Commodity Research Note
Vanadium

Q1 2018

MiFID II compliant*

Key themes

Chinese environmental legislation restricts available vanadium supply

Geological scarcity of economic primary mine vanadium

Chinese tensile strength standards drive vanadium-steel rebar demand

Emerging energy storage system technology trend accelerates consumption

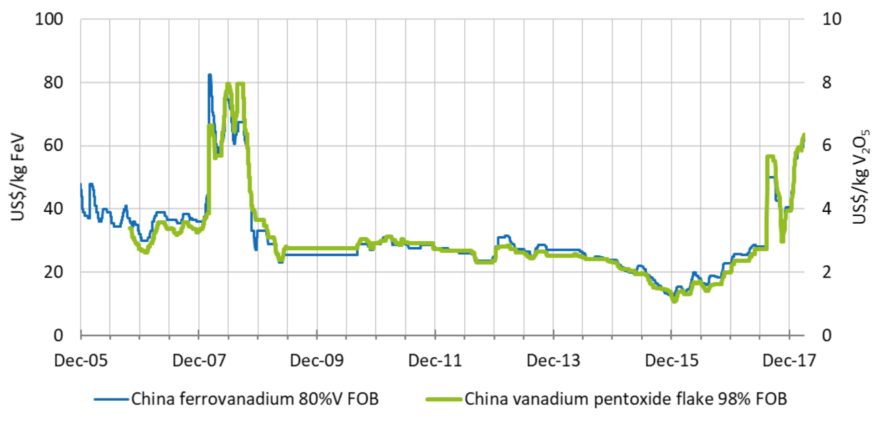
Price Outlook

The combined impact of recent Chinese vanadium steel standards and environmental policy change, focusing on improving air emission standards and waste import bans (fundamental supply of vanadium slags), has triggered significant positive price momentum with ferrovanadium and V_2O_5 climbing 37% and 44% respectively year-to-date (March 2018).

We forecast a sustained global deficit resulting from a tightening supply base coupled with robust consumption from traditional metallurgical applications and inchoate energy-storage solutions has drawn broad vanadium prices from the multi-year lows of late 2015-early 2016. After bottoming out two years ago, the price of Chinese FOB ferrovanadium and vanadium pentoxide have swelled 406% and 596% respectively to 2018 highs.

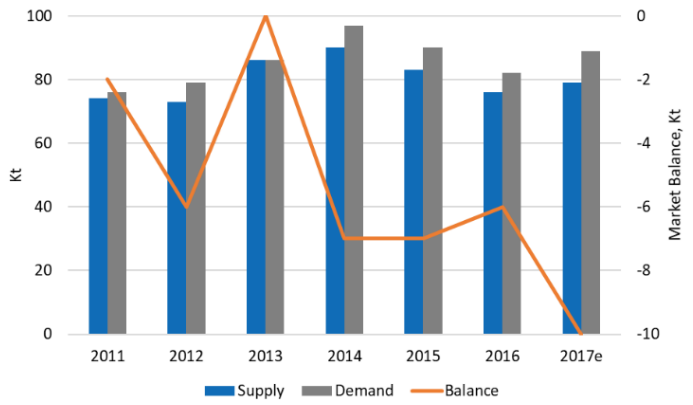
V_2O_5 represents the most common intermediate product of purities ranging from steel-grade at least 86% up to 99.8% via the treatment of magnetite iron ores, vanadium-bearing slags, and secondary materials. Additional processing via aluminothermic reactions of the V_2O_5 red cake yields ferrovanadium products. The three major ferrovanadium grades include 40%V, 60%V, and 80%V.

Vanadium-containing products are centralized around commercially-traded ferrovanadium (FeV) and vanadium pentoxide concentrate (V_2O_5). While there are no benchmark exchange-based prices for vanadium, indicative prices are published by a number of commodities market intelligence organisations including Metal Bulletin and Metal Pages, based on buy/sell contracts negotiated directly between suppliers, consumers and traders.



Source: Bloomberg

Global vanadium market balance, Kt (2011-2017e)



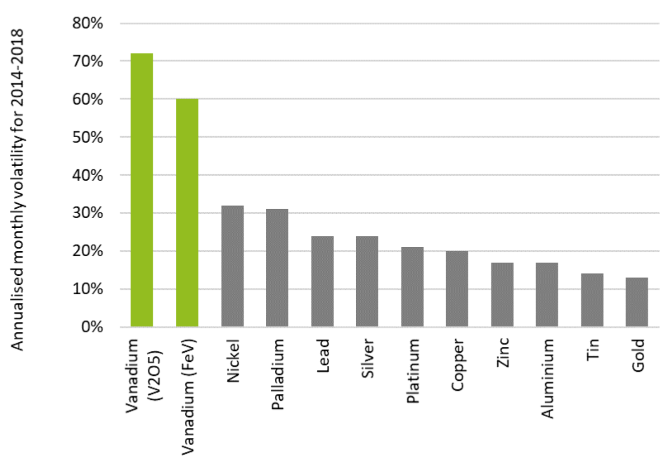
China vanadium FeV and V_2O_5 prices, US$/kg (2006-2018e)

Source: Vanitec, Metal Bulletin

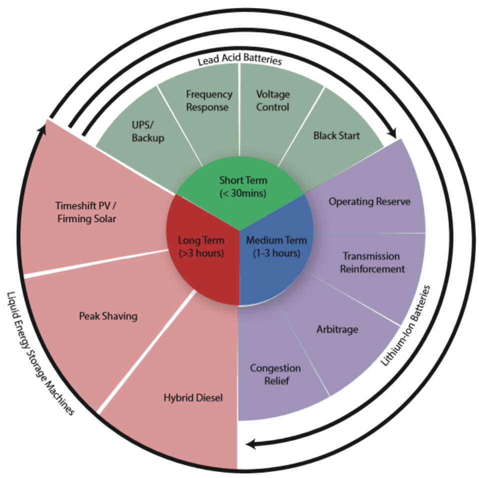
Due to illiquid market fundamentals, vanadium prices are associated with elevated volatility, with historic prices surging during 2005 (not presented when FeV prices spiked over US$100/kg) and 2008. In particular, the price surge of 2005 is attributed to a significant fall in inventory as China accelerated the use of grade 3 reinforcing bars (0.03% V) at the expense of grade 2 rebar (0% V). Revisions to the GB 1499.2-2007 construction regulations eliminating 335MPa strength rebar with higher intensity vanadium utilisation 600MPa reinforcing bar is expected to drive consumption and therefore stimulate prices.

Meanwhile tumbling iron ore prices back into the $60s/t on record swelling China stockpiles is improbable to support the resurrecting of mothballed vanadium-magnetite-ore fed steel operations which dominate global vanadium production. Unlike the 2005 surge, no new vanadium production from steel mills is expected under stringent environmental restriction. While a number of primary output is under advanced development, future global production will be constrained by the geological scarcity of deposits with the requisite scale and grade to be economically viable.

Vanadium price volatility vs. base and precious metal complex, %



Energy storage system application vs technology type



Source: Bloomberg, redT energy Plc

Emerging consumption from energy storage systems (EES) is generating a structural change in the vanadium market, developing sustained demand for high-purity vanadium electrolyte in alternative utility-scale energy storage technology. The infant sector is gaining significant traction with applications across broad energy storage systems, with China at the forefront of installed and developing capacity. Major global growth in electrified power will draw resilient demand, with a single 800MWh facility consuming over 5% of 2016 production. With vanadium comprising 30% total cost of vanadium flow redox battery solutions, prolonged elevated vanadium prices could constrain mass adoption and growth in a sector dominated by first-mover lithium-ion batteries.

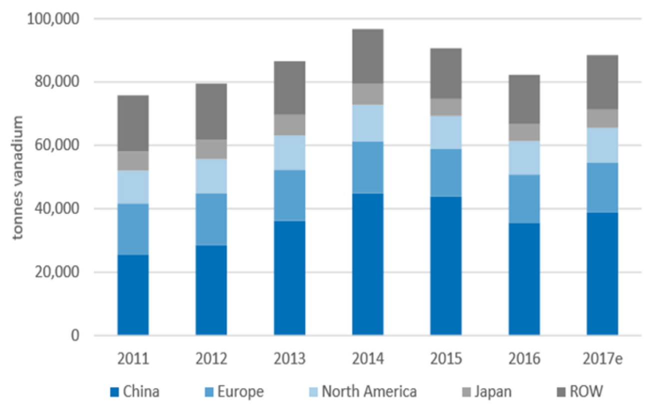
In the near-term, market tightness is expected to remain, with prices forecast to average US$50/kg over 2018 and US$35/kg long-term prices. However, distinctly elevated volatility of the two primary vanadium products, recording 60% for FeV and 72% for V_2O_5 highlights potential downside risk to prices.

Demand

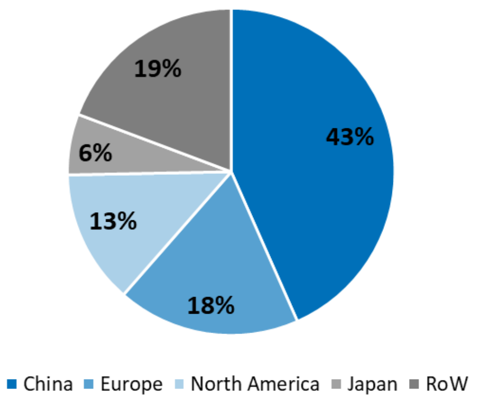
Summary

The Asian market continues to dominate vanadium consumption with at least 49% aggregate global usage in 2016, split across China (43%) and Japan (6%), consequent of the significant output in worldwide steel manufacture. Ex-Asia demand trends are the same as global steel consumption, with European demand topping NAFTA with 18% and 13% respectively.

Global vanadium demand, tonnes (2011-2017e)



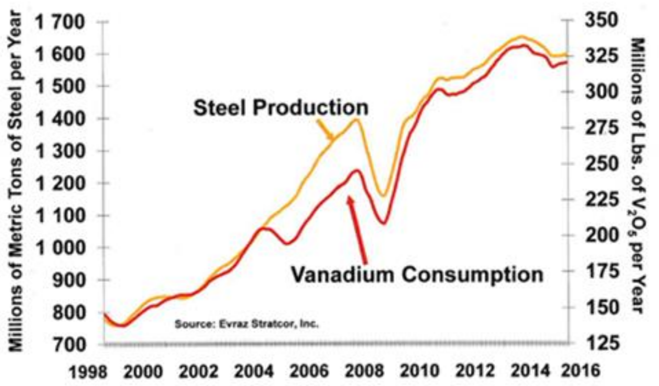
Global vanadium consumption, % (2016)



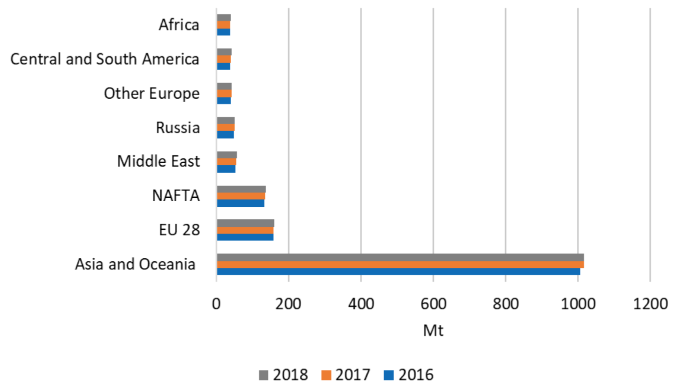
Source: Vanitec

Following its peak in 2014, vanadium demand contracted 16.8% from c97Kt annual usage in the following two years, a trend which traces a lulling high-strength steel market during the same two-year period. Global vanadium consumption shows strong resurgence from 2016 low of c82kt on improving steel fundamentals and revised Chinese vanadium standards incorporated within broad high-strength construction steel production. The cumulative impact of rising steel rebar vanadium intensities and emerging energy storage demand encouraged global consumption 7.2% higher to an estimated annual level of 89Kt in 2017.

Global 12m moving average vanadium consumption vs. steel production (1998-2016)



Global steel demand, Mt (2016-2018e)

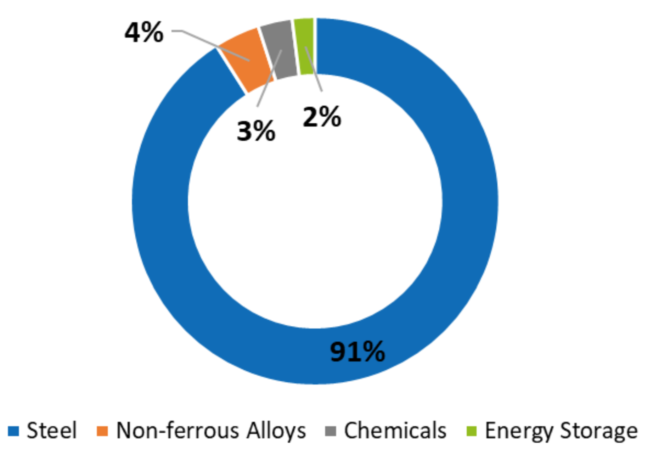


Source: Evraz Stratcor, Statistica

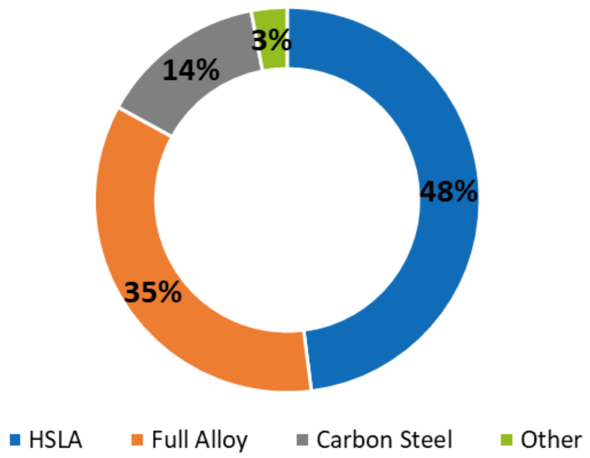
The vanadium end-use market is dictated by movements in steel manufacturing, with the industry accounting for 91% aggregate demand. The transition metal provides broad industrial applications as an alloying agent in a range of different steels. Vanadium steel enhances durability while considerably reducing weight and increasing tensile strength. The addition of 1kg vanadium to a single tonne of steel has the effect of doubling the strength of the alloy. Typically containing less than 0.2% of vanadium, the alloy can be utilized in "as-forged" condition, removing the necessity for additional heat treating or alloy additives. The steel creates good castings, retains a cutting edge, and exhibits very little wear even at high-temperature. Often desirable for its light weight, vanadium steel is also desired for its resistance to erosion by salt water, hydrochloric and sulphuric acids.

The predominant alloy production outputs high-strength, low-alloy (HSLA) steel, making up 48% total vanadium applications in steel. HSLA steel contains ≤8% alloying elements including Cr, Ni, Mo, Co, Nb, Ti, N and Zr, to create superior mechanical properties against conventional carbon steels.

Vanadium consumption by end-use market, %



Vanadium use in steel alloys, %

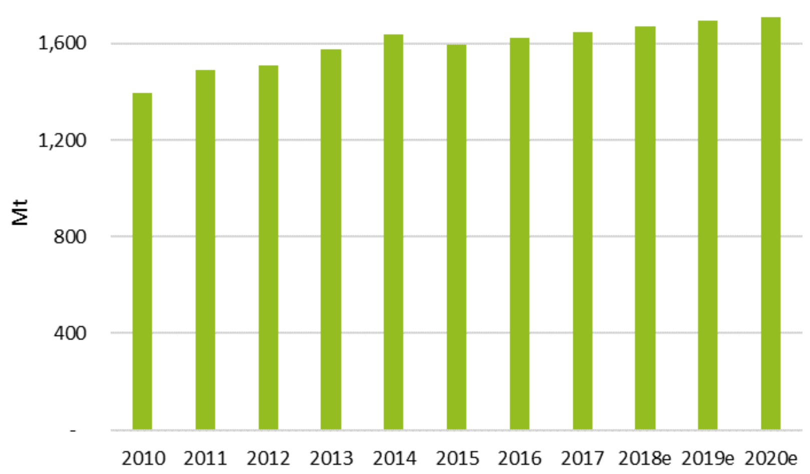


Source: Vanitec, Largo Resources

Henry Ford utilised vanadium metal in the production of chassis for the famous Ford Model T back in 1908. Modern end-use application focuses on construction reinforcing bars for buildings, bridges, automotive manufacture, oil pipelines, railway lines and heavy machinery tools.

In a steadily diminishing sector, vanadium steel is valued within the oil and gas industry for its high tensile strength to endure high pressures, thereby significantly reducing transportation costs. The low temperature resilience of the alloy also provided resistance to brittle fracture in cold climates of Alaska, Russia and Alberta. Fast weldability of the alloy also allowed minimal susceptibility to hydrogen cracking.

Global crude steel product, Mt (2010-2020e)



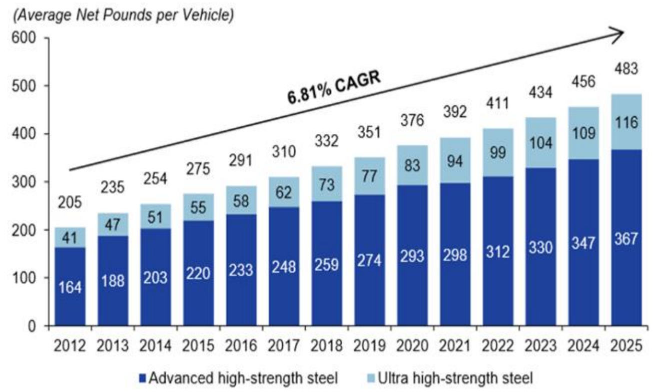
Source: Statistics

While world crude steel output has advanced 5.3% in 2017 to the equivalent of 1,691.2mt, according to Worldsteel data, the intensity of vanadium usage within specialist alloys has increased at an average 8% CAGR. Though steel production is expected to have a modest CAGR through 2020, approx. 1.2%, increasing rebar standards and consequently vanadium intensity coupled with specific end-use growth drivers will allow vanadium demand growth to continue to expand beyond steel growth.

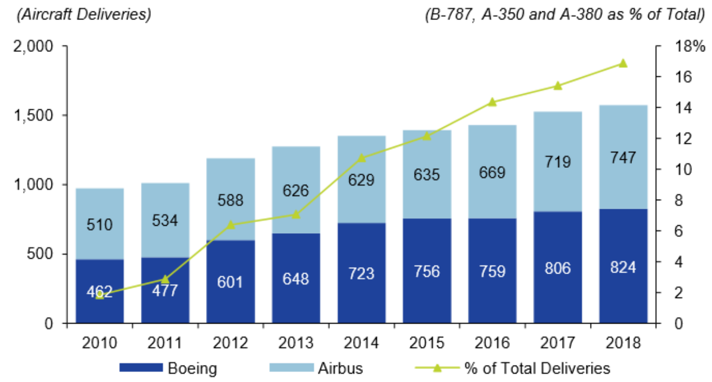
More stringent Corporate Average Fuel Economy (CAFE) standards are driving automotive manufacturers to enhance consumption of high-strength, low-weight steels, expected to grow at 6.8% CAGR through 2025.

Aircraft manufacturers are utilizing higher amounts of titanium-vanadium alloy, with Boeing's new 787 Dreamliner and Airbus' A380 and A350XWB models consuming 75-100+ tonnes vanadium alloys per aircraft.

Growth of high-strength steels in automotive (2012-2025e)



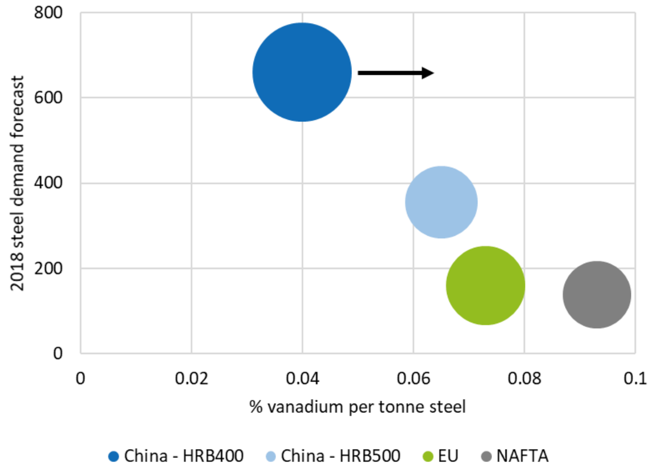
Aerospace delivery schedule (2010-2018e)



Source: *Roskill (2014), Steel Market Development Institute, Company disclosures*

There is a global discrepancy in vanadium intensities within steel alloy manufacture, with emerging markets setting significantly lower standards for output. North America heads apparent vanadium consumption with an average 0.093% intensity, followed by Europe with average 0.073%. Chinese steel standards fell almost half, averaging 0.037%, before authorities revised steel product standards in an effort to combat recurring risk from structural damage caused by a series of earthquakes in 2008.

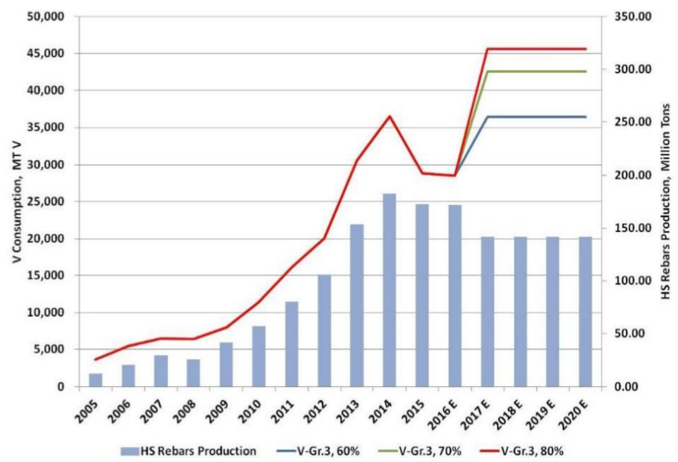
Vanadium consumption by end-use market, %



Bubble size – relative vanadium demand

Black arrow -impact of Chinese rebar standards

Vanadium use in steel alloys, %



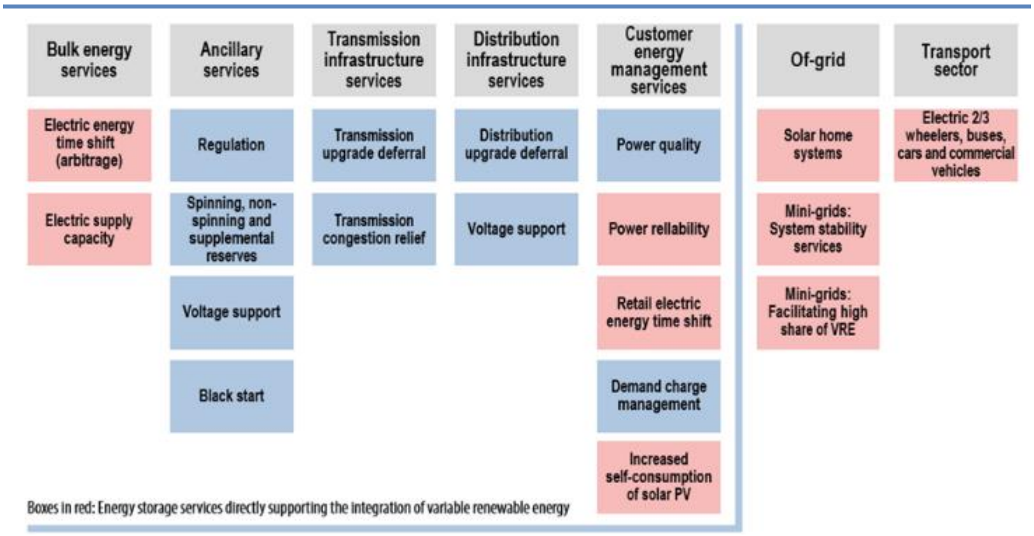
Source: *Vanitec, Metal bulletin, Largo Resources*

Data from the China Iron & Steel Research Institute (CISRI) show revisions to the GB 1499.2-2007 construction regulations propose the elimination of the 335MPa strength rebar, and replacing it with a 600MPa strength rebar in an effort to enhance the rebar grades within earthquake resistance. CISRI data indicates of the 160 million tonnes of hot-rolled high strength steel rebar through 2016, accounts for 65% HRB400 products (≥400MPa), 20% HRB500 (≥500MPa) and 15% other products. The required amount of vanadium to be added is **0.03-0.05%** for HRB400 steel and **0.05-0.08%** for HRB500. Consequently, more stringent safety standards will drive strong vanadium steel demand as higher intensities are adopted across the construction sector. The CISRI foresee the revision to the standard tensile strength of rebar products in China to advanced 30% growth of vanadium metal consumption in the country, equivalent to **10Kt per year or c12% 2016 global demand**.

Rising vanadium prices typically drive some steel mills to favour vanadium nitrate or ferro-niobium, a cheaper and less effective substitutions in HSLA steel manufacture, drawing cost savings to 30-40%. In order the meet growing standards, consumption of FeNb in high-tensile strength steels are higher than vanadium; ~110g/t in North America, ~80g/t in Europe and Japan, while the Chinese market falls ~25g/t. However, introduction of the revised rebar standard gives steel mills' precise regulations and the risk of substitution is expected to decline.

9% global consumption is attributed to other notable end-uses including an additive in non-ferrous alloys including titanium-aluminium-vanadium alloy utilised in high-speed aircraft and jet engines, a catalyst utilised in the production of maleinanhydride, sulphuric acid and petroleum cracking; and numerous chemical applications.

Range of services provided by electricity storage

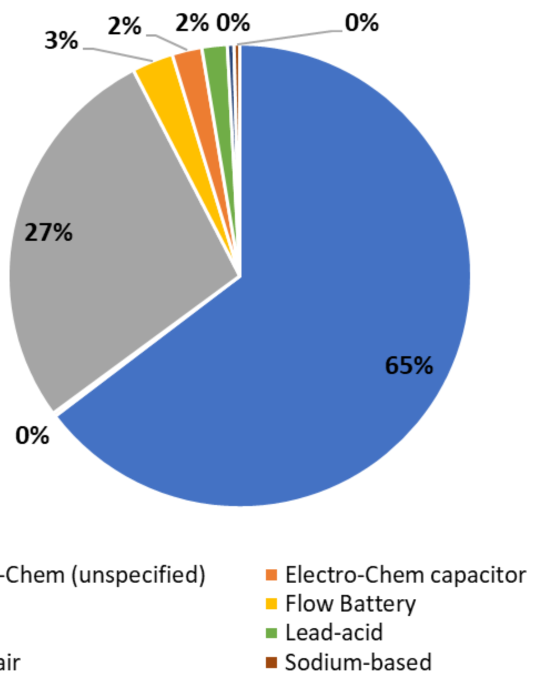


Source: IRENA

Vanadium electrolytic incorporated within Vanadium Redox Flow Batteries (VRFBs) represents a breakthrough technology in energy storage solutions, aimed at supporting the increasing global shift toward renewable power generation. The innovative battery application provides advantages over commercially available energy storage market technologies including being non-combustible, modular design and readily scalable to provide rapid-responding power (<70ms due to liquid nature) with near unlimited recharging/discharging capacity (>10,000 cycles). While commercialization of VRFBs is a rapidly accelerating sub-sector of the energy storage market, mass adoption has been limited due to elevated capital costs of battery manufacture.

Due to its low energy density (up to 5x less than lithium-ion examples), VRFBs are not suitable for mobile applications, but are useful in load levelling at power stations, peak shaving for industrial users and storage for renewable sources of energy. Consequently, battery-grade vanadium demand may be considered a market function of global energy storage capacity.

2017 announced, contracted, and under construction storage capacity by technology type



Source: US DOE, 2017

Electricity systems already require a range of ancillary services to ensure smooth and reliable operation, requiring a degree of flexibility services, which allow grid operators to react to unexpected changes in demand or losses in supply. Electricity storage will be fundamental to the energy transition, with services directly supporting the integration of variable renewable electricity.

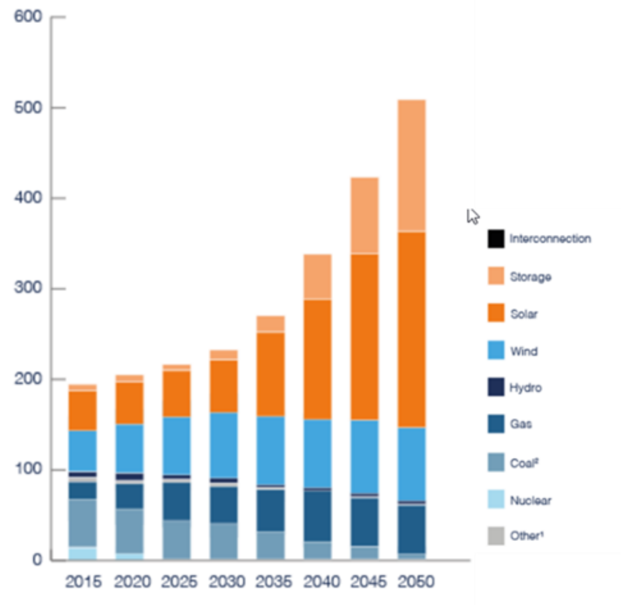
Commercial operations for flow batteries could capture 5% global storage capacity, according to the Global Energy Storage Database, with vanadium flow batteries representing 25,250kW capacity (2.1%) of the total 1.2GW.

By contrast Lithium-ion, with its first mover advantage, has already captured 27% worldwide capacity. Lithium batteries have relatively short life and are more prone to degradation and failure.

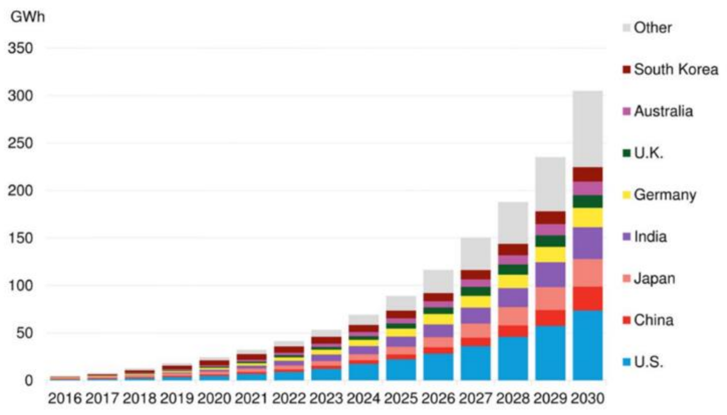
The global power sector is at the forefront of an energy transition as declining technology costs buoy electrification. Strong electrified growth is expected to boost power demand almost four times as fast as other fuels. While most project capacity focuses on an additional 20-40GWh of storage deployed by 2025, by 2030 forecast capacity targets a supplementary 125GW/305GWh for the energy storage market (Bloomberg). Citigroup present a more bullish case, forecasting VFRB capturing up to 400GW by 2030.

The expansive trajectory indicates the global energy storage market will double more than six times between 2016 and 2030, while deployed capacity will be focused across eight countries; with 70% capacity split across the US, China, Japan, India, Germany, UK, Australia and South Korea.

Generation capacity, GW (2015-2050e)



Global cumulative storage deployment, GWh (2016-2030e)

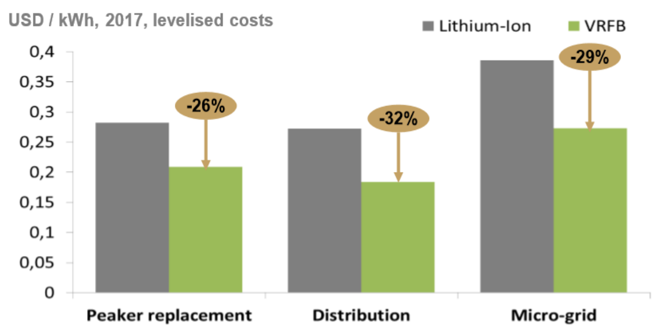


Source: McKinsey, Bloomberg New Energy Finance

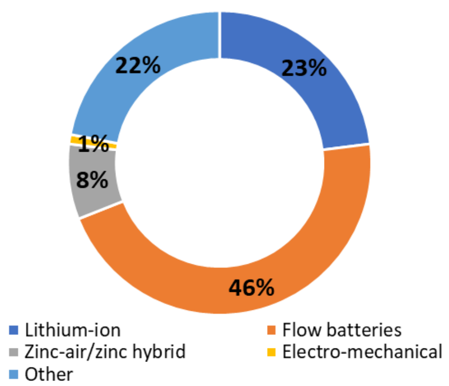
Forecasts from Navigant and Boston Consulting Group expect VRFBs to capture 15-25% of the market, although superior cost reduction potential of the technology is expected to drive the market share significantly higher. Lazard's analysis already concludes that VRFBs already demonstrate the lowest levelized costs across the sector in 2017. Mass adoption of commercial systems such as those developed by RedT, UniEnergy Technologies and Bushveld Minerals should assist with the penetration of VRFBs into the fledgling market.

Results from Greentech Media's 2017 Energy Storage Summit polling 500 professionals also revealed 46% sentiment toward VRFBs dominating utility-scale advanced storage technology.

2017 levelized cost comparison Lithium-ion vs. VRFB, US$/kWh



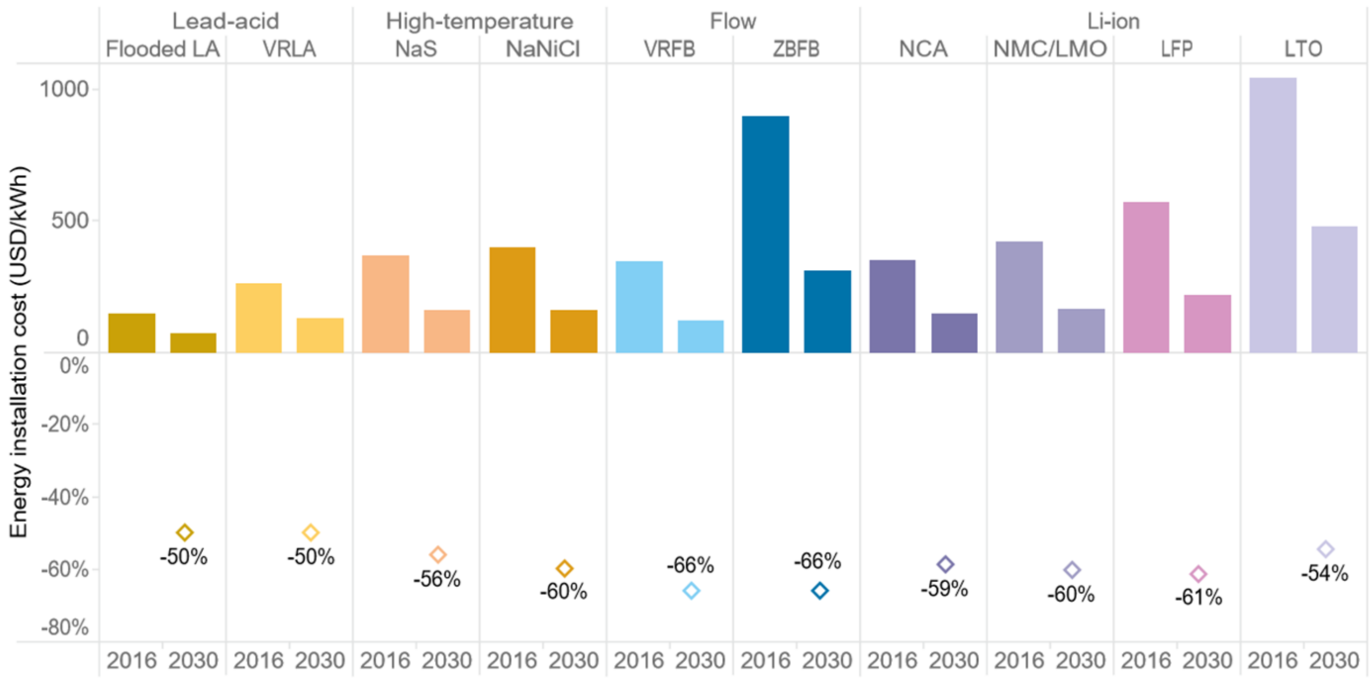
Greentech Media's 2017 Energy Storage Summit sentiment poll



Source: Lazard. Greentech Media

Energy installation costs in 2016 for flow batteries ranges USD315-1,680/kWh, which are expected to diminish by approximately two-thirds to range USD108-576kWh. According to the International Renewable Energy Agency data, the VRFB technology is not forecast to exceed $360/kWh, with a central estimate of approx. $120/kWh. Although cost reduction estimates require coordinated adoption within uncertain markets, most reductions would derive from items affected by a competitive environment, with the benefits of a larger-scale market being very important. The figure below indicates the cost reductions associated with flow batteries to dominate various battery technologies, thereby promoting the mass adoption of the system as installed capacity gains traction.

Battery electricity storage system installed energy cost reduction potential (2016-2030e)

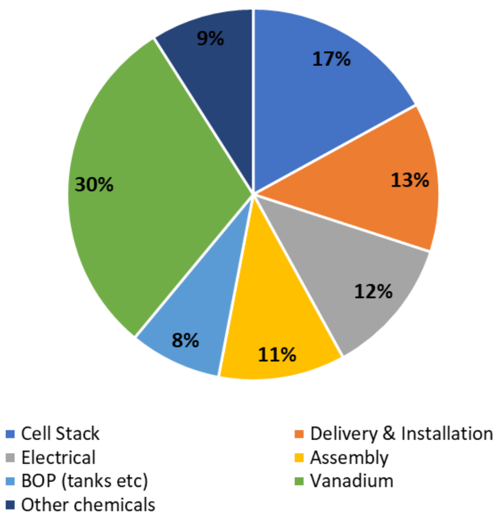


Note: LA = lead-acid; VRLA = valve-regulated lead-acid; NaS = sodium sulphur; NaNiCl = sodium nickel chloride; VRFB = vanadium redox flow battery; ZBFB = zinc bromine flow battery; NCA = nickel cobalt aluminium; NMC/LMO = nickel manganese cobalt oxide/lithium manganese oxide; LFP = lithium iron phosphate; LTO = lithium titanate.

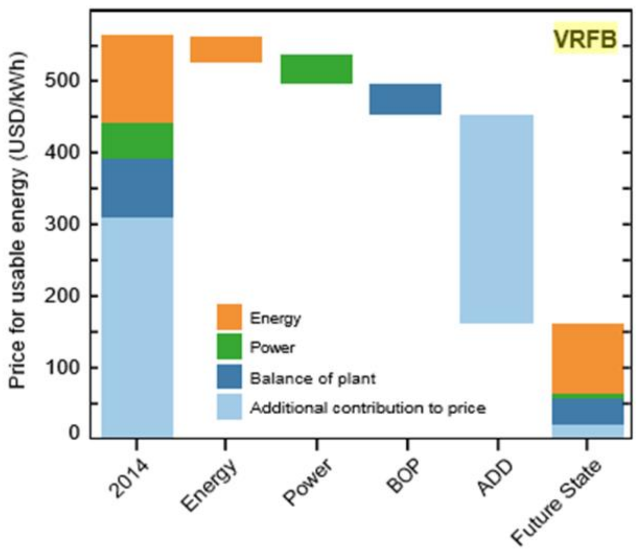
Source: *IRENA*

The vanadium redox flow battery storage mechanism involves redox reactions in the cell that are fed by active ionic vanadium materials from electrolyte tanks, resulting in electron transference. The circuit relies on four oxidation states with V^{2+}/ V^{3+} and V^{5+}/ V^{4+} couples in a mild sulphuric acid solution. The simple circuit relies on an ion-selective membrane within the cell to separate the electrolytes on each side of the cell to prevent ion cross-contamination. Consequently, the single active vanadium dominates almost 30% of the cost breakdown of the battery, with the mammoth 800MWh VRFB storage facility requiring c4,400t of vanadium (EPRI). Therefore, each additional utility-scale operation may consume 5.7% 2016 global production. The cost of production for the vanadium electrolyte will be fundamental in the successful cost reduction of the systems, therefore securing cheap, long-term high-quality vanadium feedstock material is crucial.

VRFB cost breakdown, %



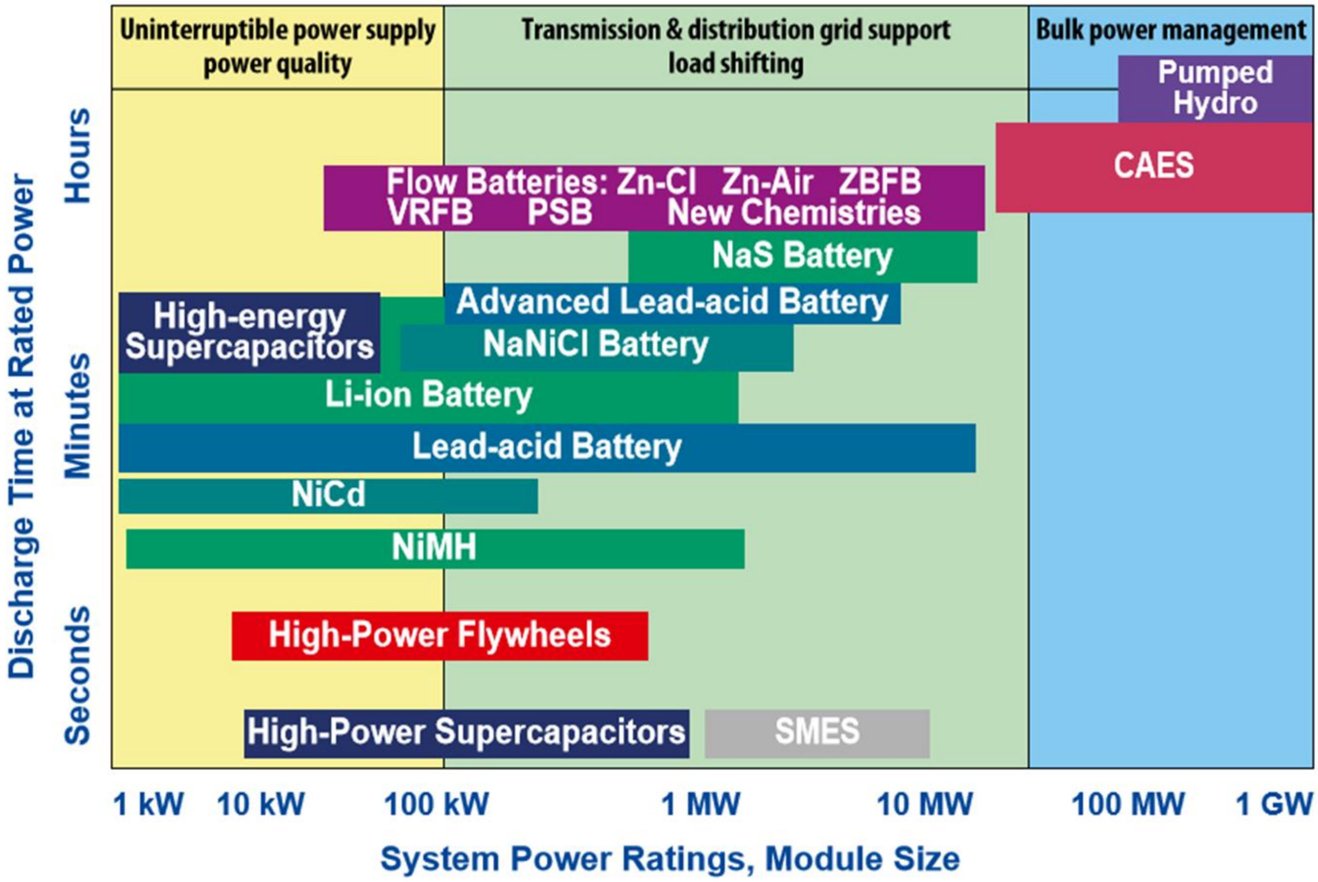
Potential pathway to reach cost-effective VRFB storage, US$/kWh



Source: EPRI – Vanadium Redox Flow Batteries, Bushveld analysis, International Renewable Energy Agency, based on Darling et al., 2014

Energy storage technologies are underpinned by different intrinsic properties which determine their technical suitability for applications and services to electricity systems. Technological traits of each system favour specific application, with flow batteries spanning a broad power rating from 10kW-100MW. Within the power range for flow batteries there is strong competition from diverse energy storage technologies, demanding future capacity and therefore represent a risk to future vanadium demand and market capture.

Positioning of diverse energy storage technologies, discharge time vs. power rating



Source: *IRENA, US DOE/EPRI, 2015*

China is leading the charge into the disruptive energy storage solution, with the National Development and Reform Commission recently releasing a policy document that called for the launch of pilot projects which ramp up utilisation of VRFBs for its electric grid by the end of 2020.

VRFBs offer a solution to the nations limited distribution networks which makes intermittent renewable energy sources a more desirable electricity option. In order to further develop its installed capacity of over 160GW, China plans to expand its redox storage in parallel with its wind and solar initiatives (IEA).

Early adoption by the Chinese government forms a strong strategic push for energy storage to yield large flow battery projects, while hosting the largest VRFBs installation is expected to "*be the cornerstone of a new smart energy grid*". A project demonstrating the integration of energy storage onto grid networks in Hubei, China, will see the first phase of a 10MW/40MWh operation constructed by Pu Neng, a major vanadium flow battery manufacturer. While the first stage of the Hubei Zaoyang Storage Integration Demonstration Project looks to assist the integration of power from large-scale photovoltaics locally, the scale is already dwarfed by a mammoth 200MW/800MWh energy system. Manufactured by Rongke Power and UniEnergy Technology, the battery will provide power during peak hours of demand, enhance grid stability and deliver energy during black-start conditions in case of emergency. The station will help balance supply and demand on the Liaoning province power grid, which serves around 40 million people.

The world's largest electric power VRB storage system (200MW, 800MWh) installed by Rongke Power. The system utilized abundant wind and photovoltaic energy generation and expected to support 8% of Dalian's, China, city load needs.

Source: *Rongke Power*

The above installation represents a surging interest toward vanadium redox flow batteries. According to the US Department of Energy's global energy storage database, since 2014 there are **more than 30 cumulative projects spanning 11 countries** which are under construction or in deployment. These project range in power from a few tens of kilowatts up to the major Dalian facility.

The current flow battery market is expected to swell from $230 million in 2018 to $946 million by 2023, at a CAGR of 33% (energy and capital).

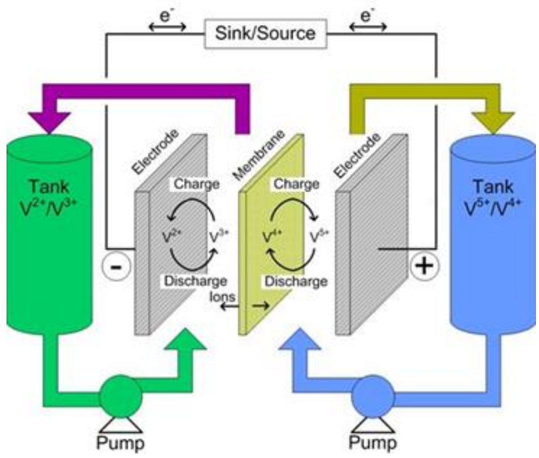
The widespread adoption of VRFB's as an effective energy storage solution could emerge as a disruptive trend in the vanadium market, driving a structural change in a market dominated by steel manufacture. If realised, projected growth in the energy storage sector could see the shares of vanadium consumption rise from 2-3% of current demand to up to 20% by 2030, according to Bushveld Minerals.

Appendix: A summary on vanadium redox flow battery technology

Vanadium chemical application across energy storage systems (ESS) is a rapidly developing global market which is set to expand significantly with demand for large, reliable and efficient batteries with swift response properties. Target markets for vanadium redox flow batteries (VRFBs) include off-grid power supply, grid connected power stabilization systems and revenue, and energy storage for intermittent renewable energy generation units.

Modern iterations rely on technology originally conceived by NASA during the energy crisis of the 1970's, with the first demonstration VRFB carried out in Australia in 1980 undergoing patenting by Professor M. Skyllas-Kazacos at the University of New South Wales in 1986.

Redox reaction inside a VRFB



Vanadium oxidation states may be distinguished by multiple colors. Each color relates to a separate vanadium ion contained within the sulfuric acid in a VRFB

Source: SP Angel, MESSIB

Redox batteries operate by converting chemical into electrical energy during discharging mode and back in the charging process using the vanadium ability to exist in 4 different oxidation states. Each oxidation state relates to a different charge of the vanadium ion (V2+, V3+, V4+ and V5+) with 4 of those participating in the reduction/oxidation “redox” process. During the discharge, two reactions run simultaneously in two half-cells: oxidation in the anode (conversion of V2+ to V3+ by the release of electrons which by travelling through a conductor create an electric current) and reduction in the cathode (conversion of V5+ to V4+ by accepting additional electron). Effectively, vanadium is used on both the cathode and the anode, eliminating any risks due to contamination and crossover of elements in the battery. The process is continuous with electrolytes allowing the reaction to occur being pumped through the battery from external tanks until the reservoir of charged electrolyte runs down. The reaction is reversed once the battery is being charged.

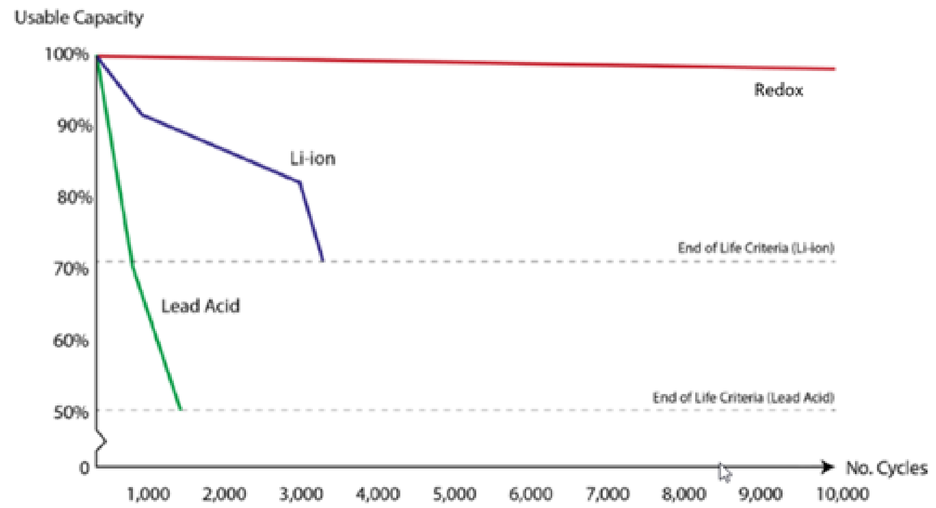
VRFBs possess a number of advantages when compared to other types of batteries (see table below) including lithium and lead acid based systems including a longer life cycle, short recharging time, low self-discharge and ability to expand power and energy capacity in a modular approach (the size of reservoirs storing electrolyte defines the energetic capacity (kWh) while the number of cells (2 electrodes, 2 reservoirs and a conductor) dictate the power (kW) if the system).

Comparison of VRB and Li-ion systems	Vanadium Redox Batteries	Li-ion
Relative advantages:		
Number of cycles	>10,000 (10-20 years)	3,500 (Li-ion)
		1,500 (Li-ion polymer)
Low self-discharge	+	-
Expandable (in terms of energ and power capacity)	+	-
Generates low levels of heat	+	-
Charges and discharges simultaneously	+	-
Suitable for connection to power grid	+	-
Response to changing loads	+	-
Relative drawbacks:		
Dimensions	Large footprint	Small footprint
Energy density (Wh/kg)	25-35	110-160 (Li-ion)
		100-130 (Li-ion polymer)
Operating temperatures	-5/+50 C	-20/+60 C
1MW system cost, $/kW	6,000-7,000	3,000
Cost per US$ per kWh per cycle	0.08	0.05
Charge time	5h	2-4h

Source: *SP Angel, UNSW, Battery University, PNNL*

As the reaction in the VRFB occurs between two electrolytes rather than between electrodes and electrolyte there is no wear of electroactive parts as the battery continuously charge/discharge. Further, the single element electrolyte overcomes cross-contamination degradation, allowing battery cycles to extend >10,000 cycles, compared to 3,500 for Li-ion (~70% end-of-life usable capacity) and 1,500 for Lead Acid (~50% end-of-life usable capacity). Maintenance costs are principally limited to the replacement of the polymer membrane, while the vanadium electrolyte offers recyclable potential following the 25-year machine life.

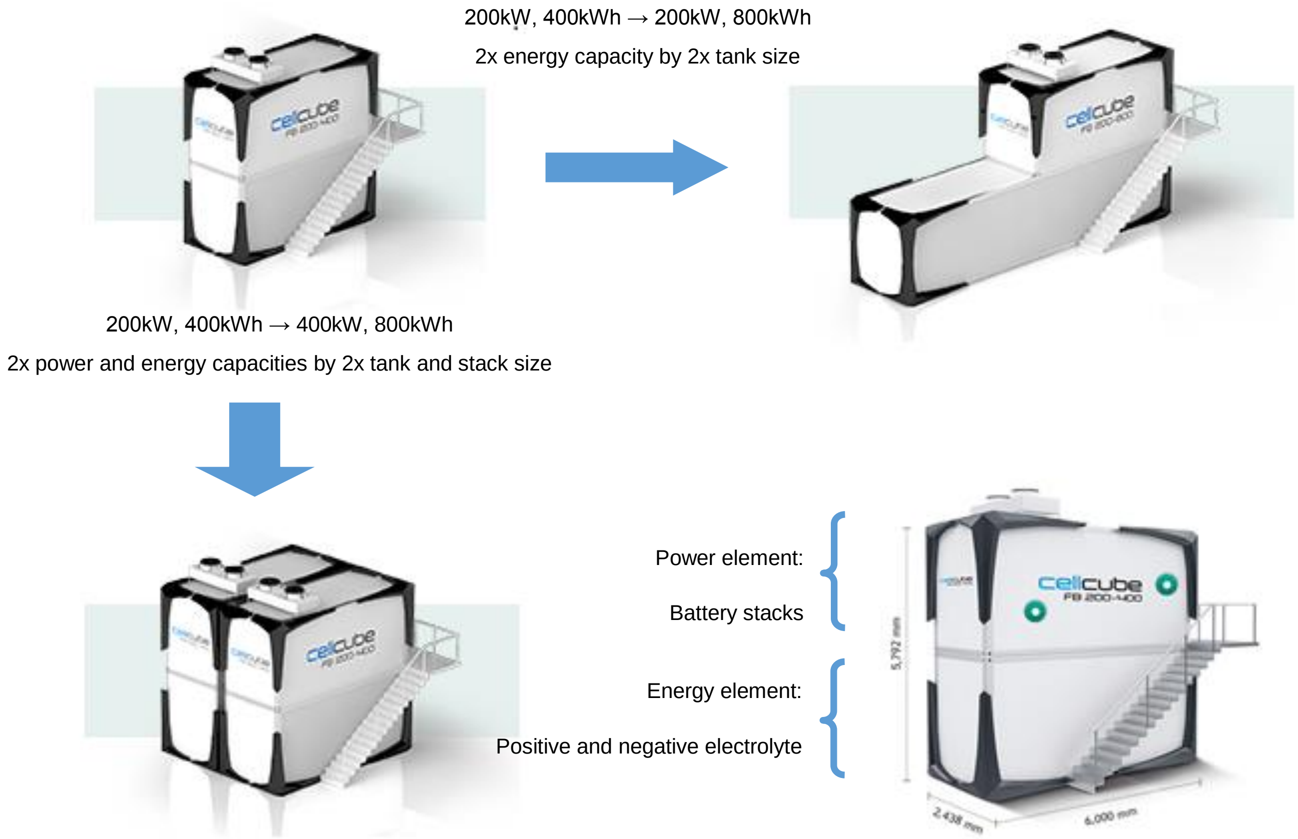
Usable capacity of energy storage systems over cycle life



Source: *redT energy*

Given that the amount of energy stored by VRFBs is directly linked to the size of tanks containing liquid electrolytes, the use of VRFBs in the mobile applications is limited. On the other hand, the flexibility in adding/cutting energy and power capacities by installing modular VRFB units allows to scale the system within kW and MW ranges in mid- to large-scale applications such as grid support and power storage for renewables.

An example of modularity of VBR systems using Gildemeister's CellCube product



Source: *Gildemeister*

Producers and developers have been heavily involved in VRFBs research looking at ways to improve operational characteristics of the battery and reduce capital costs. Research out of the Pacific Northwest National Laboratory developed mixed sulphate (SO_4^{2-}) and chloride (Cl^-) electrolyte solution which increases the energy storage capacity of the battery by some 70%, which in turn reduces the $/kWh VRFB cost. The use of Cl^- also increases the operating temperature window by 83% to -5-50°C, with other properties such as electrochemical reversibility, conductivity, and viscosity also showing improvement.

Research and development avenues for flow batteries

RESEARCH AND DEVELOPMENT AVENUE	APPLIES TO SUBTECHNOLOGY	TECHNOLOGY SHIFT	REDUCES PRODUCTION COST	INCREASES PERFORMANCE
Improved membranes: Lower resistance	All flow batteries (except ZBFB)	No	Yes	Yes. Higher efficiency
Improved membranes: Reduced cross-contamination	All other flow batteries (i.e. excluding VRFB and ZBFB)	No	No	Yes. Less maintenance
Improved membranes: Reduced leakage	All flow batteries (excluding ZBFB)	No	No	Yes. Less maintenance
Integrated stacks	All flow batteries (excluding ZBFB)	No	Yes. Higher degree of automation	Yes. Reduced leakage
Salt water electrolyte	New technology	Yes	Yes. Potential for very low energy costs	No. Electrical performance not better than status quo

Source: International Renewable Energy Agency

Efficient ESS will be playing increasingly important role in grid management and power demand optimization amid expanding renewable energy market and rising power costs. We believe VRFBs have significant potential in the ESS space and is set to cement a fast-growing niche in the batteries' market.

Major VRB uses and applications

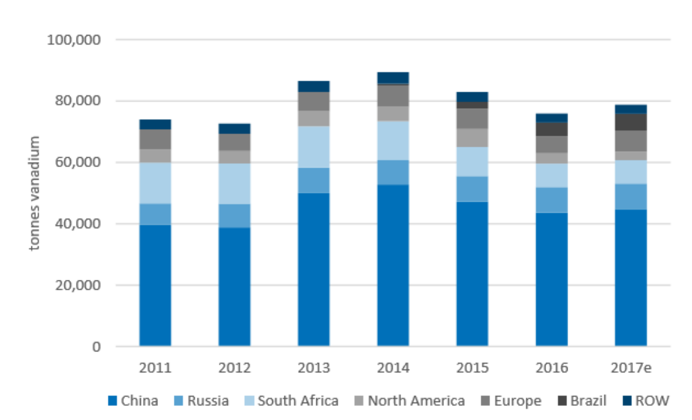
Large scale (MW) grid-connected storage
- smart-grid applications
- integrating wind and solar to complement existing baseload generation
- load levellingand peak shaving
- stabilisingvoltage and frequency
- improve power quality
- deferring upgrade investments for large genrators
- uniterruptible power supply for industrial/commercial applications
Small (kW) to large scale (MW) distributed storage
- combined with solar or wind generation for remote communities (Remote Area Power Systems – RAPS)
- replacement of diesel generation for inaccessible installations
- uninterruptible power supply for communication

Source: UNSW

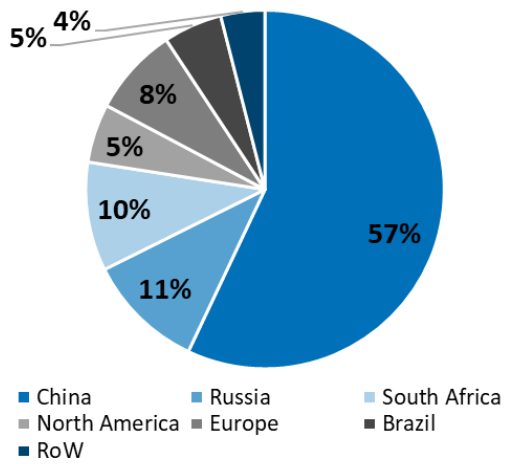
Supply

Global vanadium supply is expected to have climbed c3.9% throughout 2017 to 79,000 tonnes in response to advancing vanadium consumption within high-tensile strength steel rebar and budding chemical vanadium redox-flow battery output. Production is dominated by three majors; China accounting for 57% (2016 output), Russia 11% and South Africa 10%.

Global vanadium production, tonnes (2011-2017e)



Global vanadium production, % (2016)

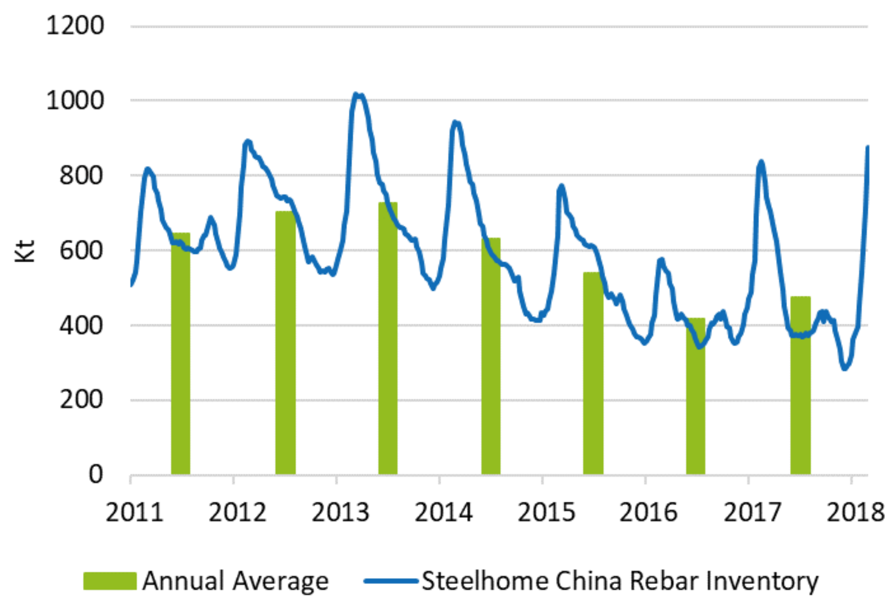


Source: Vanitec

Global production is estimated to rebound through 2017 after contracting from highs of c90,000 tonnes in 2014 to 2016 lows. The two-year fall represented approximately 18.4% equivalent to 14,000 tonnes vanadium, which matches a comparable downward trend in Chinese steel production and demand covering the same period. A significant decline in co-produced vanadium from Chinese processing of magnetite iron ore resulting from financially constrained production led to a material decline in global vanadium supply.

South Africa has also historically been the largest supplier of primary vanadium, and supplemented with significant quantities of co-product sourced material. Output has drifted with the closure of EVRAZ Highveld Steel and Vanadium's operations during 2016, leaving Vametco and Glencore's Rhovan operation as the only active vanadium producers.

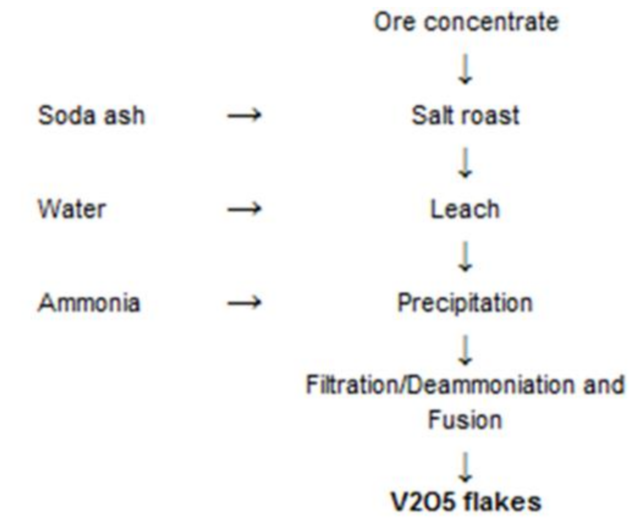
China Steelhome Rebar inventory, Kt (2011-2018)



Source: Steelhome

In a unique market fundamental to vanadium the principal consumer, steelmakers, also indirectly represent the most significant global source; with 73% generated through the processing of magnetite iron ore as co-product slag (containing up to 20% vanadium). Consequently, the outlook for the iron-ore and steel industry can provide insight into the vanadium industry.

World vanadium production flowsheet



Source: TTP Squared Inc.

Co-produced vanadium represents an inexpensive, low-cost curve source as the production costs are borne by the primary iron supply and absorbed within an integrated steel mill operation. Major vanadium feedstock supply in China is co-produced from low-grade, high-cost vanadium-bearing magnetite ores, where generated slag undergoes addition processing techniques to supply intermediate oxide products.

Substantial economic pressure is negatively impacting magnetite iron-ore processing steel plant operations, as the elevated costs associated with mining and processing low-grade magnetite ore relative to high-grade haematite ore translate into reduced margins. Further, the complex operating flow to co-produce vanadium and titanium in integrated steel plants significantly raises operating costs compared to simpler blast furnaces. Any downward movement in steel prices are expected to curtail or suspend production across more marginal magnetite operations.

Growing Chinese environmental legislations are also applying significant pressure on more-polluting magnetite operations, with the Ministry of Environmental Protection targeting emissions standards through 2020. The Asian nation plans to cut emissions of sulphur dioxide and nitrogen oxide, major sources of hazardous airborne PM2.5 particles, via continued reduction of steel capacity according to reporting by the National Development and Reform Commission (NDRC).

> Cutting 30 million tonnes of steel capacity in 2018 will draw the total across the last three years to 145 million tonnes. The initial target aimed for 150 million tonnes by 2020, with further capacity restrictions indicating the dedication to improving air quality across China.

> The air quality department at the Ministry of Environmental Protection urges responsible regional industrial output, with officials in key steel hubs such as Tangshan City proposing an extension of the winter production curbs enforced during November through March, equivalent to 10-15% output.

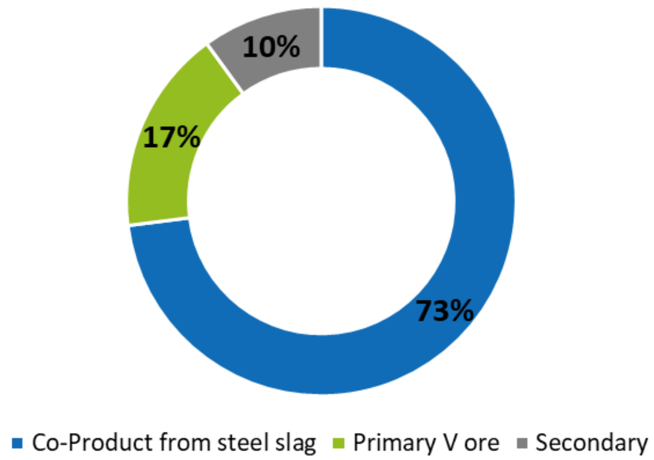
Consequently, there is a broad industrial preference for higher-quality, more efficient haematite ore; evident in the enlarging price disparity in benchmark quality ores and rising low-grade iron ore stockpiles across Chinese ports, which have surged to record breaking levels of 159.13 million tonnes (February 2018).

Further, in an effort to heighten the environmental clean-up, China's Ministry of Environmental Protection have also acted to ban imports of 24 types of waste including 4 metal slag varieties containing vanadium. From December 31, 2017 new regulations are forecast to forbid imports, primarily from Russia and New Zealand, which will account for approximately 4,500-5,500 tonnes from China's annual vanadium pentoxide (V_2O_5) according the Metal Bulletin data. While the move appears counterproductive for sourcing vital vanadium slag raw material, the focus on environmental preservation is likely to extend China investment outside of the Asian nation and a relocation of primary vanadium steel plants.

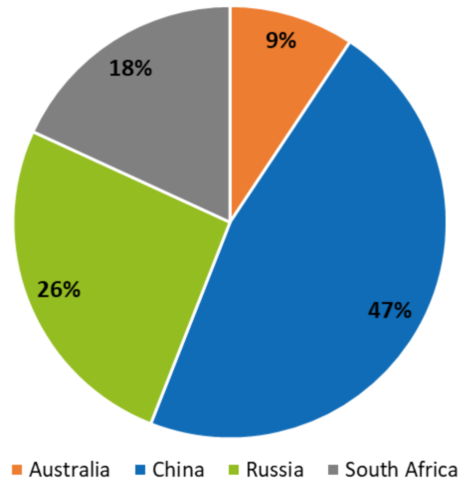
The cumulative impact of China's war on smog and promotion of environmentalism is driving iron ore blends to lower vanadium content raw material, and therefore reducing global production via co-production. More stringent air quality targets set to cover the 2018-2020 period will only exacerbate the focus on high-grade and limit the principal source of global vanadium.

The downside pressure from environmental restrictions could significantly hamper global output, with only eight operating vanadium steel mills across China (MSA Group) producing over 50% feedstock. Environmental or economic issues restricting a single operation could therefore reduce global vanadium production by up to 10%.

Vanadium supply by production source (2016)



Global vanadium reserves (2016)



Source: Vanitec (reproducing data from TTP Squared), USGS

Primary mining and processing operations account for 17%, despite world resources exceeding 63 million tonnes (USGS). China dominates global reserves with 47% equivalent to 9 million tonnes, followed by Russia with 5 million tonnes and South African reserves totaling 3.5 million tonnes.

The most significant source of vanadium, accounting for around 85% of world production is titaniferous magnetite. Major vanadium-bearing titaniferous magnetite deposits are found in Bushveld complex in South Africa, the Kachkanar Massif of the Ural Mountains of Russia, and the Sichuan province in China. Subject to deposit characteristics, titaniferous magnetite ores present a global source of vanadium, iron ore and ilmenite.

Additional global uraniferous sandstone and siltstone containing 0.1-2% vanadium represents the primary US source of the metal, co-produced as vanadium silicates and oxide-vanadates in association with uranium from the Colorado Plateau operation. Kazakhstan, Uzbekistan, Gabon and South Africa also have large uraniferous sandstone deposits.

Phosphate rock also hosts vanadium, however typically produced as a fertilizer by-product, the rock is not a major source of commercial vanadium.

Significant quantities are also recovered from bauxite and carboniferous materials, such as coal, crude oil, oil shale, and tar sands. Typical vanadium recovery occurs as a by-product or co-product, therefore demonstrate world resources are not fully indicative of available supplies.

Major established vanadium producers include:

Pangang Group Vanadium & Titanium Resources Co. is the largest vanadium producer in China with operations located in Pazhihua, known as the '*Vanadium City*', generating vanadium slag alongside iron ore and ilmenite concentrates. The company has the capacity of approx. 10mt steel and 24,000 tonnes vanadium co-product.

EVRAZ, a vertically integrated steel producing and mining group, comprising the most significant ferrovanadium operation outside of China, providing 23% global supply in 2016. EVRAZ Vanady Tula is the largest Russian producer of ferrovanadium, with capacity to produce 5,000 tonnes ferrovanadium and 7,500 tonnes vanadium pentoxide. EVRAZ Nikom in Czech Republic reprocesses vanadium pentoxide received from EVRAZ Vanady Tula and China to 4,940 tonnes ferrovanadium. The US and South African Stratcor operation is a producer of the highest-purity vanadium oxide with annual capacity of 2,750 tonnes.

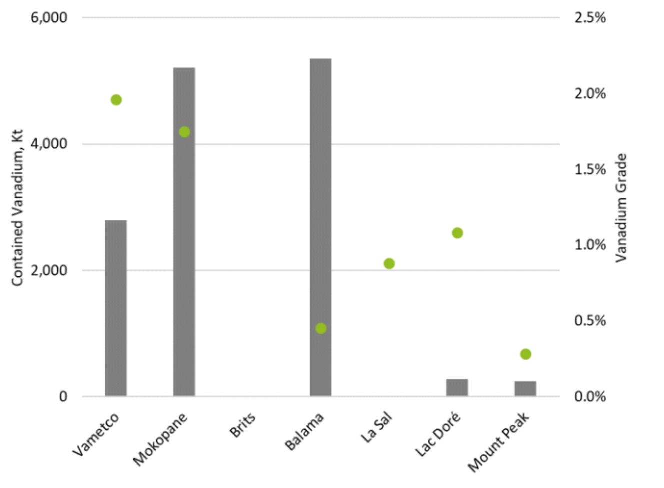
The Rhovan primary vanadium mine owned and operated by Glencore in the Bushveld Complex in South Africa generated 9,480 tonnes vanadium during 2017.

Largo Resources operates its flagship Maracás Menchen mine in Brazil, boasting the highest-grade vanadium resource in the world at 1.17% (P&P). Production commenced in August 2014, with annual output averaging 9,600 tonnes V_2O_5, although there remains tremendous upside potential for expansion of the 18.4 million tonne resource base and production rates.

Vanadium supply by production source (2016)

Company	Project	Contained V2O5, kt	V2O5 grade
Bushveld Minerals	Vametco	2791	1.96%
	Mokopane	5,215	1.75%
	Brits		<2.6%
Syrah Resources	Balama	5,355	0.45%
Energy Fuels	La Sal	12	0.88%
VanadiumCorp	Lac Doré	282	1.08%
TNG	Mount Peak	243	0.28%

Global vanadium reserves (2016)



Source: Vanitec (reproducing data from TTP Squared), USGS

With global demand for vanadium expected to vault production significantly, a limited number of vanadium companies are developing and advancing projects:

The major Bushveld Minerals vanadium project located in South Africa contains approximately 20 billion tonnes of vanadium as well as titanium, representing 26% of the world's vanadium reserves. The company aims to be the most vertically integrated primary vanadium platform, developing downstream operations extending to the manufacture of vanadium electrolyte and large-scale VRFB assembly. Exploration targets mineralisation in the Main Magnetite Layer and comprises three key assets;

Vametco Vanadium Mine – 142.4Mt resource with average in-magnetite grade of 1.96% V_2O_5

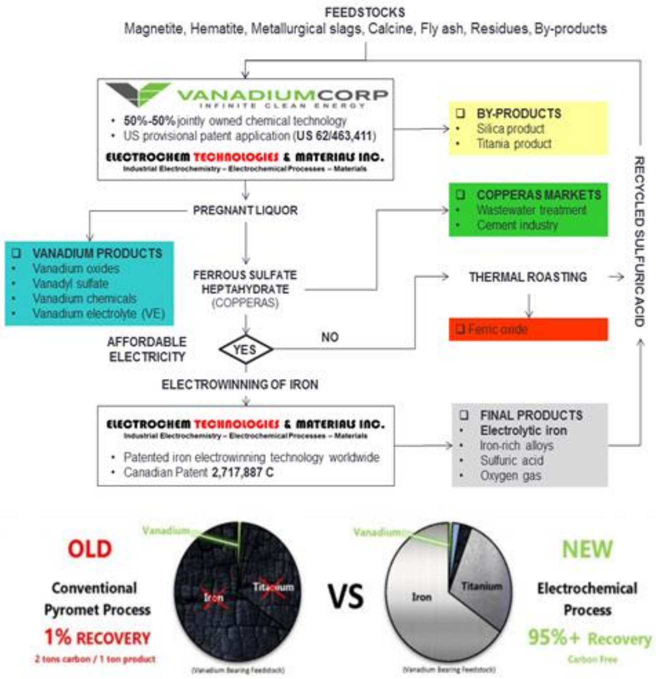
Mokopane Vanadium Project – 298Mt JORC with average in-magnetite grade of 1.75% V_2O_5

Brits Vanadium Project – Outcropping, strike extension of Vametco mine with historic drilling with indicative 2.6% V_2O_5 max grades

Syrah Resources is developing the Balama Project, the world's largest graphite deposit with vanadium as a by-product, in Mozambique. The resource is estimated to host 1.19Bt at 11% TGC and 0.45% V_2O_5 (Mephiche Zone resource statement), for 128.5Mt contained graphite. This compares to total global reserves of 253Mt, according to the latest USGS report. Metallurgical testwork on the vanadium stream highlights potential for a two-step development program focusing on the production of 99.9% V_2O_5 chemical powder and 98.5% V_2O_5 flake. While the project initially focuses on developing the graphite reserves, high purity vanadium samples produced from Balama pilot plant have been sent to a number of major vanadium redox flow battery producers.

Uranium miner Energy Fuels overturned federal Bureau of Land Management and US Forest Service approvals in February 2018 to expand operations at two mines in southeast Utah, following years of challenges from conservation groups concerned with radon gas emissions. Current mines are not operational due to sustained low uranium prices, however the company is evaluating the La Sal complex as a vanadium resource. The La Sal complex hosts 1327Kt ore with an average 0.88% grade, thereby hosting 11.7Kt V_2O_5.

VanadiumCorp-Electrochem integrated vanadium electrolyte process



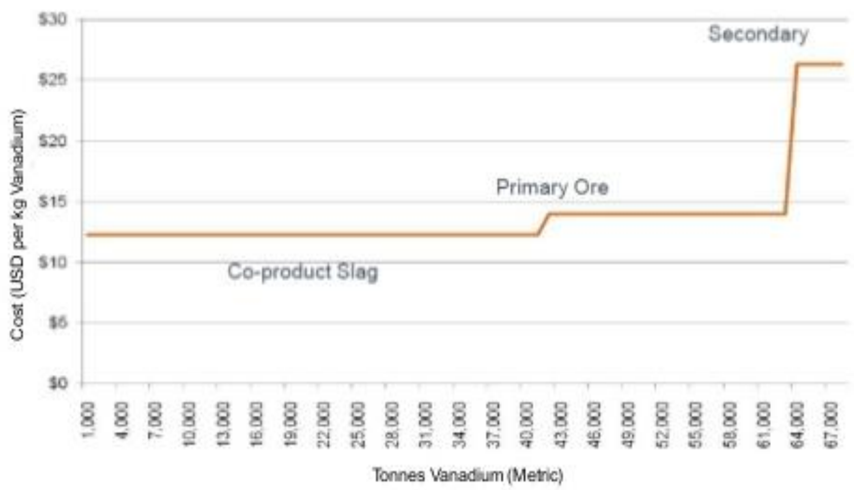
Source: VanadiumCorp

VanadiumCorp's integrated operation targets vanadium ore across Quebec, Canada, for direct recovery into flow battery electrolyte. The company's flagship Lac Doré project resource measures 282Kt V_2O_5 from VTM (vanadiferous titanomagnetite) concentrate grading 1.08% V_2O_5. VanadiumCorp partnered with Electrochem Technologies & Materials Inc. to develop a new electrochemical patent-pending process 'VanadiumCorp-Electrochem Process Technology' to extract vanadium without slagging, smelting or roasting. The vanadium bearing feedstock promises 95% recoveries of VTM compared to average 0.5-1% for conventional salt roasting primary production methods. While bench-level testwork reveals positive processing, it remains to be proven the success of commercial-scale production of vanadium electrolyte.

TNG Ltd advance the Mount Peak deposit in Australia after executing a series of life-of-mine binding off-take agreements for its titanium oxide, pig iron and vanadium products; WOOJIN metals (leading supplier of FeV) secured a minimum 60% of vanadium output, with Guvnor targeting iron products. The company will implement its patented TIVAN hydrometallurgical process for treating vanadiferous ores via acid leaching and solvent extraction of vanadium, titanium and iron from the magnetite concentrate. The 160Mt resources grades at 0.28% vanadium, 5.3% titanium and 23% iron, equating to 243Kt V_2O_5.

Secondary sources of vanadium represent the most marginal operations, relying on elevated vanadium prices to sustain production. 10% of aggregate supply is derived from oil residues, spent catalysts and power station fly ash, which exposes operations to fluctuating market pricing and availability of raw materials. Crude oil in the Caribbean basin, parts of the Middle East and Russia, tar sand in western Canada and coal in parts of China and the US contain vanadium, which is recovered as part of the refining and burning of fuel sources.

Vanadium supply cost curve



Source: TPP Squared Inc. (Note – axis values may not be representative)

*SP Angel corporate clients with vanadium assets: Bushveld Minerals***

***SP Angel act as Nomad and broker to Bushveld Minerals*

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Hold	8	16%	4	13%
Sell	1	2%	-	-
N/R	20	39%	18	63%
Total	51	100%	32	100%

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SP Angel Contact List

Research

Sergey Raevskiy
+44 20 3470 0474
sergey.raevskiy @spangel.co.uk

John Meyer
+44 20 3470 0470
john.meyer@spangel.co.uk

Simon Beardsmore
+44 20 3470 0484
simon.beardsmore@spangel.co.uk

Sales

Richard Parlons
+44 20 3470 0472
richard.parlons@spangel.co.uk

Elizabeth Johnson
+44 20 3470 0471
elizabeth.johnson@spangel.co.uk

SP ANGEL

SP Angel Corporate Finance LLP

Prince Frederick House
35-39 Maddox Street
London, W1S 2PP
United Kingdom

Tel: +44 20 3463 2260

Fax: +44 020 7629 1341