive, pharmaceuticals, oil and gas, mining, clothing and textiles and, more recently, in the manufacturing of LIBs. In the future, it will be imperative for companies to tap into capabilities outside their own sectors to effectively pursue their strategic goals. This approach is precisely what automotive and battery companies are currently adopting. As competition intensifies within the LIB and NEV manufacturing sectors, automotive companies have turned to strategic partnerships as an effective strategy to capture market share and reinforce their positioning. These partnerships enable them to offer a broader product range, fulfil e-mobility targets, and reduce carbon emissions within the transport industry. Achieving these goals often involves vertical integration with chemical or mining companies, as well as establishing joint ventures and alliances between automotive OEMs and LIB manufacturers, and in some cases technology companies. For example, Honda announced in 2022 that it would collaborate with LG Chem to produce NEV batteries in the US. Ford also established a joint venture with SK Innovation in the US, bringing battery production and supply closer to Ford's biggest market, the US (Ford Media Center, 2021). Volkswagen's new battery company, PowerCo, announced that it would form a joint venture with material technology company Umicore to manufacture cathodes and battery precursors (Electrek, 2022).

Collaborations have played a crucial role in not only the development of products but also in their successful commercialisation. This is particularly evident in cases when research institutions, private sector entities, and occasionally state actors have worked together towards building local industries. Through the pooling of resources and expertise, these partnerships have been able to achieve significant cooperation, as exemplified by the Energy Storage Consortium initiated by the Department of Science and Innovation (DSI) as part of the HySA initiative. This consortium has effectively fostered R&D as well as skills development for the local LIB industry. Such collaborative endeavours highlight the potential of South Africa and its ability to form effective partnerships with various stakeholders in the industry.

The South African HySA Energy Consortium also emphasised the significance of investing in domestic partnerships, as it enables local players to swiftly deliver products to meet the needs of their customers. Moreover, domestic supply chains contribute to reducing the carbon footprint and aid in achieving corporate sustainability targets by minimising the transportation distance between manufacturers and end-users. In the context of batteries, localisation is pivotal in enhancing integration within various value chains, including the automotive industry and renewable energy, and creating opportunities for remanufacturing. Strong domestic partnerships should yield benefits beyond the participating companies, generating a positive impact on the overall economy. Collaborating with South African-based manufacturers creates a ripple effect, ensuring the resilience of domestic supply chains and fostering economic growth in the local economy.

Partnerships and alliances are crucial and necessary in the battery manufacturing industry, providing various advantages and opportunities for the parties involved, such as enhancing the value chain, increasing market access, improving capabilities and innovation, developing or enhancing intellectual property and transferring knowledge (Ayoku, 2022). In addition, collaborations help to reduce the significant burden of manufacturing costs and other sunk costs related to production, particularly in emerging technologies such as batteries. As a result, the risks associated with production are distributed among partners. KPMG (2016) notes that partnerships often incorporate outsourcing and collaborating with local suppliers as part of their value chain.

Several agreements and acquisitions have taken place in the vanadium industry. For instance, metals exploration firm Margaret Lake Diamonds and KORID Energy joined forces to construct a VRFB plant in the US. In addition, Largo Clean Energy, a subsidiary of vanadium mining company Largo Resources, is working with Ansaldo Green Tech to explore the potential of a joint venture aimed at deploying VRFBs in Middle Eastern, African and European markets (Murray, 2022). Another potential approach adopted by international entities seeking entry into the VRFB market is the acquisition of an existing OEM. However, acquiring a company alone may not be sufficient to establish local manufacturing capacity, thus it may be necessary to explore alternative options (Rebel Group and TIPS).

In addition to these agreements, establishing subsidiaries presents another potential avenue for alliances. AVL, for instance, has set up a subsidiary named VSUN Energy, which serves as its battery storage manufacturing and design division. Bushveld has constructed a vanadium electrolyte production plant through its subsidiary, Bushveld Energy.

In the local industry, partnerships and collaborations can involve multiple stakeholders, including government departments and institutions such as DSI, IDC, the Department of Trade, Industry and Competition (the dtic) and DMRE, local component suppliers and manufacturers, procurement companies as well as international partners. These partnerships can offer financing, expertise, licensing and IP support, among other offerings.

Given South Africa’s emerging position in vanadium battery production, collaborations and partnerships may prove advantageous for the country. Collaborations can exist between local firms and state-owned companies, in which the state company provides financial or other support to help develop the local firm’s capabilities or production capacity, depending on the specific needs and goals of the parties involved. While Bushveld does not currently plan to launch its own flow battery systems, the company has entered into partnerships and investments with manufacturers in the space, including Invinity Energy Systems, and Enerox/CellCube. The partnership between Bushveld Minerals and the IDC is a notable example, highlighting the importance of alliances and collaborations within the South African battery market. This strategic partnership plays a key role in driving the development of VRFB technology and facilitating industrialisation. It also presents an opportunity for South African suppliers and institutions to enhance their competencies in battery equipment through collaborative efforts with other companies. Acting swiftly is crucial for the country and is important to avoid missing out on the significant potential and opportunities presented by VRFBs.

At the foundation of the value chain lies the need to establish an R&D ecosystem that possesses a deep understanding of VRFB technology and can effectively support all segments across the VRFB value chain. Similar to the HySA programme, which encompassed R&D spanning material synthesis, cell development and manufacturing, recycling and component development, this ecosystem is crucial in providing a knowledge base to support both existing and emerging innovations and manufacturing capabilities within the industry. Ideally, partnerships and alliances in South Africa's VRFB industry should span across various segments of the value chain, encompassing R&D, stack development and battery assembly. Both the government and business sectors should actively contribute to fostering the growth of VRFB knowledge and skills development within the country.

Testing and certification services play a crucial role in ensuring that batteries cells, packs, and modules meet both national and international standards. The process of testing and certification remains a vital component within the battery industry, and it is imperative for R&D efforts to support and enhance these services.

South Africa has already made notable progress in VRFB electrolyte manufacturing, which is subject to considerable patent activity. Supporting electrolyte production is important, but equally important is the development of local knowledge and capabilities in VRFB technology to bolster existing initiatives and accommodate future players. Research institutions such as CSIR, Mintek and NECSA, and universities, renowned for their support of emerging technologies, can extend their focus and support to VRFB technology, particularly in electrolyte manufacturing and stack development. Just as HySA relied on international partnerships to enhance local institutions and facilitate sharing information and developing expertise in the LIB industry, such collaborations would prove beneficial for the VRFB industry as well. Apart from electrolyte manufacturing, there are South African companies with the potential to produce critical components such as membranes, bipolar plates and inverters, which form the core of the VRFB cell stack. However, these companies would require investment in R&D (and scale) to facilitate their growth and ensure their ability to meet the industry's specifications. Thus, R&D support becomes an integral part of the VRFB industry as a whole. The importance of R&D is exemplified in the LIB industry, where institutions and companies have invested in or benefited from R&D, such as in cell manufacturing, component production (BMS and EMS), and in exploring local recycling opportunities. As mentioned, R&D plays a crucial role in achieving cost reductions. Companies consistently strive to lower costs while seeking superior products. If South Africa can produce high-quality membranes and bipolar plates at a lower cost compared to existing options, there is a potential opportunity for exporting these components to VRFB companies.

According to Mining Review Africa, 2022, Bushveld has strategic plans to become a supplier of electrolyte both locally and internationally, which makes partnering with VRFB OEMs a viable option. This collaboration has the potential to enhance South Africa's export capabilities and establish the country as a significant VRFB electrolyte manufacturing hub outside of China. In addition, for locally based VRFB companies, Bushveld could form partnerships with local manufacturers and suppliers of BOP components, including tanks, pumps, valves and other relevant components for electrolyte storage. By doing so, Bushveld would be able to offer a complete electrolyte storage system to local VRFB companies, further strengthening its value add in the market.

Partnerships can also be established between local battery assemblers and VRFB OEMs for local battery assembly. Drawing a parallel with the automotive sector, where South Africa functions as a completely knocked-down (CKD) and SKD assembler of vehicles. The country has the potential to assemble cell stacks or even entire battery packs by leveraging locally sourced components and expertise. However, it is crucial for South Africa to avoid being solely an assembly hub reliant on imported core components, as this would limit the value addition it can offer. To overcome this, it would be advantageous to establish local suppliers to supply components to the local battery industry. This would be based on the assumption that VRFB OEMs will decide to establish their presence in South Africa, emphasising the critical importance of favourable local market demand conditions for VRFBs.

The potential advantages of locating battery assembly or other battery activities within the ELIDZ, close to the electrolyte manufacturing plant, could be significant. This proximity opens up the possibility of establishing a battery industrial park that includes VRFB and LIB manufacturers and various related operations. In addition, establishing a battery supplier park in the Coega Industrial Development Zone could also be an option. This would facilitate the co-location of multiple battery value chain activities, such as cell imports, battery pack assembly, the manufacturing of enclosures and harnesses, and software development (Customized Energy Solutions, 2023).

Given the significance of procurement and the promotion of local demand in the VRFB industry, the state assumes two roles. First, it provides financial investment to companies involved in the VRFB value chain, and second, it participates in the procurement of VRFBs. Consequently, there are opportunities for partnerships between the state and manufacturing companies, as well as opportunities for financial support in establishing a local pilot plant. Local demand is important for creating an enabling environment for local suppliers. Eskom and municipalities could partner with OEMs to procure VRFBs with high local content targets in order to assist local players. In addition, mining companies, as major drivers of energy storage demand, can partner with OEMs to procure VRFBs. Moreover, if feasible, the state can explore the establishment of a pilot plant for local VRFB assembly. This initiative can leverage the experience and expertise of local and international companies involved in VRFBs, as well as draw insights from existing battery assemblers and manufacturers. It is crucial again to emphasise that the viability of component suppliers relies heavily on local demand.

According to Whitfield, et al. (2021), strategic partnerships play a significant role in industrial policy, and governments can support these agreements to promote developmental objectives. This study explored the potential of African countries to deepen industrialisation and build regional value chains. While Whitfield, et al. (2021) based their research on the clothing and apparel sector and building global value chains, their findings may be relevant across various industries and sectors. Instead of solely focusing on either foreign investment or local firms, governments should develop industrial policies that facilitate technology transfer by leveraging foreign expertise. To achieve this, governments can demand that foreign companies or VRFB OEMs support local firms in exchange for fiscal and financial benefits. This may involve requiring foreign companies or VRFB OEMs to assist local firms in exchange for fiscal and financial benefits and using specific knowledge transfer indicators and performance criteria to evaluate the progress and challenges of these partnerships.

Various departments can also establish partnerships for long-term sourcing or procurement of VRFBs. As stated by Whitfield et al. (2021), industrial policy can play a crucial role in facilitating local-foreign investor partnerships, which provide opportunities for local investors and managers to learn from their foreign counterparts. However, for such partnerships to be successful, incentives and necessary conditions must be in place to ensure that local firms are active and proactive partners rather than passive ones. It is essential that local partners are active participants in partnerships to facilitate learning and maximise benefits to the local companies and economy, as emphasised by Whitfield, et al. (2021). In addition, industrial parks and SEZs financed by governments can be helpful in lowering production costs and improving lead times in specific locations, but they are not enough if they do not include and benefit local firms. It is crucial for local firms to co-locate near foreign firms to take advantage of direct and indirect spillovers that occur in industrial clusters.

10.2. The role of skills in VRFB manufacturing

The availability of skills is a crucial factor to consider when establishing a new industry locally. Local knowledge and expertise, including both explicit and tacit information, have been recognised as essential for the success of OEMs in the local market. It is imperative that local suppliers possess the necessary skills and knowledge to fill the gaps of a foreign company. In particular, local partners that can offer market-specific knowledge, engineering expertise, and O&M support are of great importance (Thielmann et al., 2021).

Battery manufacturing and assembly require a distinct set of skills and qualifications, including technicians and engineers specialising in mechanical, electrical, automation, and industrial fields, as well as software developers and highly skilled PhD graduates. Relevant experience in battery manufacturing and assembly is also highly valued. Therefore, having access to a pool of skilled and experienced workers is crucial for the growth of the battery manufacturing and assembly industry, as noted by Montmasson-Clair et al. (2021). South Africa has a well-established and competitive lead-acid manufacturing industry, owing to a skilled workforce, access to battery raw materials and proximity to vehicle manufacturing and assembly. In addition, South Africa also has a vibrant, local LIB assembly industry, using imported cells mainly from East Asia (Montmasson-Clair et al., 2021). Montmasson-Clair et al. (2021) report that South Africa’s LIB assemblers, which mainly consist of SMMEs, are involved in the development and design of balance of plant components, specifically the BMS and EMS. These assemblers use their own proprietary BMS, which includes patents and intellectual property, as previously stated. In addition, some companies have invested in developing in-house training programmes, at their own expense, to train new hires in battery manufacturing. This effort has resulted in an increased supply of skilled labour in both battery assembly and component manufacturing.

Furthermore, South Africa has managed to develop a local knowledge base in battery R&D and manufacturing of LIBs through the Energy Storage Consortium. This DSI initiative, in collaboration with companies and local universities, has positively contributed to the development of relevant battery skills in the country (Montmasson-Clair et al., 2021). Establishing partnerships with leading institutions in countries such as the US, Germany, Singapore and China has also allowed for the development of skills and R&D capabilities. As a result, to date, access to skills has not been a key constraint for most companies operating in the LIB value chain (Montmasson-Clair et al., 2021). However, South Africa remains far behind leading countries in LIB-related R&D and skills development. However, if the industry expands, skills could become a limiting factor.

Lead-acid batteries and, to a certain extent, LIBs are more manageable because of the existing knowledge base and skilled expertise available on the continent. However, there is a scarcity of experts in VRFB technology who could easily provide maintenance and operational support, which is a crucial factor to consider when deploying these batteries.

VRFBs and fuel cells share some components. South Africa could look to the fuel cell industry to support the production of vanadium and the wider ecosystem of vanadium batteries, particularly for the membrane and separators. South African manufacturers possess the necessary equipment and expertise to produce BOP components such as pumps, pipes, and valves for a range of industries, including mining, industrial, and chemical sectors. However, these components are not specific to battery manufacturing, and workers would need to acquire additional skills and competencies that can be readily applied or adapted to battery production processes. Furthermore, workers should be trained to understand the risks and safety considerations associated with various battery technologies.

The development of VRFB technology in South Africa would require local workers to possess the necessary skills and capacity to support its advancement and provide continuous support to O&M. Although the country may not currently have access to IP or licenses in VRFBs, fostering a culture of continuous learning, innovation, and knowledge-building would be crucial in developing local knowledge and expertise. South Africa has demonstrated this capability in several industries, including LIBs, fuel cells and nuclear power.

11. CONCLUSION AND RECOMMENDATIONS

In conclusion, the potential of VRFBs to transform the energy storage sector has sparked widespread interest in their production. South Africa, being one of the world’s largest vanadium producers, has a unique opportunity to capitalise on the growing demand for battery storage by investing in local manufacturing. Benefits include value addition to vanadium mineral, economic growth, investment in new technologies, and development of high-value products for export. In addition, exploring opportunities for localising the vanadium electrolyte can lead to cost savings and increase the affordability of VRFBs, thereby assisting with their widespread adoption in a market currently dominated by LIBs. To establish and advance battery industries, investment in R&D is critical, and the country has successfully demonstrated its capabilities in investing in R&D for emerging technologies in the past. South Africa has the necessary components to support the battery industry, although it is worth investigating whether the industry can cater to vanadium batteries specifically. In summary, South Africa has a compelling rationale to explore VRFB prospects and can gain significant advantages from local production if there is sufficient demand and policy support.

Based on the analysis of the VRFB value chain, several policy recommendations can be made to support demand and the development of a local VRFB industry in South Africa.

The initial recommendation pertains to establishing a local market for VRFBs. To encourage the adoption of VRFBs and strengthen the prospects of local VRFB manufacturing, policies need to ensure the inclusion of long-duration storage systems. South Africa's procurement approach is technology-neutral, but it could be made to be inclusive of long-duration storage technologies, particularly in utility scale applications. This could be done through ensuring that procurement tender specifications are inclusive of the different battery technologies, including VRFBs. However, policymakers should exercise caution when using policies to reduce the costs of one technology at the expense of another (beyond market dynamics). Japan and China, the two biggest markets for VRFBs, have implemented policies that prioritise long-duration storage to foster local VRFB demand. In both countries, the market for VRFBs is supported by locally manufactured batteries. This approach may be suitable for South Africa as well. Government support and assurance in long-term policy objectives is important for VRFBs. Government procurement is essential. Governments play a crucial role in reducing uncertainties and mitigating investment risks. Given the uncertainties brought about by battery technologies, policy frameworks should have a level of flexibility to effectively respond to changing conditions, such as evolving environmental risk evaluations, emerging technological options, or fluctuating prices.

Another aspect of value that should be considered is the emphasis on VRFBs’ long lifespan. This means that the system can operate reliably for 25 years. Therefore, even with the high costs, considering that solar PV and wind turbines for example also have a lifespan of 20 years on average, VRFBs become an ideal technology to complement this renewable energy source. If complementing renewable energy value or technology value is high, then policies geared to establishing support for systems to operate reliably for 25 or 50 years become important for VRFBs and could offer an advantage for the technology. Such policies would grant VRFB technology and other long duration technologies a distinct advantage in terms of long-term reliability, thereby enhancing the overall value of integrating renewable energy sources. Still, it's 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. Another crucial factor is the implementation of technical requirements for BESS projects that stipulate a minimum number of cycles per annum or a system’s operation for over 20 years. With a reusable electrolyte and the ability to have infinite cycles, VRFBs have exceptional durability, allowing the battery to last more than 20 years. Although VRFBs may have higher initial costs, they offer a reliable operational capacity of at least 20 years, resulting in a relatively low TCO compared to LIBs. Therefore, VRFBs provide an advantageous complementary storage option for integrating renewable energy sources. Customers can benefit from the assurance that the VRFB system will last throughout the lifespan of the renewable energy sources without the need for frequent battery replacements, which result in high OPEX costs.

Third, lowering the price of vanadium is important for lowering the high capital cost of VRFBs. 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. While South Africa's vanadium reserves offer the potential for gaining access to cost-competitive 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 Group and TIPS, 2022). Achieving this may be possible through vertical integration in the value chain. However, there is no guarantee that a local VRFB OEM in South Africa would be able to acquire vanadium at a preferential price. For numerous sectors, including chemicals, iron and steel, the problem of local upstream producers charging import-parity prices instead of export-parity prices to downstream manufacturers has been a persistent and unresolved issue (Parr, 2005; Rebel Group and TIPS, 2022).

Fourth, strategic business models such as renting or leasing of the electrolyte could be considered to further reduce the relatively high CAPEX for VRFBs. For example, the VERL model offered by Bushveld Minerals to Invinity Energy Systems may serve as a potential solution to address the instability in vanadium prices and the high costs associated with VRFBs.

To foster local VRFB manufacturing, the government should establish a supportive policy framework that includes financing, strategic industrial policy interventions and leveraging on existing policy incentives aimed at attracting investment. To establish new industries, access to state funding is key. The LIB industry has faced setbacks due to insufficient financing, which could have been remedied by providing LIB producers with opportunities to scale up. The partnership between IDC and Bushveld Minerals in the VRFB industry serves as a prime example of how state funding can foster emerging industries. This collaboration is set to propel the company to become a significant player in the industry, and OEMs are expected to set up operations in South Africa to access its electrolyte, which can also be exported. Consequently, this is likely to attract further investments, both local and international suppliers and manufacturers, thereby boosting the country's economic development.

In addition, the government can provide funding for R&D, access to technology and expertise, and promote partnerships between local and international companies to support VRFB component manufacturing. DSI is an important stakeholder for driving R&D in battery technologies. Government should also promote international cooperation and knowledge sharing and technology transfers with other countries that are leaders in VRFB manufacturing and R&D. The development of a local VRFB industry will require a skilled workforce. The government, or DSI, could support the R&D and development of training programmes in VRFB manufacturing and related technologies to ensure a pipeline of skilled workers. R&D also assumes a critical role in providing support for testing and certification services, ensuring that VRFBs conform to both national and international standards.

Lastly, manufacturers can leverage on existing policies and programmes, such as for example the SEZ policy, the 12B tax allowance and the Manufacturing Competitiveness Enhancement Programme (MCEP) Production Incentive (PI). Section 12B(1)(h) offers a deduction for CAPEX used in generating electricity from renewable energy sources, including wind, solar PV and CSP, among others. Expanding this incentive to encompass BESS or ESS projects in general could be beneficial to VRFBs. This expansion would promote the co-location of renewable energy sources with BESS/ESS, resulting in additional benefits such as maximising land usage and grid capacity. 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 therefore aid in boosting both market demand and local manufacturing.

By implementing these policy recommendations, South Africa could create a local VRFB industry with high levels of local content that can support economic development, job creation, and technological innovation. The country could also play a leadership role in the global VRFB market, providing a competitive advantage and supporting a more sustainable energy system.

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