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The Vanadium Grid-Storage Economy

Can South Africa turn vanadium, electrolyte and domestic storage demand into a competitive long-duration battery industry?

4.5%	≈16 h	8m L/y
of 2025 world vanadium output	central model parity	BELCO electrolyte design

South Africa | Vanadium | Long-duration energy storage

Inside the note

A map of the argument, model, evidence, and qualifications.

PART I
The answer

PART I: The answer

Build for the hours lithium finds hardest

South Africa can build a meaningful vanadium battery industry, but not by assuming that a domestic mineral automatically creates a domestic technology advantage. The country produced about 5,000 tonnes of vanadium in 2025, roughly 4.5 per cent of estimated world output, and held about 520,000 tonnes of reported reserves, around 2.5 per cent of the world total. That is a useful industrial base, not a commanding resource monopoly. China and Russia remain much larger producers. US Geological Survey, *Mineral Commodity Summaries 2026*.

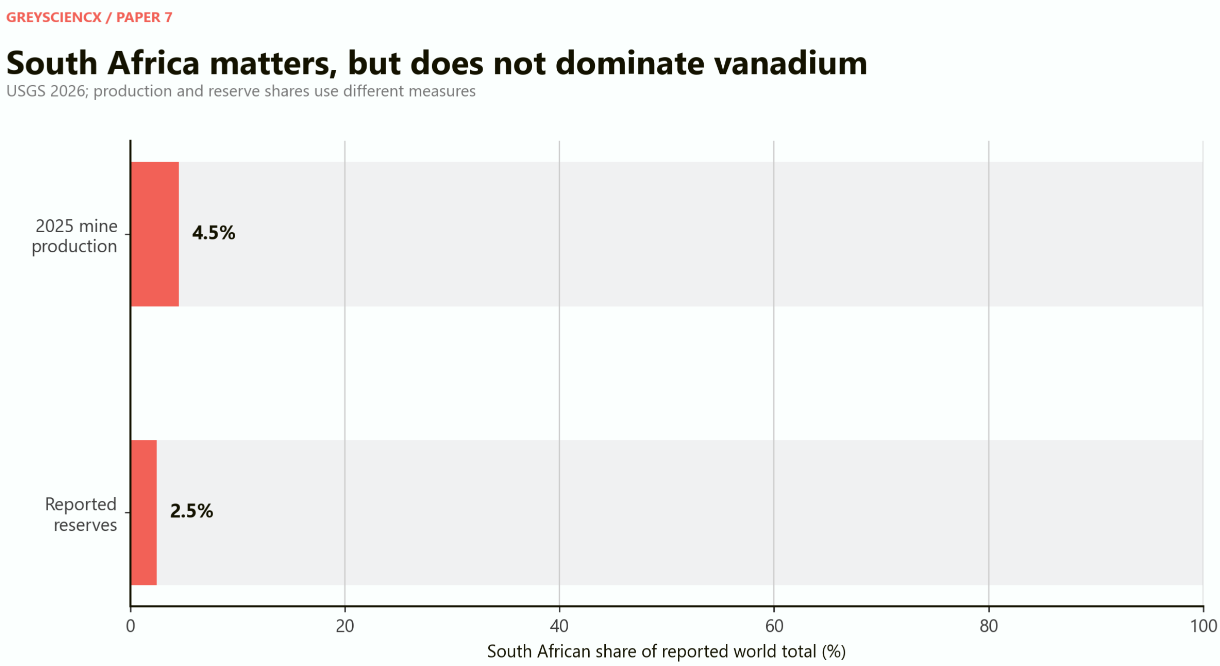

Figure 1. South Africa is a material vanadium producer, but it does not dominate supply. Production and reserve shares use different denominators and should not be added.

The country nevertheless has three advantages that rarely occur together. It has vanadium-bearing mineral and processing experience. It has a real, growing need for stationary electricity storage. And it has already built a commercial-scale vanadium-electrolyte facility in the East London Industrial Development Zone. These advantages create a credible opening for a mine-to-storage industry.

They do not eliminate the harder facts. Lithium-iron-phosphate batteries already dominate new stationary deployments. Their supply chain is enormous, their prices have fallen quickly, financiers understand them, and South African procurement has largely been designed around four-hour lithium systems. Vanadium-redox-flow batteries, or VRFBs, are less efficient and often dearer at short durations. Their suppliers are smaller, their bankability is weaker and their operational record is less standardised.

The strategic question is therefore not whether vanadium can store electricity. It can. The question is where the whole system - capital, charging losses, replacements, life, safety, degradation, recyclability and finance - beats the alternatives.

The central conclusion: South Africa should build a focused long-duration-storage platform around qualified electrolyte, tanks, pumps, balance-of-system equipment, power electronics, containerisation, project integration and closed-loop recovery. It should partner for membranes and stacks until demand and manufacturing yield justify deeper localisation. The first market should be high-cycle, fire-sensitive and space-tolerant stationary applications at roughly twelve to twenty-four hours, not the four-hour market already occupied by lithium-ion batteries.

Under this paper's central assumptions, lifetime cost parity with lithium iron phosphate appears at about sixteen hours. That is a model result, not a physical law. Cheap lithium, low cycling, high interest rates or poor flow-battery performance move the crossing point later. Strong cycling, lower-cost vanadium, patient finance and valuable safety or longevity move it earlier.

Seven findings

First, the domestic demand is real but not automatically vanadium demand. South Africa's 2025 Integrated Resource Plan assigns 8.5 GW to storage by 2039, while Eskom and the battery independent-power-producer programme are already procuring material capacity. Yet the official cost basis is a four-hour lithium-ion battery. A storage target creates an opportunity to compete; it is not an order book for VRFBs. Department of Electricity and Energy, *Integrated Resource Plan 2025*.

Second, duration is the market wedge. The power equipment in a flow battery and the energy-holding electrolyte can be sized separately. Adding hours largely means adding tanks and electrolyte, whereas a lithium system adds complete battery modules. This makes flow batteries progressively more interesting as duration increases.

Third, electrolyte is strategically important but commercially incomplete. The Bushveld Electrolyte Company, or BELCO, was designed for eight million litres a year and was described as capable of serving roughly 200 MWh annually. A single 100 MW, ten-hour project in this model needs about fifty million litres - more than six years of that design output. One facility is a base from which to scale, not a full industrial ecosystem. Bushveld Minerals, BELCO.

Fourth, factory capacity is not demand. Bushveld Minerals later moved away from its integrated energy strategy and sought to divest the energy business; related operating entities subsequently entered business rescue. This is not proof that VRFB chemistry failed. It is evidence that a mining company can overextend itself by carrying mine risk, commodity-price risk, technology development, manufacturing and project finance at the same time. Bushveld Minerals, *Annual Report 2023*; Matuson Associates, Bushveld Minerals business rescue.

Fifth, the best early localisation is not necessarily the most glamorous. Tanks, piping, pumps, thermal management, skids, containers, civil works, controls, power electronics, commissioning and maintenance can create more robust domestic income than an underused membrane plant. Imported stacks inside a locally integrated, warranted system may be a better first industrial product than nominally local stacks with no bankable customer.

Sixth, leasing changes who finances the vanadium; it does not make it free. Electrolyte can remain the property of a lessor and be recovered after the project. This lowers project capital and can protect residual value. But a commercial lease must still cover the metal, financing, insurance, price risk, logistics and recovery. A public or development-finance vehicle can reduce the cost if it genuinely has cheaper capital and disciplined take-back rights.

Seventh, South Africa should export systems only after it can service them. A complete storage container has more gross sales than exported oxide, but much of its invoice belongs to non-vanadium components and warranty obligations. The defensible export product is not a container with a South African flag. It is a tested, certified system with performance data, a solvent guarantor, spare parts and technicians who can keep it operating for two decades.

PART II

What a vanadium flow battery actually is

PART II: What a vanadium flow battery actually is

Energy in liquid, power in a stack

A vanadium-redox-flow battery stores energy in two tanks of water-based electrolyte containing vanadium ions in different oxidation states. Pumps circulate the liquids through an electrochemical stack. During charging, electrical energy changes the ions' oxidation states. During discharge, the process reverses and releases electricity. A membrane separates the two sides while allowing charge-carrying ions to pass.

This architecture separates two functions that are bundled together inside a conventional battery cell. The **stack and power electronics** determine how quickly the battery can charge or discharge. The **amount of electrolyte and tank volume** determine how much energy it can store. A 100 MW four-hour plant and a 100 MW twenty-hour plant can use similar power equipment but very different tank volumes.

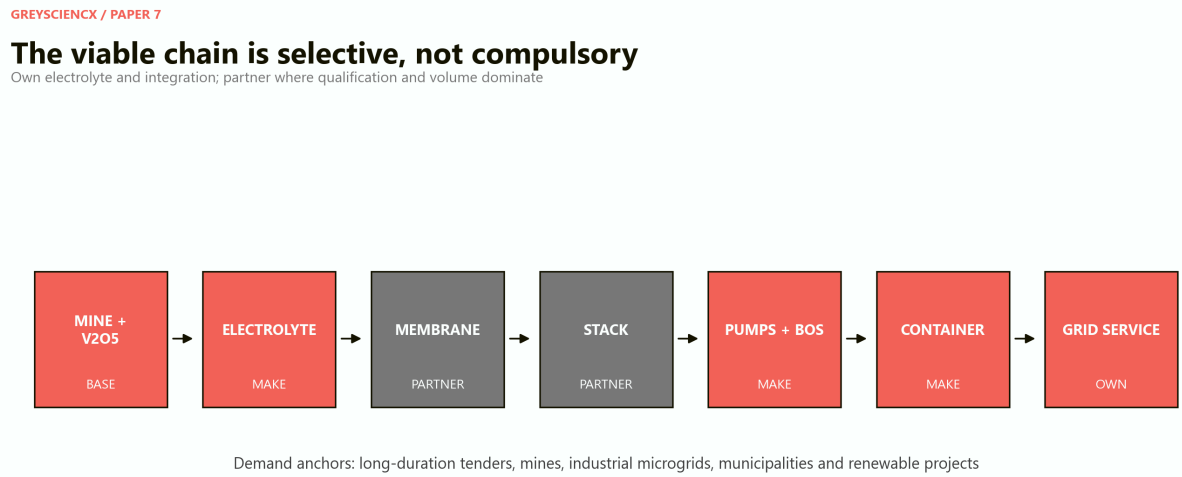

Figure 2. The chain contains several distinct businesses. The recommended early strategy owns electrolyte, mechanical balance of system, integration and recovery while using qualified partnerships for the most difficult electrochemical components.

The separation produces the technology's main economic attraction. At long duration, the cost of added energy capacity can rise more slowly than in a modular lithium system. It also creates operating advantages. The aqueous electrolyte is non-flammable, the system can cycle deeply without the same degradation mechanism as lithium cells, and the liquid can be rebalanced or recovered. Tanks and piping can be designed for a long service life, while stacks are replaced or refurbished separately.

The same architecture creates disadvantages. Pumps consume energy. The stack, membrane and plumbing add complexity. Round-trip efficiency is commonly lower than for lithium-ion systems, so more electricity must be bought to deliver the same output. The footprint is larger. Electrolyte contains a valuable commodity whose price can move sharply. Leakage and contamination must be controlled. And a twenty-year technical life does not help if the supplier providing the warranty fails after five.

The chain is wider than vanadium

Mining produces vanadium-bearing ore or recovers vanadium as a co-product from steel-related feedstock. Economics depend on ore grade, recovery, power, labour, logistics and the prices of associated products.

Refining converts feedstock into vanadium pentoxide or other high-purity compounds. Battery electrolyte requires consistent purity: contaminants that are acceptable in metallurgical use can impair electrochemical performance.

Electrolyte production dissolves and chemically conditions vanadium into the required ionic states. The product is heavy and mostly water, which favours production near the deployment market once quality can be guaranteed.

Membranes permit ionic transport while limiting unwanted crossover. They are a small physical component with a large effect on efficiency, durability and cost.

Stacks contain repeating electrochemical cells, electrodes, bipolar plates, seals and compression structures. Manufacturing yield, electrical resistance, leak prevention and field durability matter more than the mere presence of a local assembly line.

Pumps and balance-of-system equipment move electrolyte, manage pressure and temperature, monitor the plant and keep it safe. These are promising localisation areas because South Africa already has industrial fluid-handling, mining-equipment and fabrication capabilities.

Power electronics and controls connect the direct-current battery to the alternating-current grid. Inverters, transformers, switchgear, protection systems, dispatch software and grid-code compliance are central to what the customer buys.

Containerisation and civil integration convert components into a project: tanks, bunding, pipework, buildings, foundations, fire and environmental systems, commissioning and site acceptance.

Operation, leasing and recovery continue for decades. Monitoring, electrolyte testing, stack refurbishment, vanadium rebalancing and end-of-life take-back can create a recurring service industry.

The further downstream the country moves, the smaller vanadium becomes as a share of the invoice. That is not a reason to remain upstream. It is a reason to measure domestic value honestly.

PART III

The resource advantage - and its limit

PART III: The resource advantage - and its limit

A useful position, not mineral sovereignty

South Africa was the third-ranked vanadium producer in 2024, according to the US Geological Survey. Production fell from an estimated 8,050 tonnes in 2024 to 5,000 tonnes in 2025 in the 2026 commodity summary. China accounted for about 82,000 tonnes and Russia 21,000 tonnes in 2025. South Africa's 520,000 tonnes of reported reserves compare with a world total of roughly 21 million tonnes. USGS, South Africa minerals information; USGS, *Mineral Commodity Summaries 2026*.

These figures matter because industrial strategies often begin with an exaggerated premise: that South Africa "has the vanadium" and can therefore set the terms of the downstream market. It cannot. It has enough material and knowledge to support a domestic chain, but customers can source vanadium elsewhere and competing countries can build factories without South African ore.

The advantage is more practical:

- established knowledge of vanadium-bearing ores and refining;
- the possibility of traceable local feedstock and shorter working-capital chains;
- an incentive to develop purification, electrolyte analytics and recycling;
- a domestic customer base that can validate products near the factory; and
- industrial capabilities in tanks, piping, mining equipment, power systems and project construction.

The resource is most valuable when paired with a customer problem. South Africa has that problem in abundance: variable renewable generation, weak networks, costly diesel backup, congested substations and industrial users that place a high value on continuity.

Vanadium demand must not be confused with steel demand

Most vanadium is used in steel alloys, not batteries. The battery industry therefore competes with a larger incumbent market for feedstock. A storage boom can lift the value of vanadium, but a high metal price also makes electrolyte expensive and can damage VRFB competitiveness. The supplier benefits from a price increase while the battery developer suffers.

That conflict is one reason vertical integration is not automatically stabilising. A group owning both mine and battery company can transfer material internally, but the economic opportunity cost remains. If steel buyers pay more, subsidising the battery arm means foregoing mining profit. If vanadium prices collapse, the battery looks cheaper but the mine's balance sheet deteriorates.

A durable industry therefore needs commercial tools rather than accounting illusions: long-term offtake bands, transparent transfer pricing, indexed customer contracts, metal leasing, inventory finance and recovery rights.

PART IV

South Africa's real starting point

PART IV: South Africa's real starting point

BELCO proves capability, not utilisation

The Bushveld Electrolyte Company facility at the East London Industrial Development Zone is the clearest physical starting point. Bushveld described the plant as designed to produce eight million litres of vanadium electrolyte a year using more than 1,100 tonnes of vanadium-oxide equivalent, with possible expansion to 32 million litres. A 2023 company presentation described commissioning as completed and indicated capacity equivalent to about 200 MWh a year. The ELIDZ announced the investment in April 2024 at about R400 million and 59 direct jobs. Bushveld Minerals, BELCO; East London IDZ, new investments; Bushveld Minerals, *H1 2023 Results Presentation*.

Public descriptions do not establish sustained output, qualification volumes or an order book. This distinction matters. Commissioning proves that equipment can be installed and brought into operation. Commercialisation requires repeat batches that meet customer specifications, sales at a viable margin, working capital, transport arrangements, bankable warranties and projects large enough to use the line.

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One long-duration project can absorb several years of electrolyte output

BELCO design capacity compared with an illustrative 100 MW / 10 h VRFB

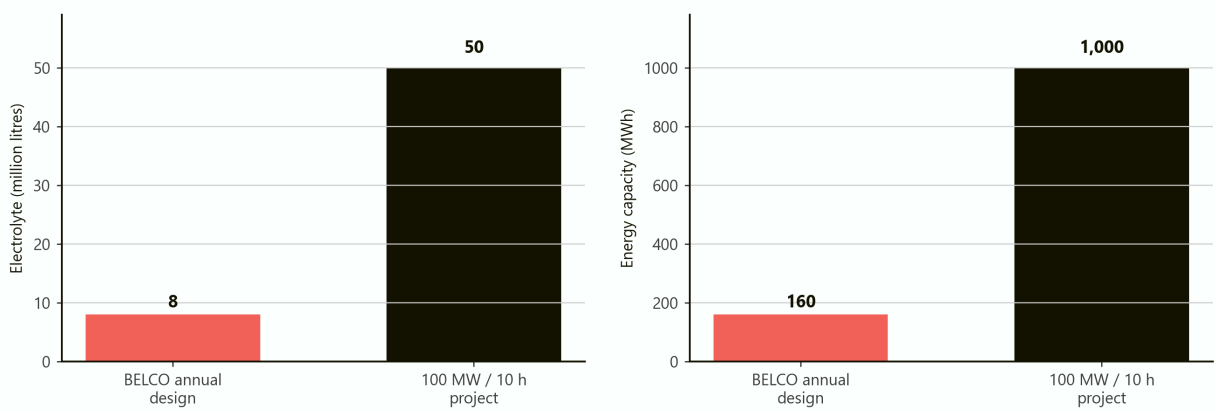

Figure 3. Under the paper's physical assumptions, a 100 MW, ten-hour VRFB requires about fifty million litres of electrolyte - 6.25 years of BELCO's eight-million-litre annual design capacity. Bushveld described a somewhat higher MWh equivalence; chemistry and litres per kWh vary by design.

The comparison cuts both ways. A single utility project can overwhelm the existing line, which makes expansion plausible. Yet an eight-million-litre plant can also sit underused if projects do not reach financial close. The industrial bottleneck is not merely litres. It is bankable demand timed to production.

The Vametco mini-grid is a useful but small proof point

Bushveld reported a hybrid mini-grid at the Vametco mine combining 3.5 MW of solar with a 1 MW, 4 MWh VRFB. It demonstrates local integration and gives operators experience with the technology. Four megawatt-hours, however, is far from the scale required to establish a competitive manufacturing supply chain. A demonstration becomes industrial evidence only when it produces open operating data and repeat orders. Bushveld Minerals, *Annual Report and Financial Results 2022*.

Corporate distress is part of the technology economics

Bushveld's later retreat from vertical integration is one of the most important facts in this paper. The 2023 annual report described a strategy to focus on core mining and divest the energy business, including BELCO. Subsequent business-rescue proceedings involving Bushveld-related entities make the bankability problem concrete.

This history should not be simplified into “flow batteries failed.” Commodity operations, debt, operational performance and corporate structure all matter. Nor should it be ignored as irrelevant finance. A twenty-five-year battery depends on its supplier's ability to honour warranties, supply spares, maintain software and process electrolyte. Corporate durability is a component of levelised cost.

The institutional lesson is to separate risks:

- mines should sell qualified material under transparent contracts;
- an electrolyte vehicle should carry inventory and recovery rights;
- technology partners should guarantee stacks and membranes;
- project companies should finance operating assets against customer revenue; and
- public support should pay for measurable learning, not absorb every loss in one conglomerate.

PART V

The domestic market

PART V: The domestic market

Storage has moved from experiment to infrastructure

South Africa's power system needs several different products that are casually grouped under “storage.” Millisecond response stabilises frequency. One to four hours can shift solar energy into the evening peak or defer local network upgrades. Eight to twenty-four hours can cover longer ramps, reduce curtailment or support an industrial micro-grid through a prolonged interruption. Multi-day shortages require still more energy and may favour pumped hydro, thermal storage, fuels, demand response or a portfolio rather than electrochemical batteries alone.

The 2025 Integrated Resource Plan reports about 0.2 GW of battery storage installed, all by Eskom, and assigns 8.5 GW of storage by 2039. Eskom's first battery phase covers 199.04 MW and 833.16 MWh across eight sites, an average duration of roughly 4.2 hours. Separately, the first three bid windows of the Battery Energy Storage Independent Power Producer Procurement Programme total 1.744 GW of power capacity: 513 MW, 615 MW and 616 MW. Energy capacity, operating specification and site contracts determine the actual market, so gigawatts alone cannot be converted into electrolyte demand. Eskom, Battery Energy Storage System; Eskom, *Integrated Report 2025*; South African Government, BESIPPPP Bid Window 3.

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The domestic storage market is becoming material

GW; installed capacity, awarded/procured rounds and a planning allocation are not equivalent

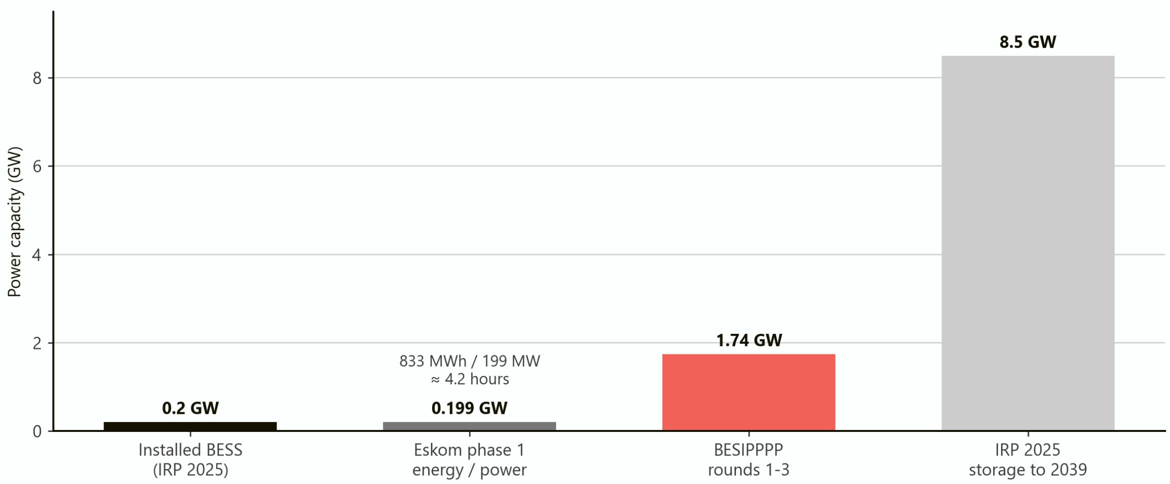

Figure 4. Installed capacity, awarded procurement and the 2039 planning allocation are different categories. The 8.5 GW figure is a system-plan opportunity, not a contracted VRFB pipeline.

Official planning assumptions reveal the commercial challenge. The Electric Power Research Institute's cost work for the IRP models a 100 MW, four-hour lithium-ion battery. Procurement shaped around that reference naturally rewards the mature incumbent. A bidder offering a long-duration flow battery may have to price unused hours into a contract that pays mainly for four. EPRI, *Supply-Side Cost and Performance Data for IRP 2023/2024*.

A technology-neutral market still needs duration-specific products

"Technology neutral" should not mean buying one generic battery service and accepting the cheapest short-duration bid. It should mean defining the system problem and allowing any technology to solve it.

A serious procurement programme would purchase separate products:

Product	Indicative need	Relevant contenders	What must be paid for
Fast grid response	seconds to 1 hour	lithium-ion, flywheels, demand response	speed, availability, accuracy
Evening shifting	2-6 hours	lithium-ion, pumped storage	usable delivered energy and cycles
Long daily shifting	8-16 hours	flow batteries, pumped storage, thermal, lithium	duration, throughput and degradation
Industrial continuity	4-24 hours	hybrid batteries, solar, generators, demand response	reliability and avoided outage cost
Multi-day adequacy	24+ hours	pumped hydro, thermal, fuels, portfolios	seasonal availability and firm capacity

VRFBs should win only where their attributes are valuable. A local-content preference can help a credible product cross its early scale gap, but it should not force an expensive technology into an unsuitable service.

PART VI

Counting value without counting the same vanadium four times

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One tonne, four alternative endpoints

The model follows one tonne of contained vanadium into alternative products. It uses an analytical vanadium-pentoxide price of USD8 per pound, not a claim about the spot price on the publication date. It assumes 1.785 tonnes of V_2O_5 per tonne of contained vanadium, 0.087 kilograms of vanadium per litre of electrolyte and fifty litres per kWh of storage.

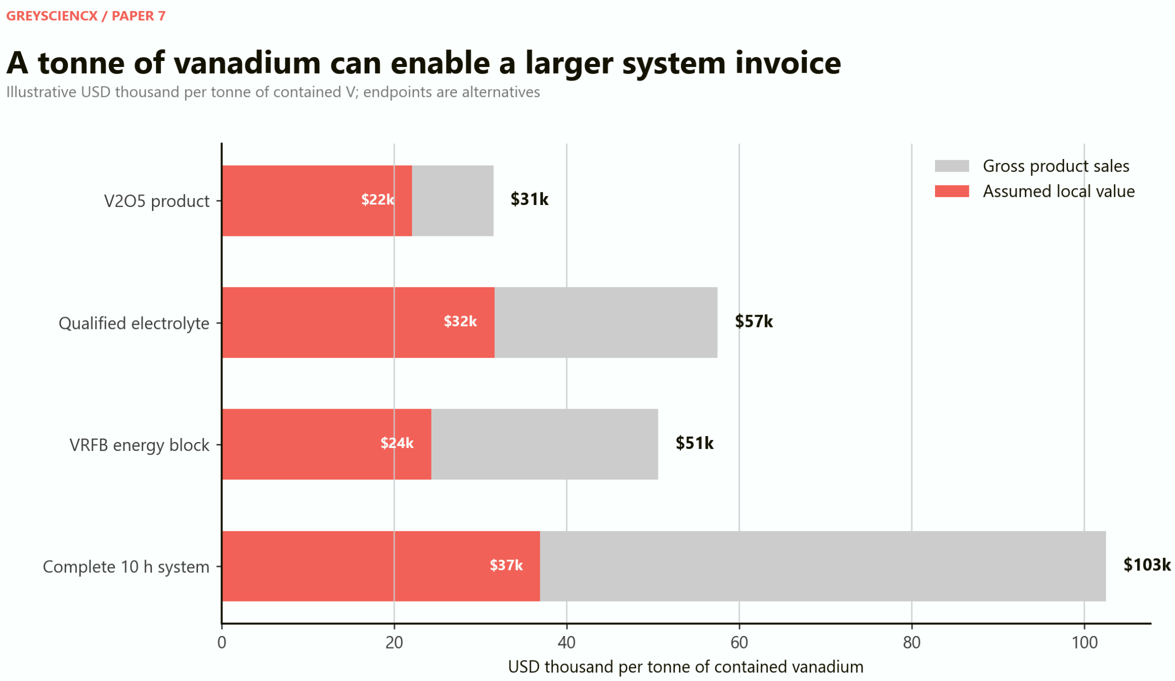

Figure 5. Gross sales and South African value added are shown for alternative endpoints. They are not sequential values and must not be summed. A complete system's invoice is mostly enabled by, rather than physically composed of, vanadium.

As V_2O_5, one tonne of contained vanadium supports about USD31,500 of gross sales and an assumed USD22,000 of South African value. As qualified electrolyte, it supports about USD57,500 of sales and USD31,600 of local value. In an energy block, the model gives about USD50,600 of sales and USD24,300 of local value. In a complete ten-hour system it enables about USD102,500 of sales and USD36,900 of local value.

Why does the energy block appear worth less than the electrolyte? Because these are separate stylised endpoints using different assumed prices and local shares, not a literal production account. The chart is designed to stop a more serious mistake: adding the oxide, electrolyte, energy block and system invoice as if the same tonne were sold four times.

Gross system revenue is not mineral beneficiation. The system includes stacks, membranes, tanks, pumps, inverters, switchgear, software, civil works, finance, testing and warranty. The policy target should be **domestic value added**, not the invoice value of imported components passing through a local assembler.

Ten modules, not one imaginary megafactory

The model compares ten illustrative investments at independent scales. They are not a single mass-balanced chain. A 250 MW membrane plant does not necessarily feed the 100 MW stack line; the refining module does not necessarily supply only the electrolyte module. The purpose is to compare capital intensity, jobs, export potential and capability.

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Systems create value only when projects create orders

Illustrative standalone modules; bubble area is direct employment and scales differ

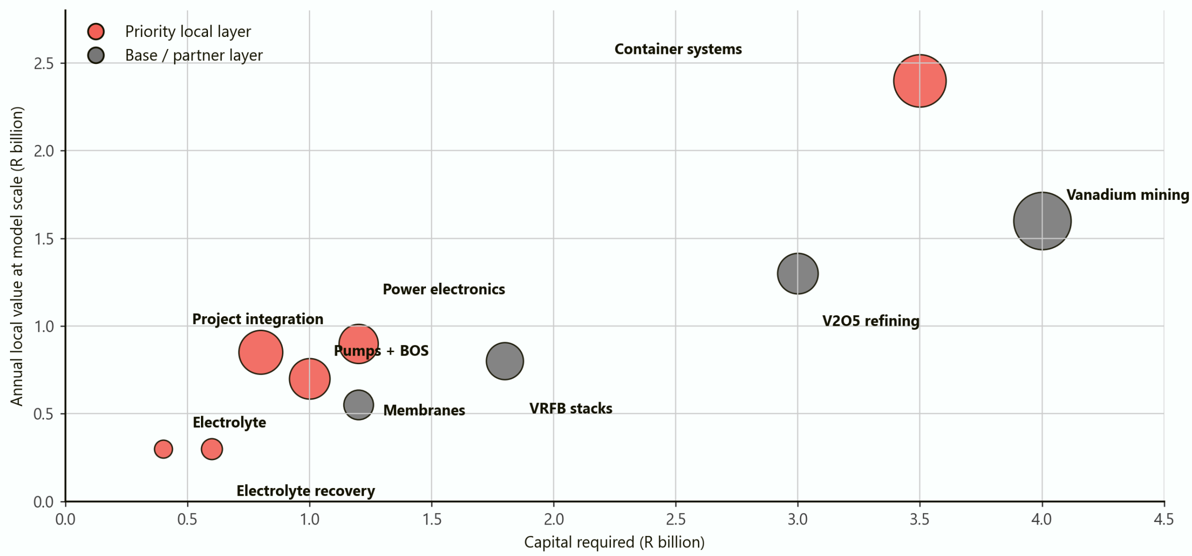

Figure 6. Illustrative annual local value versus capital required. Bubble size represents direct jobs. Project integration and equipment modules can deliver attractive value per rand without requiring ownership of the whole chain.

Module	Illustrative scale	Capital	Annual local value	Direct jobs
Vanadium mining	5 kt V/y	R4.0bn	R1.60bn	600
V2O5 refining	8 kt/y	R3.0bn	R1.30bn	300
Electrolyte	8m L/y	R0.4bn	R0.30bn	59
Membranes	250 MW/y	R1.2bn	R0.55bn	160
VRFB stacks	100 MW/y	R1.8bn	R0.80bn	250
Pumps and balance of system	100 MW/y	R1.0bn	R0.70bn	300
Power electronics	250 MW/y	R1.2bn	R0.90bn	280
Container systems	100 MW / 1 GWh/y	R3.5bn	R2.40bn	500
Project integration	same annual flow	R0.8bn	R0.85bn	350
Electrolyte recovery	8m L/y service	R0.6bn	R0.30bn	80

These are scenario assumptions, not investment quotations. They include direct operating jobs, not multiplier claims. The figures are most useful comparatively: electrolyte is relatively cheap to establish but creates few direct jobs; system integration and electrical equipment create more labour and learning; mining creates significant value but is exposed to resource and commodity cycles.

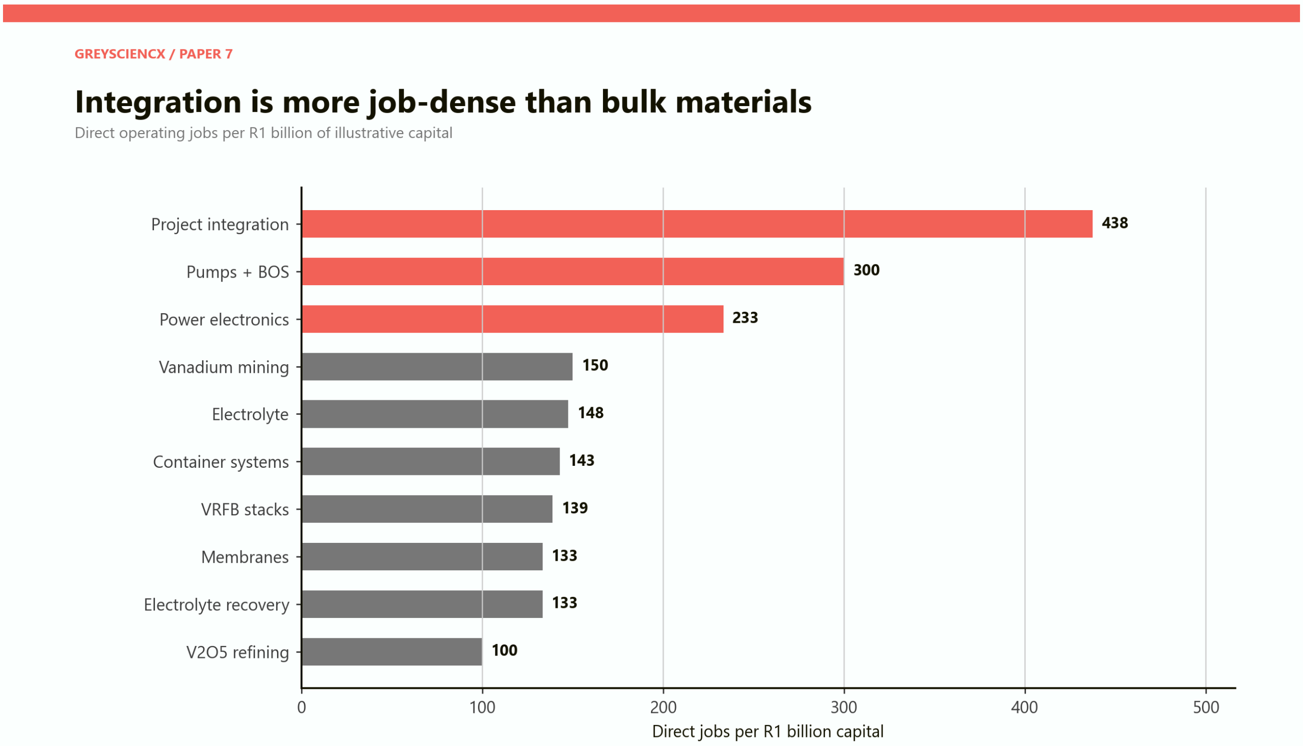

Figure 7. No module simultaneously maximises jobs, exports, value and technological depth. An industrial portfolio is more resilient than a single flagship plant.

PART VII

Where flow batteries compete

PART VII: Where flow batteries compete

Four hours is the wrong battlefield

The International Energy Agency estimates that about 87 GW of utility-scale battery storage was added globally in 2025 and that lithium iron phosphate supplied roughly 90 per cent of battery deployments. Utility-scale systems were around four-fifths of new battery capacity. Durations are increasing, with more projects at four hours or longer, but the industrial fact remains: lithium-ion manufacturing enjoys scale, competition and rapid cost reduction that VRFB producers cannot match by assertion. IEA, "Battery storage is scaling up and taking on a larger system role"; IEA, *Global Energy Review 2026: Battery storage*.

The model calibrates a 100 MW, ten-hour plant to the Pacific Northwest National Laboratory's 2024 central estimates: about USD379/kWh installed for LFP and USD446/kWh for VRFB. It then separates each technology into a power-related and energy-related component to extend the comparison across duration. PNNL's values are United States planning estimates, not South African bids. Pacific Northwest National Laboratory, *Energy Storage Technology Cost and Performance Assessment: Flow Batteries*.

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Flow batteries buy duration with tanks; lithium buys more cells

Illustrative installed cost calibrated to PNNL's 100 MW / 10 h point estimates

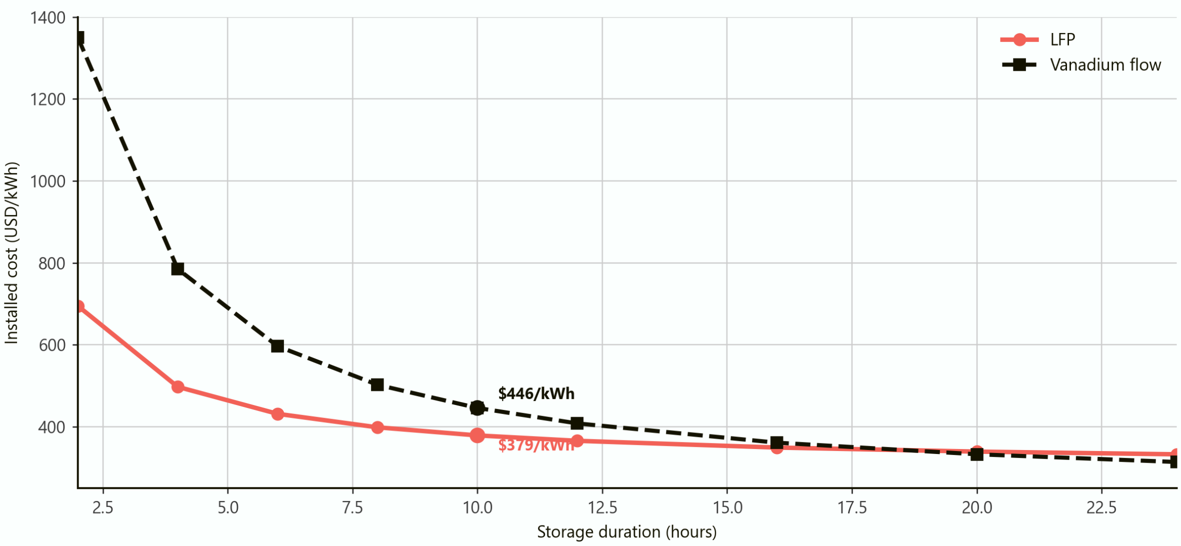

Figure 8. The stylised installed-cost curves are calibrated at ten hours. Flow batteries carry higher power-system cost but add energy capacity more cheaply, producing a duration advantage in the model.

At four hours, the model estimates USD498/kWh for LFP and USD785/kWh for VRFB. At ten hours, the calibrated values are USD379 and USD446. At sixteen hours, they almost converge at USD349 and USD361. At twenty-four hours, VRFB falls below LFP at USD314 versus USD333.

The result is intuitive rather than predictive. Every actual project has site-specific engineering, supply-chain, financing and procurement costs. It says that the flow-battery business case improves with duration; it does not identify the exact winning bid price.

Capital cost is not lifetime cost

The paper's lifetime calculation assumes twenty-five operating years, an 8 per cent real discount rate, 250 full cycles a year and charging electricity at R0.75/kWh. LFP round-trip efficiency is set at 85 per cent and VRFB at 72 per cent. The LFP system receives a replacement equal to 65 per cent of its initial installed cost in year fourteen. The VRFB receives a stack-related replacement in year fifteen while tanks and electrolyte continue.

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Vanadium reaches the contest only at long duration

Illustrative 25-year LCOS; 250 full cycles/year, R0.75/kWh charging energy, 8% real discount rate

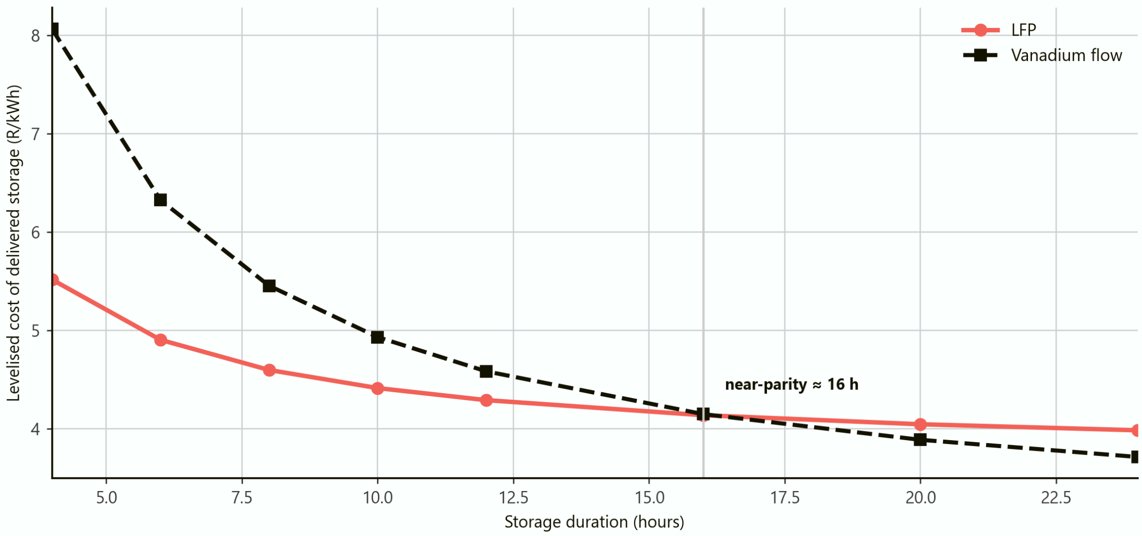

Figure 9. Under central assumptions, lifetime delivered-energy cost is close at about sixteen hours and favours VRFB at twenty-four hours. Charging losses keep the less-efficient flow battery from winning as early as installed cost alone suggests.

At ten hours, the model produces a lifetime storage cost of R4.41/kWh for LFP and R4.93/kWh for VRFB. At sixteen hours, the values are almost equal: R4.14 and R4.15. At twenty-four hours, VRFB falls to R3.71 against R3.98 for LFP.

These are costs of storing and returning energy under the stated model, including charging electricity - not the wholesale price of generated electricity. They omit site-specific network works, taxes, development fees and revenues from multiple grid services. They should not be used as tariffs.

The non-price attributes can decide a real project

VRFBs may be competitive before simple lifetime-cost parity when a customer values:

- low fire propagation risk near people, warehouses or hazardous industry;
- repeated deep cycling and high lifetime energy throughput;
- separate expansion of energy duration without replacing the power block;
- recoverable electrolyte with residual commodity value;
- operation over a long project life with replaceable stacks; or
- lower dependence on imported lithium cells.

PART VIII

The central project

PART VIII: The central project

A 100 MW battery that can run for ten hours

The central case is a 100 MW, 1,000 MWh VRFB. At USD446/kWh and an analytical exchange rate of R18 to the dollar, installed capital is about R8.0 billion. An equivalent LFP project is USD379 million, or about R6.8 billion before any South African project adjustments.

The flow battery requires an assumed fifty million litres of electrolyte. At BELCO's design rate of eight million litres a year, the electrolyte alone represents 6.25 plant-years. This highlights a sequencing problem. If South Africa waits for one enormous project before expanding the plant, the project cannot be supplied on schedule. If it expands before bankable orders, the factory may sit idle.

The answer is staged capacity supported by a portfolio of projects rather than a single bet:

1. qualify batches with multiple stack suppliers;
2. secure smaller industrial and municipal deployments;
3. standardise a container and control architecture;
4. contract a first 100-250 MWh fleet with transparent performance reporting;
5. expand electrolyte production against contracted megawatt-hours; and
6. finance the first gigawatt-hour project only after operating data and warranties are bankable.

Best, central and adverse cases

Driver	Best case	Central case	Adverse case
Project duration	16-24 hours	10-16 hours	4-8 hours
Annual cycling	350-450	250	150-200
Real finance cost	patient, concessional	8%	12% or more
Vanadium input	leased or low-price band	analytical USD8/lb V2O5	high and volatile
Stack performance	qualified, long life	one mid-life replacement	early degradation/replacement
Customer revenue	availability plus energy and grid services	energy-shifting contract	one narrow revenue stream
Domestic content	tanks, BOS, electronics, integration and service	partial localisation	imported system with local badge
Industrial outcome	repeat fleet and exports	viable niche	stranded factory

In the best case, South Africa develops a repeatable sixteen- to twenty-four-hour product, uses development finance for electrolyte inventory, publishes high-quality operating data and builds local service. The industry wins projects where land is available and safety, cycling and life matter. It exports selected systems into African mining, island and weak-grid markets.

In the central case, VRFBs remain a niche. Several hundred megawatt-hours support electrolyte, integration and service capability, but most national battery procurement remains lithium-ion. The industry is valuable without becoming dominant.

In the adverse case, policy mandates a local technology before it is bankable. A plant is expanded ahead of orders, public buyers specify four-hour services, costs rise, suppliers fail and the state inherits warranties. The failure is then wrongly described either as proof that beneficiation never works or as sabotage by imported batteries. In reality, the sequence was wrong.

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Vanadium price matters; utilisation matters more

Illustrative 10-hour VRFB LCOS in R/kWh; coral outline is the central case

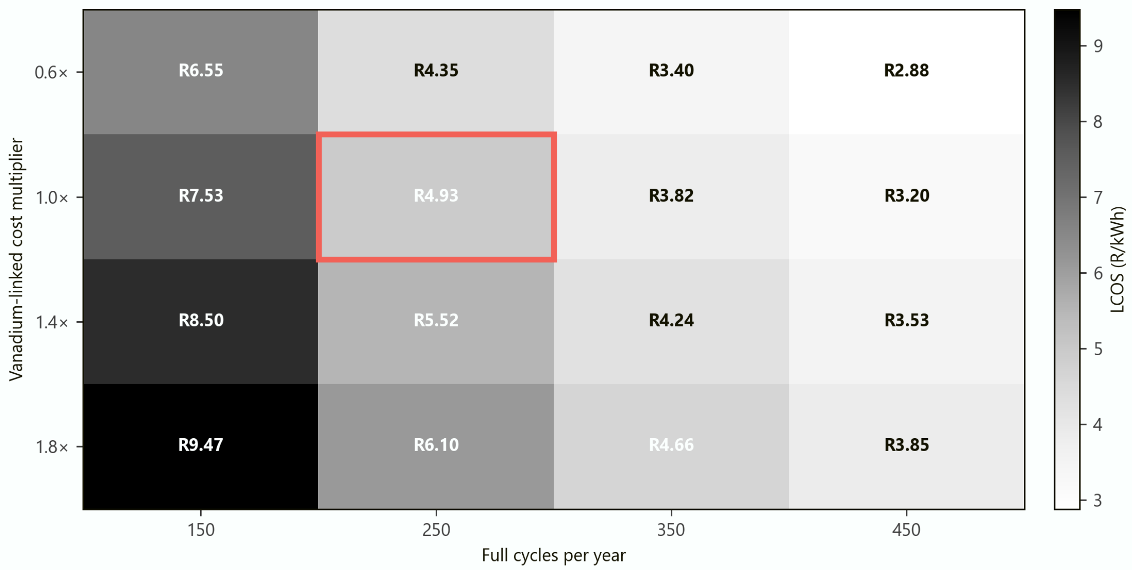

Figure 10. The central project is most credible when long duration is paired with regular use. At ten hours, lifetime cost falls strongly as annual cycling rises; low utilisation can overwhelm a favourable metal price.

PART IX

Price, cycling and finance

PART IX: Price, cycling and finance

The model is most sensitive to use

A long-lived battery earns its economics by moving energy many times. A system designed for daily cycling but used only once every two or three days spreads its capital across far fewer delivered kilowatt-hours. The same problem affects both technologies, but it is particularly damaging to a high-capital emerging technology.

The sensitivity map changes annual cycles from 150 to 450 and the vanadium-related part of capital cost from 60 to 180 per cent of its central value. The strongest policy implication is not to forecast a heroic vanadium price. It is to procure a service that will actually use the asset and to write dispatch rules that permit the required throughput.

High cycling is not free revenue. The market must contain enough daily price spread, curtailment avoidance, capacity value, network benefit or reliability value to pay for the delivered energy and losses. Stacking revenues can help, but the same unit cannot always promise all services simultaneously. Contracts should specify priorities and avoid counting incompatible revenues.

Electrolyte leasing relocates the balance sheet

The World Bank's South African critical-minerals analysis cites an industry estimate that electrolyte can represent about 40 per cent of the cost of a typical four-hour VRFB. The share varies with duration, metal price and system design. Because the vanadium is not consumed in normal operation, a lessor can own the electrolyte, charge rent and recover it later. World Bank, *South Africa: Critical Minerals for the Energy Transition*.

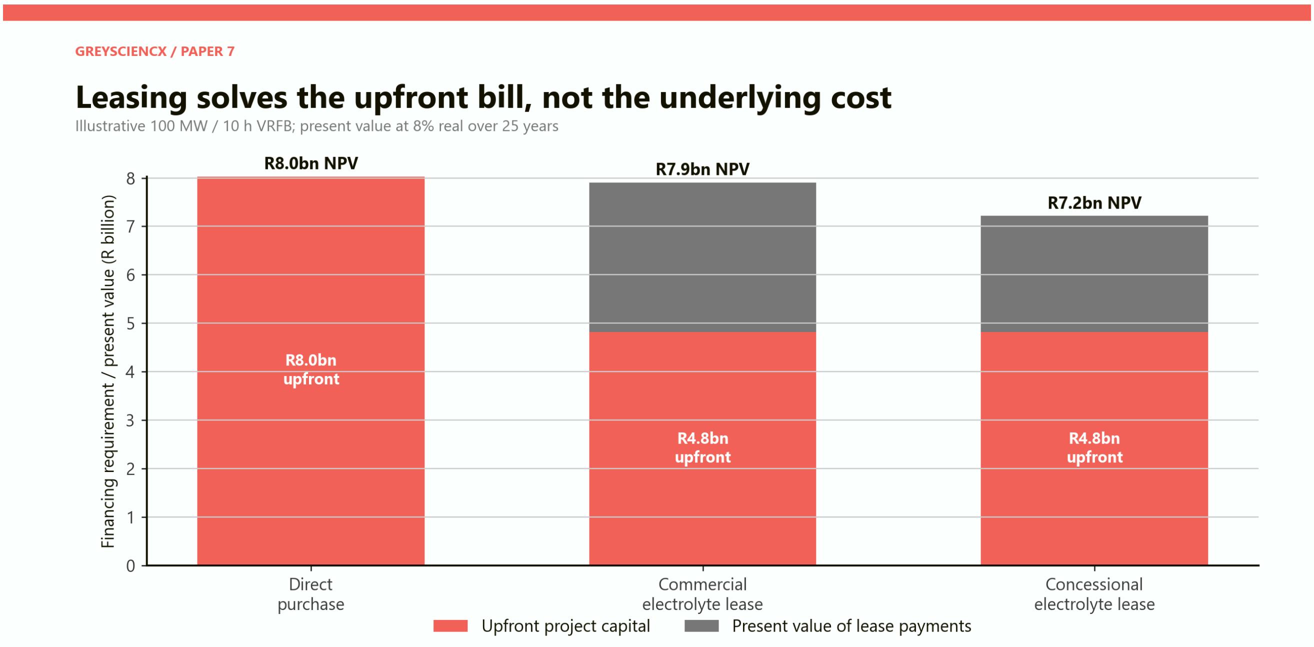

Figure 11. Leasing removes roughly 40 per cent of the illustrative project's upfront capital, but the present value of commercial rent can exceed the financed amount. Concessional capital improves the result; it does not abolish cost.

For the central R8.0 billion project, the model assigns R3.2 billion to electrolyte. Removing that amount from construction capital could materially improve project affordability. At a 9 per cent annual lease charge over twenty-five years, however, the present value of rent discounted at 8 per cent exceeds the upfront electrolyte value. A 7 per cent concessional lease comes closer to the financed amount.

Leasing is therefore valuable for liquidity, risk allocation and residual value, not as free money. A credible lease needs:

- legal title to the electrolyte even if the project company fails;
- testing and metering of volume, concentration and contamination;
- insurance and environmental responsibility;
- access rights for recovery;
- a price-adjustment rule that neither destroys the user at high prices nor the owner at low prices;
- a reserve for transport and reprocessing; and
- a solvent entity capable of funding metal inventory for decades.

A development-finance institution, mining company and private infrastructure investor could share this vehicle. The public contribution should be cheaper capital or first-loss support with a capped exposure, not an unlimited guarantee for technology or commodity losses.

Recycling closes the loop only if designed in advance

Vanadium electrolyte can be tested, rebalanced, filtered, reprocessed and redeployed. The recovery business is attractive because it retains the metal, reduces future working capital and gives customers an end-of-life route. But recovery will not happen automatically. Plants need compatible chemistry, records, sampling standards, transport rules and contractual ownership.

The country should establish a national electrolyte passport recording origin, composition, ownership, operational history and recovery status. This could become a commercial standard rather than a bureaucratic register. It would make leased inventory auditable and help secondary electrolyte earn the same trust as virgin product.

GREYSCIENCX / PAPER 7

Target the uses where duration, safety and cycling are valuable

Illustrative opportunity scores; judgement framework, not a demand forecast

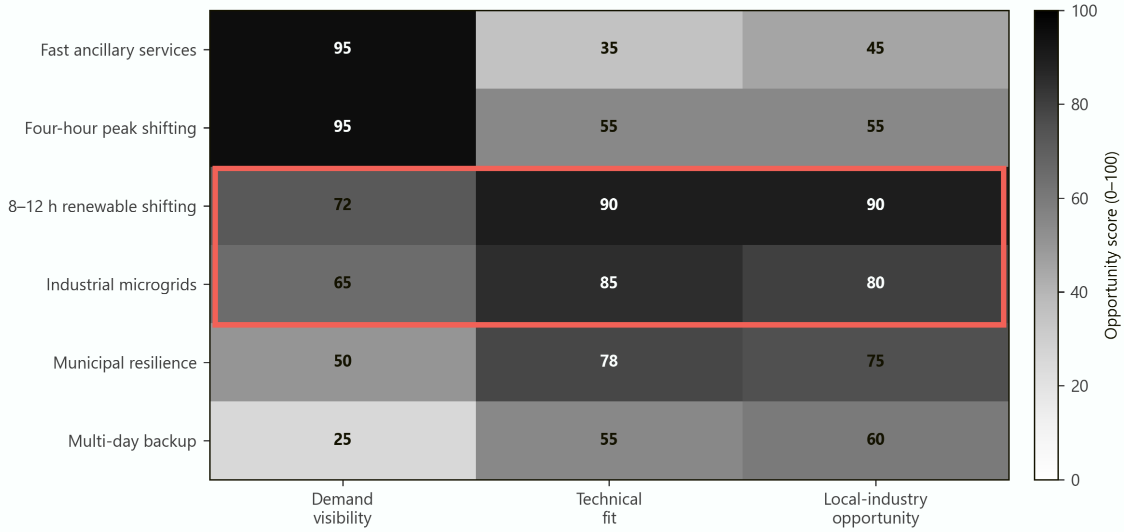

Figure 12. The commercial target follows from the financing analysis: VRFB attractiveness rises with duration, frequent cycling, available space and a high value placed on fire safety and long life.

PART X

Applications, competition and the limits of the niche

PART X: Applications, competition and the limits of the niche

The best first customers are not identical

Mines and industrial micro-grids offer concentrated demand, land, engineering staff and a high cost of interruption. Solar-plus-storage can reduce diesel use and peak purchases. The risk is that many industrial outages are multi-day or unpredictable; batteries may still need generators or grid supply.

Municipal networks can use storage to manage peaks, support constrained feeders and improve power quality. Municipal credit quality and technical capacity vary widely. A battery cannot repair a structurally insolvent distribution business.

Renewable plants can shift energy, reduce curtailment and make output firmer. Their revenue depends on market rules and grid access. Co-location is helpful only if the connection and contract value the stored output.

Eskom substations can provide a large anchor market and disciplined testing. Public procurement cycles, grid-code requirements and counterparty risk still matter. The state should not use Eskom as a buyer of last resort for products the system does not need.

Data centres, warehouses and dense urban sites value safety but often value compact footprint and efficiency even more. VRFBs can compete at suitable campuses, but lithium systems with strong fire engineering may remain preferable.

Residential and mobile applications are poor targets. Flow batteries are bulky and mechanically complex. South Africa should resist the urge to make every battery technology serve every market.

Lithium is not the only competitor

At long duration, VRFBs also compete with pumped hydro, compressed air, thermal storage, sodium-ion batteries, iron-air and other flow chemistries, hydrogen-derived fuels, flexible generation, new transmission and demand response. Some of these technologies may add hours more cheaply or solve a different constraint.

A storage project should first ask whether storage is the least-cost solution. A transmission line can move diverse generation across regions. Demand response can eliminate a peak without storing a unit of energy. A flexible industrial load can absorb surplus electricity. Gas, hydro or renewable fuels may cover rare multi-day events more cheaply than a battery used a few times a year.

The US Department of Energy's Storage Innovations 2030 programme targets a 90 per cent cost reduction for technologies providing ten hours or more. That ambition means the competitive landscape is moving. South African policy should support capabilities that can serve more than one chemistry - power electronics, controls, tanks, fabrication, integration, testing and recycling - so a technological surprise does not strand the entire strategy. US Department of Energy, Storage Innovations 2030.

PART XI

An industrial strategy that can survive contact with the market

PART XI: An industrial strategy that can survive contact with the market

Four R20 billion portfolios

The model compares four ways to allocate an illustrative R20 billion industrial envelope. These are not budget proposals. They expose the trade-offs between upstream security, technology depth, jobs, exports and delivery risk.

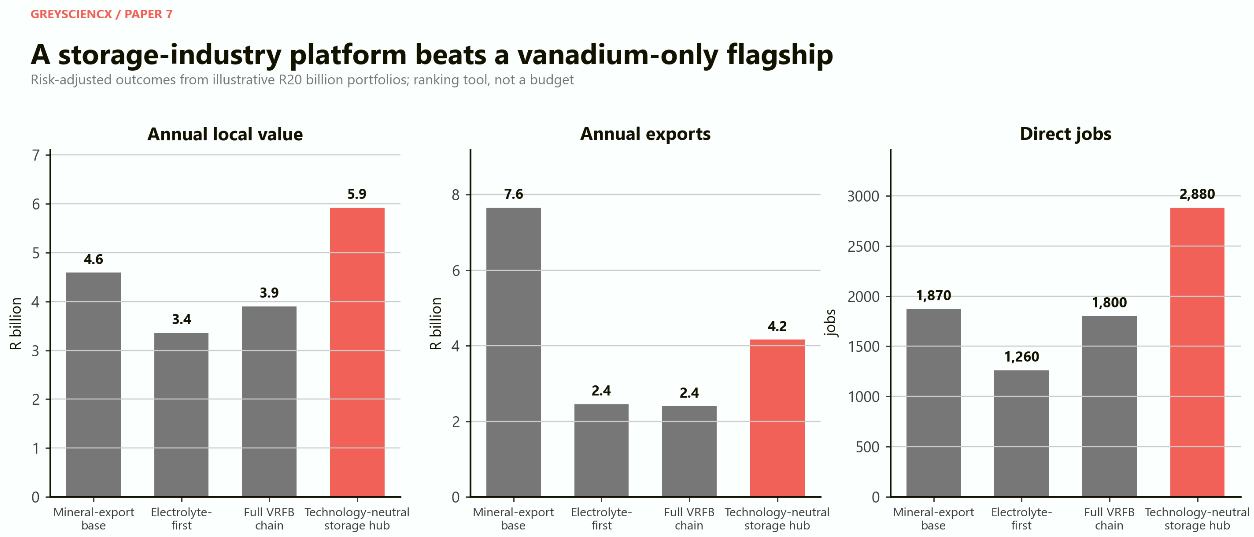

Figure 13. A technology-neutral storage platform produces the strongest central balance in the model. The fully integrated chain has deeper ambition but higher coordination and demand risk.

Portfolio	Annual local value	Annual exports	Direct jobs	Delivery score
Mineral base	R5.4bn	R9.0bn	2,200	0.85
Electrolyte-led	R4.8bn	R3.5bn	1,800	0.70
Full VRFB chain	R6.5bn	R4.0bn	3,000	0.60
Technology-neutral storage	R7.4bn	R5.2bn	3,600	0.80

The **mineral-base portfolio** expands mining, refining, logistics and reliable energy. It has strong export potential and lower technology-market risk, but captures less learning from storage.

The **electrolyte-led portfolio** builds purification, electrolyte capacity, leasing and recovery. It uses the mineral advantage directly, but demand is tied to a still-small technology market.

The **full-chain portfolio** attempts membranes, stacks, systems, projects and exports together. It creates strategic depth if it succeeds. It also concentrates qualification, utilisation, warranty and finance risks in one programme.

The **technology-neutral storage portfolio** supports vanadium electrolyte while building cross-chemistry capabilities: inverters, switchgear, controls, thermal management, containers, safety testing, grid integration, field service and recycling. It produces the best central balance because those capabilities can serve LFP, sodium-ion and future long-duration technologies as well as VRFBs.

A staged programme

/ Stage 1: prove the product, 2026-2028

Qualify locally produced electrolyte with at least two independent stack suppliers. Audit BELCO's equipment, ownership, operating condition and batch capability before committing public capital. Establish an accredited test centre that can run long-cycle, efficiency, contamination, leak, pump and stack-degradation protocols. Publish standard test results.

Procure several 5-25 MWh industrial and municipal pilots with different duty cycles. Each contract should disclose availability, delivered energy, auxiliary consumption, degradation, maintenance hours and cost. Government pays partly for the data; suppliers earn later orders only by meeting gates.

/ Stage 2: standardise and aggregate, 2028-2031

Develop one or two standard South African system architectures using local tanks, piping, controls, switchgear, civil design and maintenance. Aggregate demand across mines, municipalities and renewable projects so suppliers see a fleet rather than isolated demonstrations.

Create a ring-fenced electrolyte-leasing vehicle with capped public exposure. Expand production only against signed projects and framework orders. Establish take-back and electrolyte-passport rules.

/ Stage 3: buy long-duration performance, 2030-2035

Run competitive tenders for eight-, twelve-, sixteen- and twenty-four-hour services. Pay for delivered availability, efficiency, throughput, response and life. Allow all technologies to bid. Give a transparent, declining credit for verified local value added, not a permanent technology reservation.

Use contracts long enough to support finance but include step-in rights, spare-parts requirements and supplier-replacement plans. Require the project company to survive the failure of any single upstream shareholder.

/ Stage 4: deepen selectively, after utilisation is proven

Localise stack plates, electrodes or membranes only after recurring demand can use a commercial line and a technology partner transfers real process knowledge. Export complete systems first to markets where South African firms can maintain them: regional mines, utilities and isolated grids. Enter distant markets through a bankable OEM or engineering partner.

What the state should buy

The state should purchase four public goods:

1. **credible test data**, openly reported under a common protocol;
2. **early demand**, awarded competitively for a defined system service;
3. **shared infrastructure**, including laboratories, standards and grid-integration facilities; and
4. **patient but capped finance**, especially for recoverable electrolyte inventory.

It should not promise a domestic manufacturer a protected market regardless of performance, finance an expansion without orders, or treat every imported component as policy failure. Localisation is a learning path. A rigid percentage can encourage invoice engineering while weakening the product.

PART XII

Risks, counterarguments and verdict

PART XII: Risks, counterarguments and verdict

The strongest case against the strategy

The sceptical argument is formidable. LFP already has the factories, developers and warranties. Global storage costs continue to fall. South Africa is not a dominant vanadium producer. Flow batteries are less efficient and bulkier. The country's first major integrated champion suffered financial distress. Public procurement has a poor record of converting industrial promises into globally competitive firms. Why risk scarce capital?

The answer cannot be patriotism. It must be portfolio economics. South Africa will spend large amounts on storage in any event. Reserving a small, disciplined share of that demand for long-duration competition can reveal whether VRFBs provide value under local conditions. The country can localise broadly useful electrical and mechanical capabilities even if vanadium's market share remains small. Electrolyte and recovery use a genuine resource-processing advantage. The experiments can be staged, measured and stopped.

The case collapses if support is open-ended, procurement hides performance, or the technology is forced into four-hour projects. It strengthens if contracts buy long-duration service, factories expand after orders, and public capital earns a claim on recoverable metal rather than underwriting an unbounded corporate structure.

Twelve failure modes to design out

Ore exceptionalism. Treating domestic resources as proof of downstream competitiveness.

Four-hour protectionism. Reserving an incumbent lithium service for a higher-cost flow system.

Capacity theatre. Announcing litres or megawatts of factory capacity without utilisation or customer qualification.

Vertical balance-sheet overload. Asking one mining group to carry every risk from shaft to power project.

Single-supplier dependence. Building a public fleet whose membrane, stack or software has no substitute.

Warranty hollowing. Accepting a twenty-year technical claim from a thinly capitalised company.

Imported-value inflation. Calling the full system invoice domestic beneficiation.

Metal-price optimism. Assuming low vanadium prices for battery customers while promising high prices to miners.

Efficiency denial. Ignoring the extra electricity required by a lower round-trip efficiency.

Revenue stacking fiction. Counting grid services that cannot be delivered simultaneously.

Pilot permanence. Keeping subsidised demonstrations alive without graduation or closure gates.

Chemistry lock-in. Building capabilities that cannot adapt if another long-duration technology wins.

Decision gates

The programme should proceed only through explicit gates.

Gate	Evidence required	Decision if failed
Electrolyte quality	repeated independent qualification	fix process before expanding
Demonstration	availability, efficiency and degradation targets	redesign or stop procurement
Bankability	warranty reserve, step-in rights, service plan	use stronger partner or do not finance
Demand	signed projects covering a credible share of capacity	defer factory expansion
Local value	audited domestic wages, inputs and margin	reduce localisation support
Export readiness	certification, reference fleet and service partner	remain regional/domestic
Recovery	enforceable title and tested take-back process	do not scale leasing vehicle

Final verdict

South Africa can create a vanadium grid-storage economy, but it is unlikely to be a giant integrated national champion selling every component to the world. A more plausible success is a specialised industrial cluster: vanadium purification and electrolyte; domestic tanks, pumps and containers; strong power electronics and grid integration; a fleet of high-cycle long-duration projects; and a recovery system that keeps the metal working for decades.

The market should be won at the system boundary where flow batteries are genuinely different. At four hours, LFP's scale and efficiency are difficult to beat. At sixteen to twenty-four hours, with frequent cycling and valuable fire safety, the economics become contestable. That is where procurement should test the technology.

The mineral does not guarantee the industry. The industry will exist only if South African firms can transform a tonne of vanadium into a reliable service that a customer is willing to finance, use and buy again.

SECTION

Model assumptions and interpretation

Model assumptions and interpretation

This paper is a transparent scenario exercise, not a forecast, engineering design, feasibility study or investment recommendation. All rand values are constant 2026 rand unless stated. The analytical exchange rate is R18 per US dollar. The vanadium-pentoxide input is USD8 per pound. These are fixed model inputs chosen to make comparisons reproducible; they are not current-price claims.

The storage-cost curves are calibrated to PNNL's 2024 estimates for a 100 MW, ten-hour installation: USD379/kWh for LFP and USD446/kWh for VRFB. Power-related and energy-related cost shares are simplified so duration can vary. Actual bids will differ by country, site, taxes, financing, supplier, grid works and contract.

Lifetime storage cost uses twenty-five years, an 8 per cent real discount rate, 250 full cycles per year and charging electricity at R0.75/kWh. Round-trip efficiency is 85 per cent for LFP and 72 per cent for VRFB. The LFP replacement is 65 per cent of initial installed cost in year fourteen. The VRFB stack-related replacement occurs in year fifteen. Residual values are not credited except conceptually in the leasing discussion.

Electrolyte intensity is modelled at fifty litres per kWh and 0.087 kilograms of vanadium per litre. Commercial designs vary. BELCO's own public MWh equivalence is therefore reported separately from the model's physical conversion.

The value ladder follows one tonne of contained vanadium into alternative endpoints. Endpoints must not be summed. The complete-system figure measures sales enabled by vanadium, not value physically created by the metal. Local shares are assumptions designed to prevent imported inputs from being counted as South African value.

The ten industrial modules are independent illustrative projects and are not mass-balanced. Capital, sales, exports, jobs, energy and water are scenario values for comparing structures. Direct jobs exclude induced and economy-wide multiplier claims.

The R20 billion portfolios are judgement-based combinations of modules and enabling investments. Their “delivery score” is an index, not an observed probability. It rewards modularity, transferable capability, demand diversity and lower coordination risk.

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