India

Neutral *(no change)*

Non Ferrous

Vanadium: Redox flow battery usage is key

- Vanadium is a key metal, with over 90% of vanadium produced used in stainless steel as a strengthening substance and also in alloys.
- However, an alternate usage of vanadium in the clean energy space involves its use for power storage purpose in vanadium redox flow batteries.
- This shouldn't be a problem as generating 10GWh VRF battery storage by 2030F requires production to grow at a CAGR of 6% over the next decade.

Vanadium finds key usage in steel industry

Vanadium addition at a very low level increases the yield strength of steel and therefore plays a pivotal role as a critical energy transition metal. This is because this micro-alloyed steel is required in less quantity, compared to normal stainless steel, owing to its superior strength and toughness. As a result, it allows infrastructure development to take place using less steel, resulting in consumption of a minimal quantity of raw materials and energy. This, in turn, reduces the carbon footprint and enhances the sustainability of the steel industry as well as the construction industry.

Vanadium redox flow battery is likely key growth driver of the metal

There is potential for the battery sector to become a sizable consumer of vanadium going ahead. Vanadium is used in vanadium redox flow batteries (VRFBs), in which vanadium electrolyte is used to store energy and enable a wider use of renewable power generation such as wind and solar, when they are not operational, let's say during night-time, for solar power. VRF batteries have a critical advantage over lithium-ion batteries (LiB) as repeated charging and discharging of VRF batteries doesn't degrade the electrolyte. As a result, VRF batteries have a longer life cycle compared to LiB, 20 years+ compared to 10 years of LiB. Although the upfront costs for a VRF battery are higher, over the entire life span of the battery, low operational costs result in LCOS (Levelized Cost of Storage) for such a battery to be significantly lower than that of LiB. However, VRF batteries have low energy density i.e. require more space to store the same power compared to LiB, and thus their use is limited to grid battery storage.

10 GWh VRF capacity by 2030F looks achievable

Our estimates suggest that there will be 1,000 GWh of battery energy storage set up by 2030F. Out of this, if VRF batteries have a 10% market share i.e. 10GWh, their current production needs to have a 6% CAGR over the next decade. This is keeping in mind that 90% of vanadium produced is used by steel mills and this number is not expected to change in the coming years. Achieving this CAGR doesn't look difficult, even though historically vanadium's CAGR has been at a rate of 3% over 1990-2012. This CAGR will decrease further to the historical average of 3% if, instead of 90%, 80% of vanadium is used for steel -making and the remaining 20% is used for the manufacture of vanadium electrolyte to be used in redox flow batteries.

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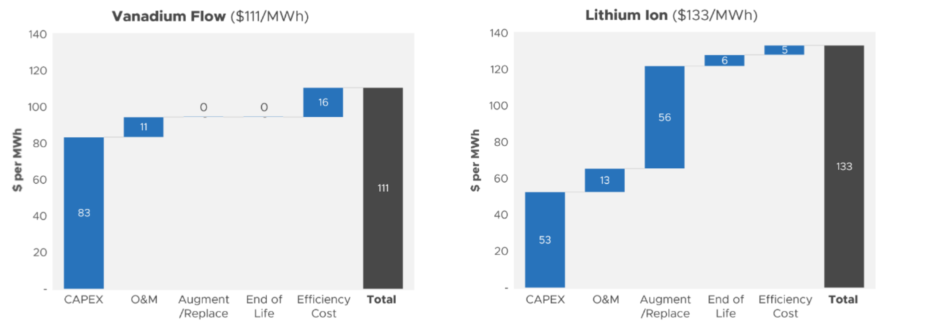
Figure 1: LCOS comparison between VRF battery and LIB over a 20-year life cycle



SOURCE: INCRED RESEARCH, COMPANY REPORTS

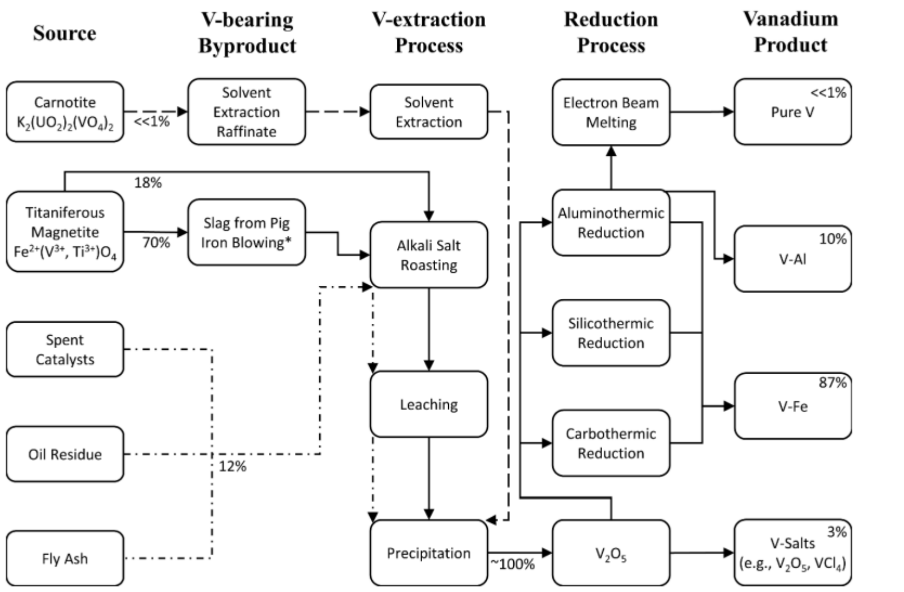
Vanadium: Catalyst for a change to green energy

Vanadium was discovered in 1801 by a Mexican mineralogist Andres del. Rio. It is a scarce element, hard, silvery grey, ductile and malleable transition metal with good structural strength. Vanadium and its compounds are gaining tremendous importance in the rapidly advancing field of science & technology. The metal occurs naturally in about 65 different minerals among which are patronite, vanadinite, roscoelite and carnotite. It is also present in bauxite and in fossil fuel deposits. Vanadium occurs in association with titaniferous magnetite and is recovered as a by-product during the manufacture of iron & steel. Vanadium is also concentrated in many end-products of organic material including coal, crude oil, shale, and tar sands. It is also found as a small percentage in meteorites. In addition, vanadium present in bauxite can also be recovered as vanadium sludge from red mud during the production of alumina. Vanadium is widely used in green technology applications, especially in battery technology. It is also used as an additive with steel to impart structural strength to steel rebars and beams.

Production of vanadium

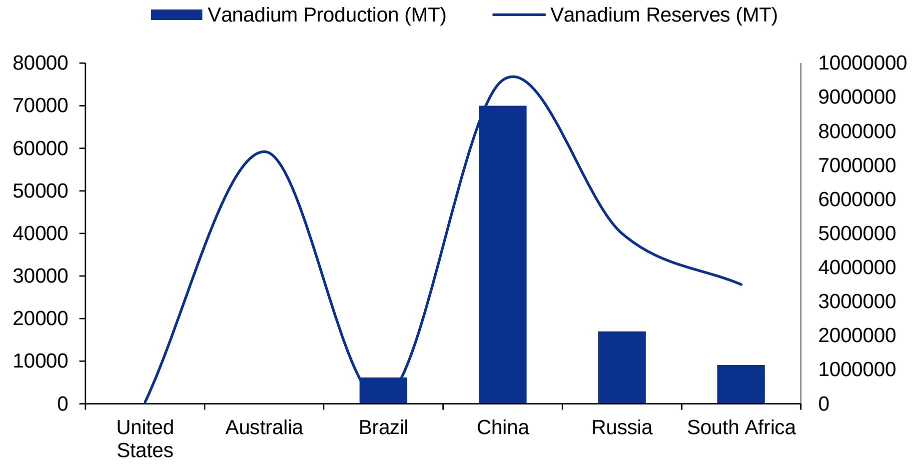
Vanadium feedstock is derived from three routes: primary production, secondary production, and co-production. Primary production sees mineral deposits exploited principally for the vanadium within. This takes place mainly in Brazil, China, and South Africa. In China, 'coal stone' (a carbonaceous shale) can also be a source of primary vanadium, depending on market prices. Secondary production is from the recycling of spent catalysts that acquired vanadium during crude oil refining, residue from alumina or uranium production, or ash derived from burning vanadium-bearing coal or petroleum. The US is the world's largest secondary producer of vanadium, with notable volumes also in various Asian countries. It is, however, co-production that accounts for a major portion (~70%) of global vanadium supply. This is where a vanadiferous titanomagnetite (VTM) ore (a form of iron ore) is used in the production of steel and vanadium reports to the slag. The valuable vanadium is recovered and subsequently processed into a vanadium product by the steel-maker. This takes place mainly in China and Russia.

Figure 2: Almost all commercial processes precipitate V2O5 as either the final or intermediate product



SOURCE: INCRED RESEARCH, COMPANY REPORTS

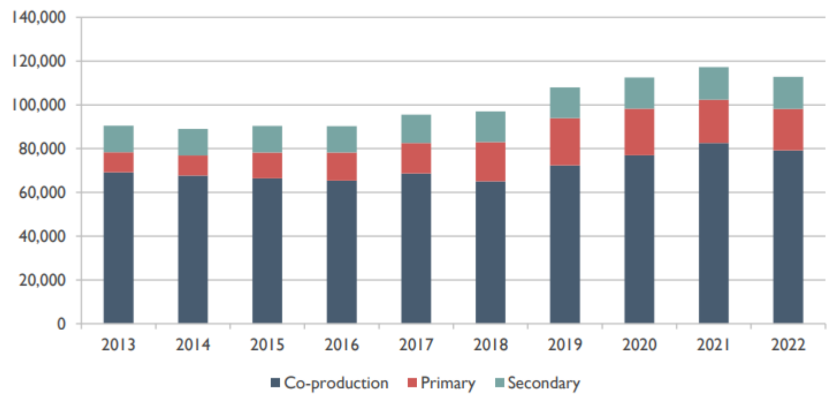
Figure 3: China accounted for most of vanadium production in 2022, although Australia has the second-largest vanadium reserves



SOURCE: INCRED RESEARCH, COMPANY REPORTS

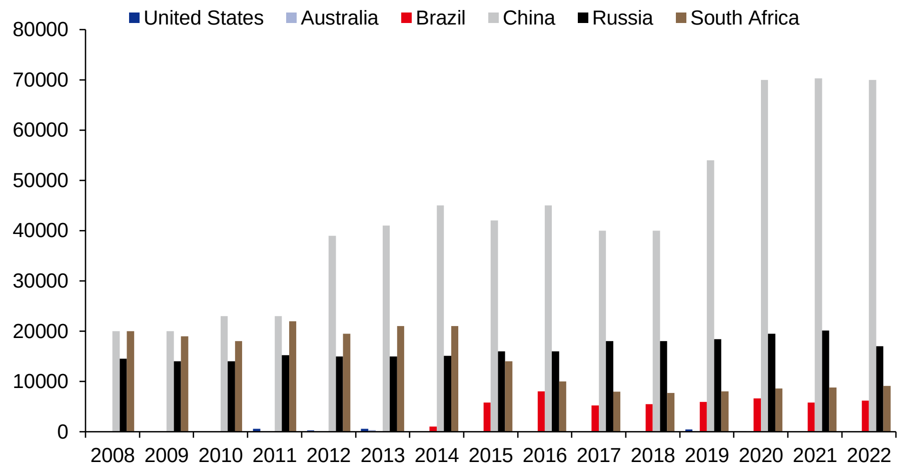
China is by far the world's main source of vanadium feedstock, with Russia, South Africa, Brazil, and the US being the 'top-five' producers. Primary, secondary, and co-produced vanadium are all converted into vanadates and subsequently into an oxide form. These vanadium oxides (vanadium pentoxide and trioxide) are mainly used as a feedstock to produce ferroalloys (alloys of iron with a higher proportion of one or more other elements) ferrovanadium (FeV) and vanadium nitride (VN). A much smaller proportion of oxides is used to produce high-purity vanadium compounds and chemicals.

Figure 4: Vanadium production by type; co-production accounts for the largest chunk



SOURCE: INCRED RESEARCH, COMPANY REPORTS

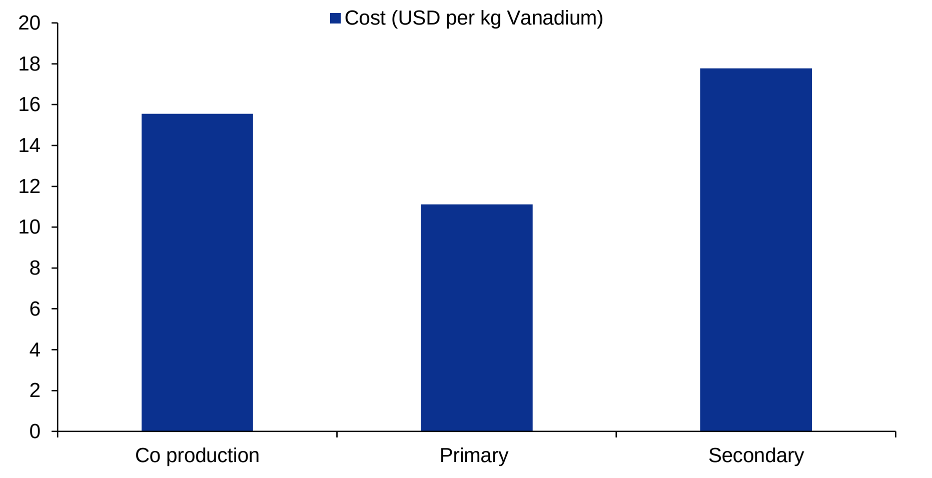
Figure 5: Vanadium production by country; historically, China has been the largest producer of vanadium



SOURCE: INCRED RESEARCH, COMPANY REPORTS

On a regional basis, China is by far the largest producer of vanadium feedstock. It has been steadily growing its market share, accounting for 55% of the global output in 2022. Vanadium output in China is mainly through the co-production route, where Pangang Group, HBIS Chengsteel, Chengde Jianlong, Sichuan Tranvic and Sichuan Deshang are the key players. An important primary source of vanadium in China is 'coal stone' (a carbonaceous shale) which, to some extent, serves as the supply chain's swing producer. At times of high vanadium prices, operations (mostly in Shaanxi and Henan) can produce significant tonnage. Russia is the world's second-largest vanadium feedstock-producing country. Most of its output can be attributed to EVRAZ, a vertically integrated steel, mining, and vanadium business house. In Russia, EVRAZ mines vanadium at its KGOK mine, which is subsequently processed into a vanadium slag at its NTMK operations. This slag is then refined into vanadium pentoxide and ferrovanadium at Vanady Tula. Some Vanady Tula pentoxide is processed into ferrovanadium at EVRAZ's Nikom plant in Czechia. South Africa is the world's third-biggest producer of vanadium feedstock. It was previously a much larger source of global supply, but its relative share of production declined and has never recovered since EVRAZ's Highveld operations (which accounted for more than 10% of the global feedstock output) shut down in 2015. Today, the supply comes from two major players, Glencore, and Bushveld Minerals. Brazil is the world's fourth-largest producer of vanadium feedstock, with the output all down to Largo. The company commissioned its Maracas Menchen mine in 2014 and has since ramped up its capacity to become one of the world's major producers. The US is the world's fifth-largest producer of vanadium feedstock. The most important producers are AMG Vanadium and US Vanadium, which produce vanadium from secondary sources. Depending on prevailing market prices, some vanadium mine production also takes place at uranium-mining operations.

Figure 6: Primary route remains the most cost-effective method to produce vanadium



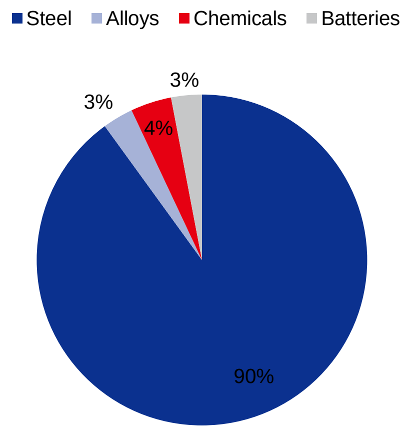
SOURCE: INCRED RESEARCH, COMPANY REPORTS

Vanadium production costs differ widely by production route and geography. The bottom quartile is dominated by primary producers who benefit from integrated operations, with processing assets (usually) close to mine sites. Production costs range between US$10-13/kg for V2O5, with quarterly fluctuations depending on specific operational issues, energy costs or currency movement. Co-producers are typically in the middle quartiles, e.g., US$15/kg V2O5, with Pangang and HBIS Chengde believed to be the lowest cost co-production operations. Chinese mills have seen their production costs increase in 2022 mainly due to higher energy costs, although the depreciation of the RMB vs. US dollar has reduced total costs in US dollar terms. There are a wide variety of secondary production routes and feedstocks, and while costs differ between these (and vary greatly depending on prevalent market prices), in general, secondary producers occupy the upper quartiles of the cost curve.

Steel production accounts for a major portion of vanadium supply ➤

Steel dominates vanadium consumption, consistently accounting for >90% of vanadium demand in any given year. Alloys and chemical markets represent mature, consistent first-use sectors for vanadium consumption, while demand from the comparatively new vanadium redox flow battery sector remains lower and, on the whole, more volatile on a year-to-year basis.

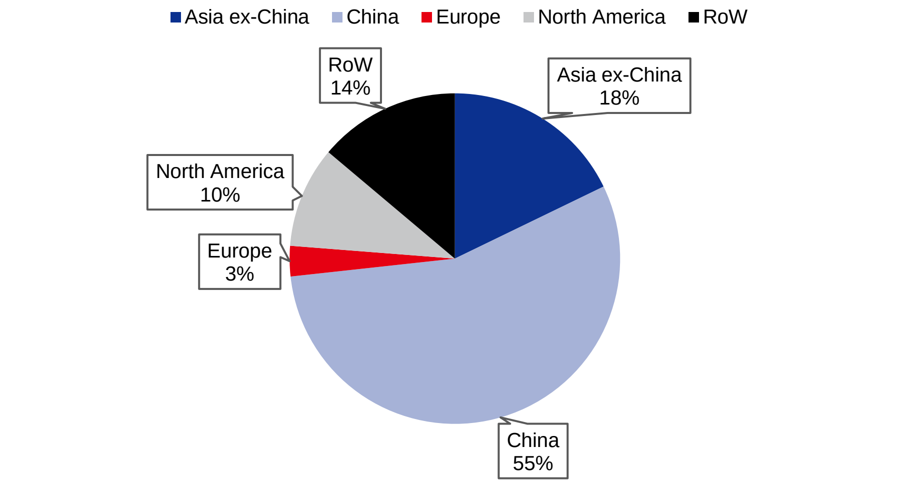
Figure 7: Vanadium demand by key applications in 2022



SOURCE: INCRED RESEARCH, COMPANY REPORTS

On a regional basis, China accounts for more than half of global vanadium consumption. This is reflective of several factors including its thirst for construction, its enormous steel sector, and the recent trend towards production of high-quality micro-alloyed steels.

Figure 8: Vanadium consumption by region

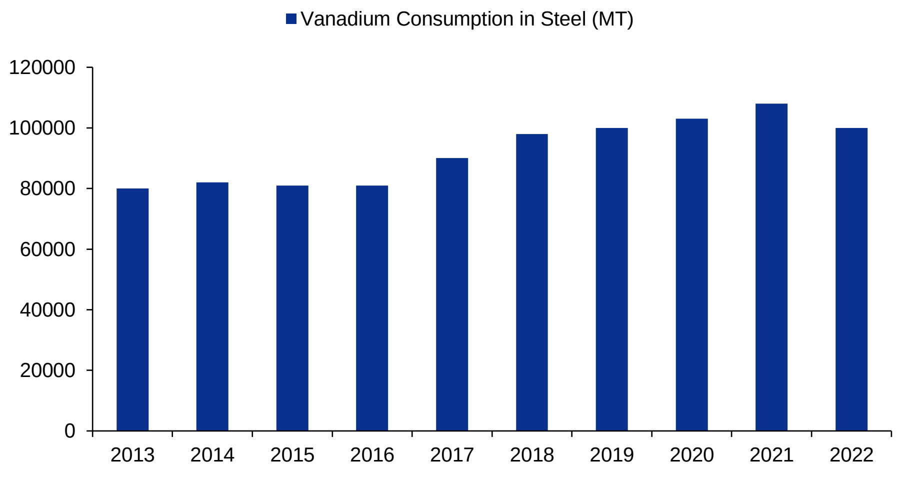


SOURCE: INCRED RESEARCH, COMPANY REPORTS

Why vanadium is preferred in steel-making

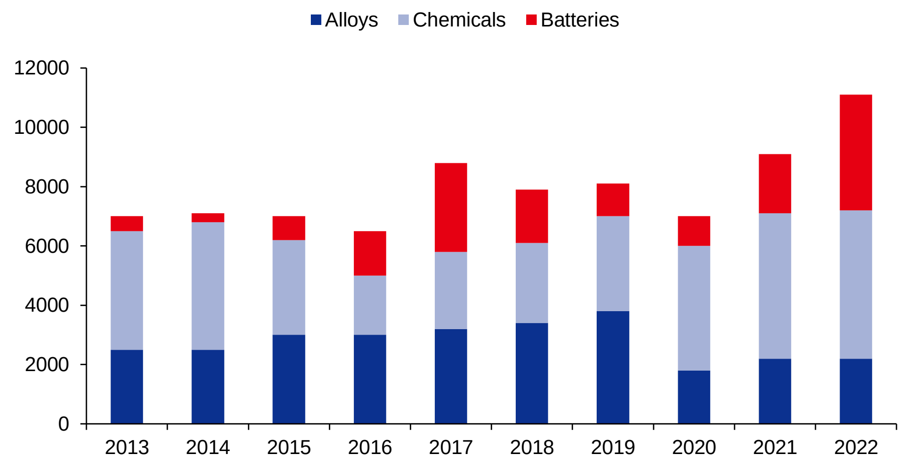
Vanadium demand is mostly driven by its use in steel, especially high-strength low-alloy (HSLA) steel. Vanadium finds application in structural long steel products, notably reinforcing bars (rebar). It is also used in a variety of other steels, including tool steels and stainless steels. Vanadium consumption in steel has risen considerably in recent years, although it declined in 2022 owing to lower than-expected construction activity in China.

Figure 9: Historical vanadium consumption in steel production



SOURCE: INCRED RESEARCH, COMPANY REPORTS

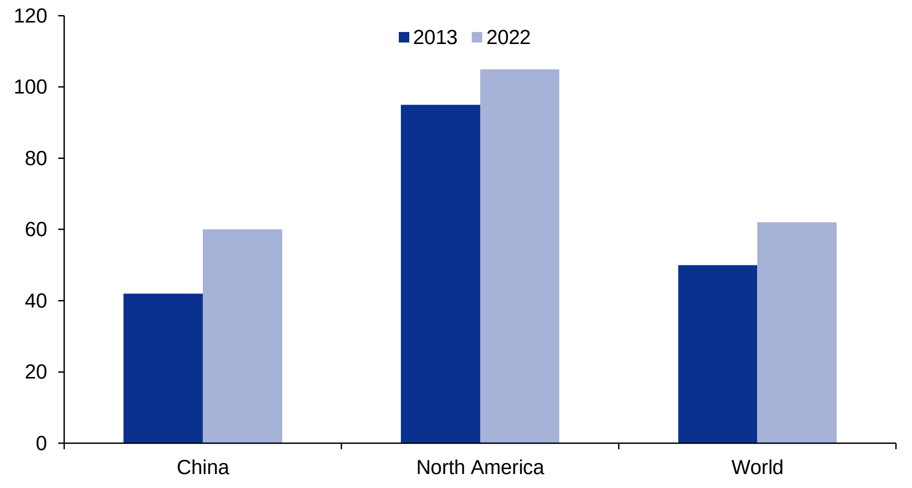
Figure 10: Non-steel consumption of vanadium (mt); application of vanadium in batteries has been on the rise



SOURCE: INCRED RESEARCH, COMPANY REPORTS

Increased vanadium demand for steel applications isn't just a factor of higher steel output (although crude steel production has increased substantially over the past decade, especially in China). It is also because the intensity of vanadium usage in steel has increased over time. Put simply, more grams of vanadium is being consumed per tonne of crude steel produced. This trend has mainly been supported by new construction standards in China mandating the use of micro-alloyed steel in rebar. Rebar is the main area of vanadium consumption in China; about 80% of vanadium consumed by steel in China is in the form of rebar. Nov 2018 saw the implementation of new Chinese rebar standards designed to promote the application of high-quality construction materials. The standard required Chinese steel mills to eliminate HRB335 grade rebar and start producing HRB600 grade rebar, which has better earthquake resistance. The standard was long overdue, with new construction codes in China having been called for since the devastating 2008 Sichuan earthquake. However, for a long time in China, lower quality 'quench and temper' rebar has been used in construction. Initially, enforcement of the standard was inconsistent. Larger mills, for the most part, conformed to new standards (in some cases before the rules came into force) while many smaller mills did not. Nevertheless, the new standards have made an impact, aided to some extent by national inspections on rebar quality in 2019, and general improvements and consolidation in the sector which have been ongoing over the past decade. While rebar is still produced using the quench and temper method in China, the proportion is diminishing on a year-on-year basis. This will continue to increase Chinese vanadium usage intensity towards the levels witnessed in North America.

Figure 11: Intensity of vanadium usage in steel over time (gram/tonne of steel)

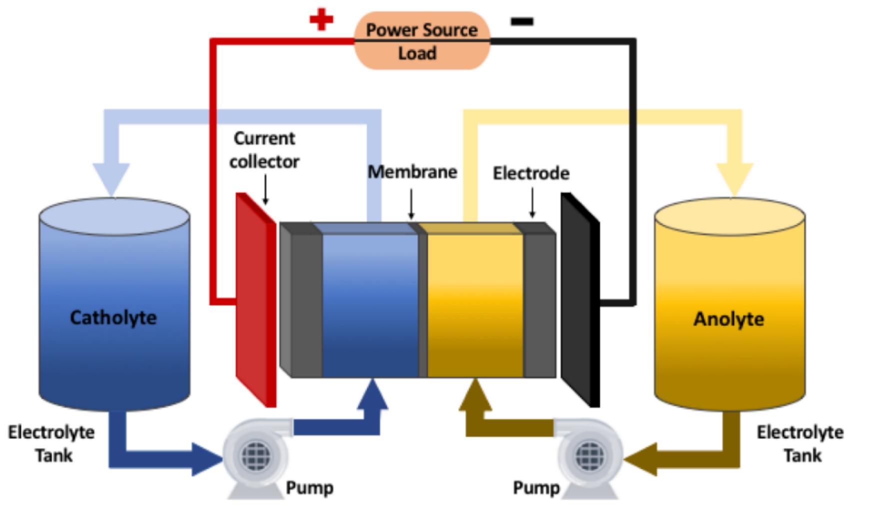


SOURCE: INCRED RESEARCH, COMPANY REPORTS

Vanadium redox flow (VRF) battery

There is potential for the battery market to become a sizable consumer of vanadium going ahead. Vanadium is used in vanadium redox flow batteries (VRFBs), in which vanadium electrolyte is used to store energy and enable a wider use of renewable power generation such as wind and solar. VRFBs were first successfully tested in the 1980s but have only seen commercial deployment since 2010. Since then, there have been several installations globally, of varying sizes, resulting in irregular bouts of vanadium consumption. **VRFBs have large and scalable capacity, can withstand being discharged for long periods, are safe and have a long cycle life. Vanadium flow batteries also have a separate electrolyte tank and a current collector tank. Thus, to increase capacity, one has to add more electrolyte, and to increase power one must change the current collector, removing the need for changing the whole system as in the case of lithium-ion batteries.** Upfront high capex compared to lithium-ion batteries acts as a detriment. Major VRFB installations now operational include the Dalian-UET/Rongke Power VRFB system, and a 200MW energy storage project in Liaoning, China. The rated storage capacity of the project is 800MWh and the battery was connected to the Dalian grid in May 2022. Another sizable installation is Sumitomo Electric's 15MW/60MWh system in Japan commissioned in 2015. Major installations planned or under development include a 100MW/500MWh project by VRB Energy in Hubei, China, a 50MW/200MWh project by KORID Energy Company in New York, a 50MW/200MWh project by CellCube in Port Augusta, Australia and a 100MW/40MWh project by Shanghai Electric in Jiangsu, China.

Figure 12: Typical diagram showing the working of a vanadium redox flow battery

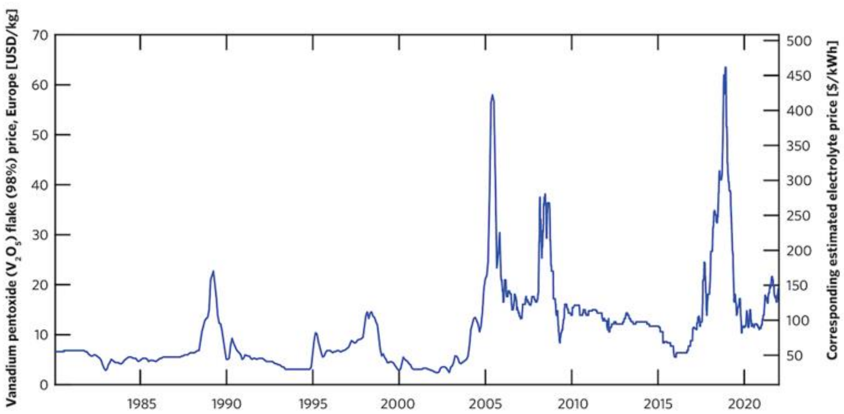


SOURCE: INCRED RESEARCH, COMPANY REPORTS

Cost dynamics for feasibility of a VRF battery system

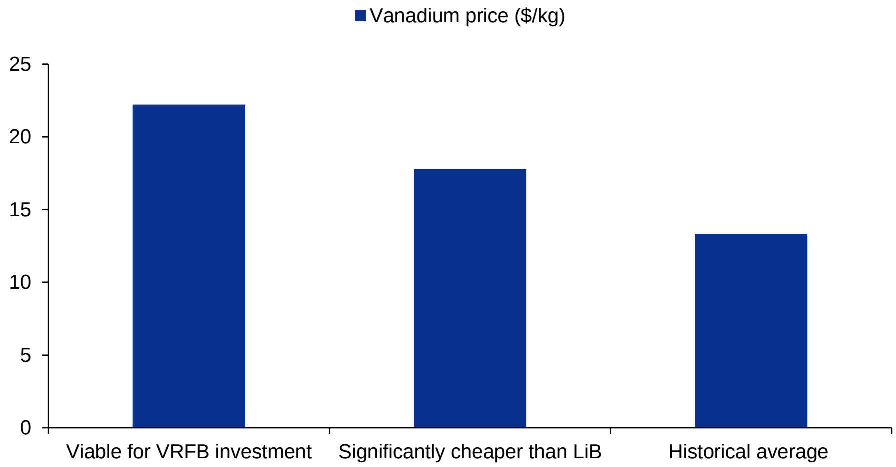
Vanadium is a major component of a VRF battery system. Hence, the price of vanadium is a major variable which decides the feasibility of a VRF battery. However, before going ahead, one needs to understand a term called LCOS. LCOS or Levelized Cost of Storage is basically discounting all the future cash inflow (from selling the energy stored in the battery) and future cash outflow (from initial capex and operating expenses). It becomes very important to compare LCOS for a lithium-ion battery and a VRF battery over the complete life of the battery to truly understand the cost effectiveness. Lithium-ion batteries have a typical life cycle of 10 years while vanadium-ion batteries can last for 20-25 years. Hence, even though the upfront cost of VRF batteries is higher, over the course of the entire lifetime, VRB batteries have a lower LCOS than lithium-ion batteries.

Figure 13: Vanadium pentoxide prices and corresponding vanadium electrolyte prices



SOURCE: INCRED RESEARCH, COMPANY REPORTS

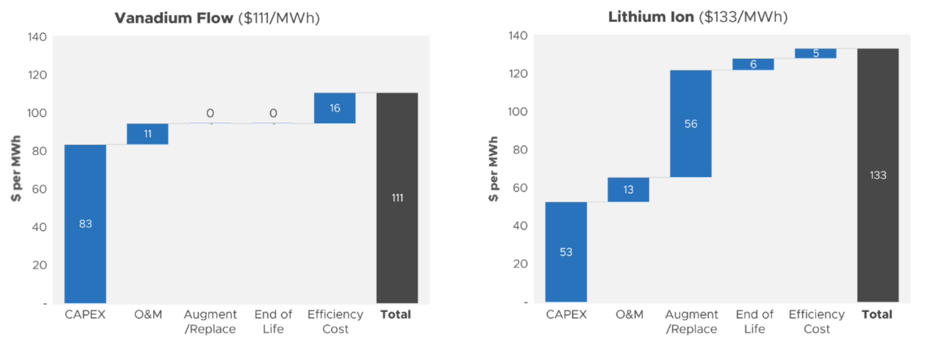
Figure 14: Vanadium's historical price average is way below the breakeven level for VRFB investment



SOURCE: INCRED RESEARCH, COMPANY REPORTS

There are enough references that suggest that VRFB projects are viable for investment when vanadium prices are below US$10/lb. At US$8/lb, the LCOS of a vanadium battery is still significantly cheaper than that of a lithium-ion battery due to its unlimited life cycle. Vanadium prices have been historically lower than US$6/lb, barring a few occasions of short spike caused by modified supply and demand. Fig. 14 shows the price trend of vanadium over the last 40 years. The trend shows that the average price of vanadium has been quite stable, with the median price below US$6/lb. So, the threat from unstable vanadium prices is relatively low for VRBs' development in the long run. **Furthermore, the best part of a VRB battery is that the lifetime of vanadium electrolyte is infinite and 100% of vanadium is reusable upon decommissioning of the system. This creates an unique opportunity for VRB developers to potentially remove vanadium from capital costs and negate the impact of vanadium metal.**

Figure 15: LCOS comparison between vanadium and lithium-ion



SOURCE: INCRED RESEARCH, COMPANY REPORTS

Due to lithium's more widespread commerciality, its capex cost per project is likely to be lower than other technologies that do not yet benefit from automotive-scale manufacturing. In contrast, as VFBs are now beginning to capture significant market share, their capex currently ranges from 1-2x that of a lithium-ion battery. In this scenario, the estimated capex works out to US$83/MWh for a VFB vs. US$53/MWh for the lithium LFP system. Operation and maintenance or O&M cost comes in slightly lower for a vanadium flow battery (US$11/MWh vs. US$13/MWh), mostly driven by the fact that there are fewer auxiliary systems such as fire detection and fire suppression to test and maintain over time. Augmentation (or in similar analyses, replacement) costs are significant for the lithium-ion system (US$56/MWh), which degrades at about 4.7% a year based primarily on cycle count. These costs are minimal for a vanadium flow battery, which exhibits zero degradation based on cycle count. End-of-life cash flows are divergent. The vanadium electrolyte retains a positive end-of-life value, which can be used to offset any recycling costs. In contrast, the lithium-ion battery, assumed to be LFP, which accounts for most sales today, has end-of-life costs which push LCOS up by US$6/MWh. Finally, there is some difference in efficiency costs as well. While both batteries charge from the same source, the lithium-ion battery has a higher Round Trip Efficiency on Day 1, it degrades with cycle life and is only fractionally recovered through augmentation. As a result, both batteries incur costs due to efficiency losses: the VFB costs US$16/MWh of throughput over the lifetime of the battery vs. US$5/MWh for a lithium-ion battery.

Scenario analysis for VRF batteries

Figure 16: VRF batteries' LCOS decrease significantly with higher cycles, as a large number of charge/discharge cycles lead to degradation of LiB viz-a-viz VRFB

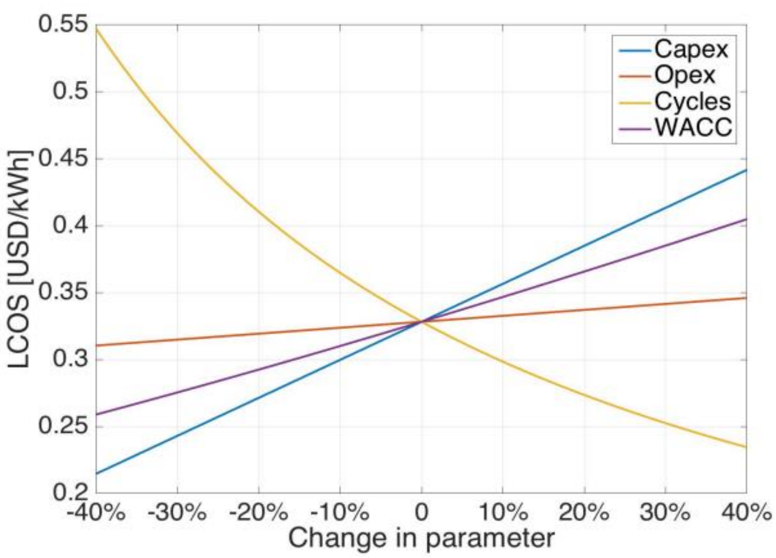


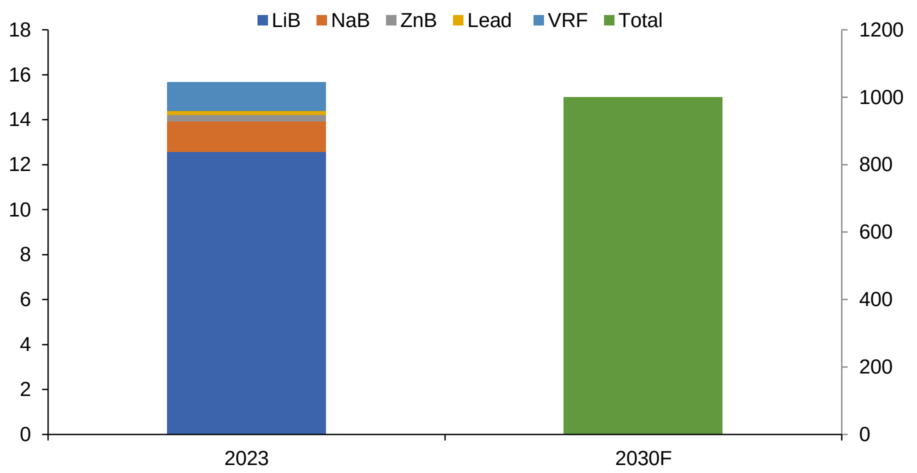
Figure 8. *Sensitivity analysis on LCOS for VFB ITM.*

SOURCE: INCRED RESEARCH, COMPANY REPORTS

Battery energy storage system to reach 1,000 GWh by 2030F

If we look at the current scenario regarding battery energy storage systems (BESS), most of it is dominated by LiB systems. However, this is expected to change in the coming years.

Figure 17: Total battery energy storage is expected to reach 1,000 GWh by 2030F

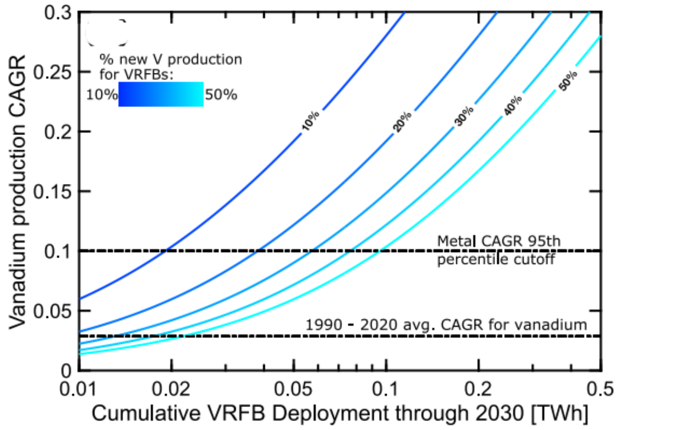


SOURCE: INCRED RESEARCH, COMPANY REPORTS

Mathematical model for vanadium demand forecast

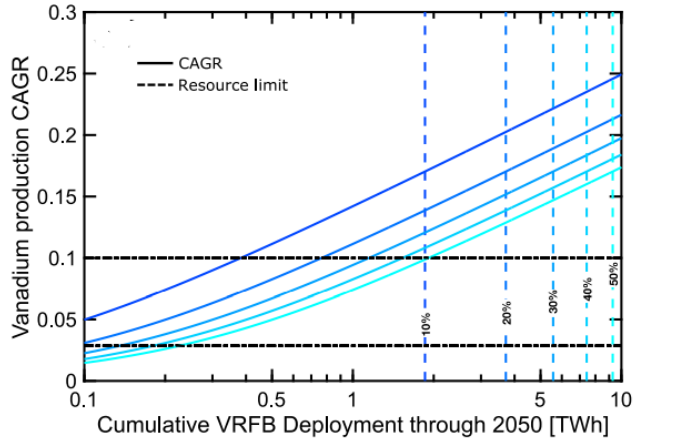
Historical ranges for growth rates of vanadium and other metals provide insight into the growth potential of vanadium production. The blue contours in the graph below represent the fraction of new production going towards VRFBs, the relevant magnitude of which depends on the competition between vanadium for steel and vanadium for VRFBs, although other use-cases may appear in the future. At present, about 90% of vanadium production goes for steel manufacturing and this demand is likely to grow going ahead, given the continued global economic development as well as a shift towards higher-strength steel in construction to reduce total material requirements. While there are opportunities to substitute vanadium with other alloying elements (e.g., manganese, molybdenum, niobium/columbium, titanium, and tungsten) – indeed, some steel mills in China have switched from ferrovanadium to ferroniobium due to high vanadium prices – it does not seem that such substitutions will allow significant vanadium supply to be re-routed away from steel demand soon. Thus, a conservative (business-as-usual) estimate would assume that steel will continue to drive the demand for vanadium at historic rates and only about 10% of new vanadium production will be available for VRFBs. However, with growing energy and sustainability concerns, a larger percentage of vanadium production (say, as much as 50%) may be diverted to VRFBs (likely influenced by national policy incentives), particularly if it is possible to more rapidly scale supply. **Hence, there can be various CAGR scenarios for vanadium growth, depending on how much vanadium is routed from steel towards production of VRF batteries.** It must be noted though, that in a study conducted on CAGR in the production of 32 metals, only the top 5th percentile of the metals sustained an average CAGR of more than 10% over an 18-year period, with none exceeding 15%. Comparing vanadium production from 2020 to that of 1990, we compute an average CAGR across this 30-year period of 3.55%. The year-to-year growth rate is generally highly variable, and vanadium is no exception: some years have seen greater than 30% or 40% growth, though the compounded annual growth rate over a longer time horizon averages much lower.

Figure 18: Vanadium CAGR scenarios to meet VRFB demand till 2030F



SOURCE: INCRED RESEARCH, COMPANY REPORTS

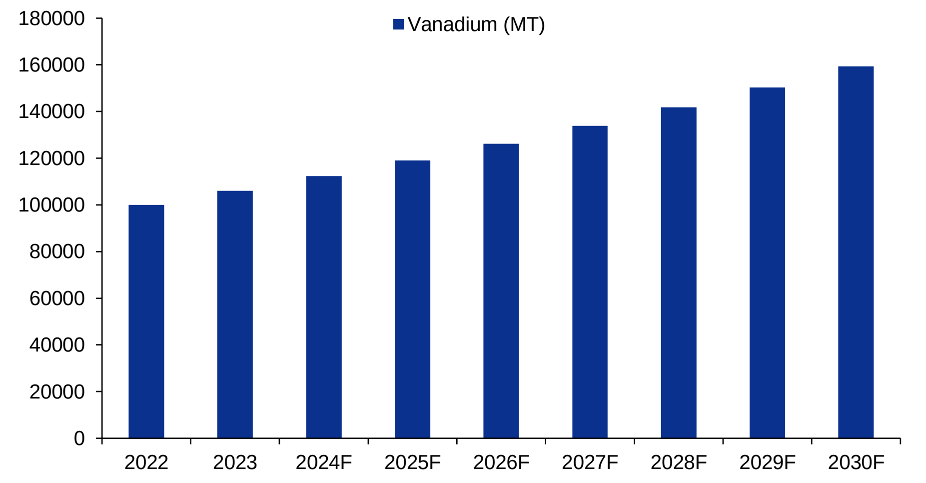
Figure 19: Vanadium CAGR scenarios to meet VRFB demand till 2050F



SOURCE: INCRED RESEARCH, COMPANY REPORTS

Historically, vanadium has only shown a CAGR of close to 3.55% and hence, going ahead if the same CAGR is sustained, then vanadium will only be able to fulfill 20GWh demand from VRF batteries by 2030F. If there is more demand for vanadium batteries, it will lead to a supply-demand mismatch. However, with this analysis we can safely conclude that for achieving 10GWh (0.01 tWh) VRF battery storage by 2030F, vanadium needs to have a 5% production CAGR over the decade.

Figure 20: Vanadium requirement, provided that 10GWh VRFB is set up in 2030F (mt)



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