GOVERNMENT OF BRAZIL MINING SECTOR TECHNICAL SUPPORT AND COOPERATION

Vanadium – Market Analysis and Competitiveness Report

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Acronyms

BES	Battery Energy Storage
BPA	Blanket Purchase Agreement
CAGR	Compound Annual Growth Rate
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CIM	The Canadian Institute of Mining, Metallurgy and Petroleum
CPRM	Geological Survey of Brazil
DOS	Department of State
EMGP	Energy and Mineral Governance Program
ENR	Bureau of Energy Resources
ESG	Environment, Social, and Governance
EV	Electric Vehicles
EVT	Vanady Tula
HSLA	High-Strength Low-Alloy
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
JORC	The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves
LCE	Largo Clean Energy
MME	Ministry of Mines and Energy
Mt.	Megaton
NPV	Net Present Value
PNM	National Plan for the Brazilian Mineral Sector
PV	Photovoltaic
REE	Rare Earth Elements
SSV	Sandstone-hosted Vanadium
USGS	United States Geological Survey
V_2O_3	Vanadium Oxide
V_2O_5	Vanadium Pentoxide
VRFB	Vanadium Redox Flow Battery
VTM	Vanadiferous Titanomagnetite

EXECUTIVE SUMMARY

Deloitte is implementing the *Government of Brazil Mining Sector Technical Support and Cooperation* Task Order (the Project) under Deloitte's Blanket Purchase Agreement (BPA) with the U.S. Department of State (DOS) in support of the Bureau of Energy Resources' (ENR) Energy and Minerals Governance Program (EMGP). The Deloitte team is providing technical assistance to support the Government of Brazil's Ministry of Mines and Energy (MME) and the Geological Survey of Brazil (CPRM) as they seek to improve their ability to:

- Develop safe, sustainable, and effective mine closure procedures and use of tailings, including methods of tailings sampling and characterization, based on international leading practices, to protect and improve the legacy of ongoing and future projects, thereby realizing sustainable benefits from the extractives industry;
- Manage a growing mineral sector and compete effectively in the global market, given a growing market and accelerated demand for critical minerals that are essential to the development of innovative technologies to advance the global clean energy transition (electric vehicles, batteries, and battery storage systems, etc.); and
- Streamline the structure of Brazil's nickel-cobalt data inventory, so Brazil can improve its understanding and increase development of critical minerals.

Under *Task 2A: Economic Viability and Global Market Competitiveness of Specific Minerals*, the Deloitte team will develop a series of reports focused on nine minerals including graphite, lithium, nickel, cobalt, rare earth elements (REEs), titanium, vanadium, tantalum, and copper. The purpose of these reports is to provide recommendations to the Government of Brazil on where and how Brazil could compete most effectively, and to inform its long-term strategic planning for mineral commercialization based on global market trends and challenges to mineral resource development that may inhibit Brazil's overall market competitiveness. The Deloitte team's recommendations will also inform the National Plan for the Brazilian Mineral Sector (PNM 2050) and future policy actions for the Government of Brazil. This report is focused on vanadium.

Key Findings

- **Brazil does not have significant vanadium reserves and resources**. Brazil has a relatively low level of vanadium reserves and resources, accounting for 0.9 percent of identified global mineralization as reported by S&P Global Intelligence (Table 1). In 2020, Brazil had reserves of 0.12 Mt vanadium.[1] China holds 40 percent of global vanadium reserves, with Russia accounting for 22 percent, Australia 18 percent, and South Africa 15 percent.
- **Brazil is a relatively small but low-cost producer of vanadium.** Brazil is the fourth largest producer of vanadium in the world; however, its production accounts for only six percent of the global output. It currently only has one mine producing vanadium (Maracás Menchen operated by Largo Resources), and one vanadium project at an advanced stage of development (Pitombeiras operated by Jangada Mines). The largest producers of vanadium are China (60 percent), Russia (17 percent), and South Africa (7 percent). Brazil exports vanadium pentoxide (V_2O_5) in concentrate (6.6 kt vanadium), primarily to the Netherlands and South Korea, with smaller quantities sent to Canada, India, Japan, France, and the United States. Brazil's vanadium production is relatively low cost due to high grades and low levels of contaminants.

[1] U.S. Geological Survey

- **Producers are seeking to expand vanadium production in Brazil.** Largo Resources, the country's sole vanadium producer, producing 13.2 kt/y V_2O_5, is currently undertaking a project to additionally produce vanadium oxide (V_2O_3), and constructing a new ilmenite concentration plant. Largo is also considering the construction of a ferrovanadium plant. Jangada Mines, an exploration company, expects to bring the Pitombeiras project (an advanced stage project) online by 2024, producing 46.5 kt/y V_2O_5 as well as titanium dioxide.

Key Recommendations

The global vanadium market is relatively small and is expected to be in deficit from 2021 to 2023, followed by a surplus in 2024 to 2029, and again a deficit in 2030, according to Roskill. It is therefore unlikely that new vanadium production is likely to benefit from sustained appreciation of commodity prices. As such, the Government of Brazil might want to consider supporting the further development of its vanadium industry, and encourage downstream opportunities, by:

- **Streamlining access to, and circulation of, up-to-date domestic vanadium resource data to domestic and international exploration companies to encourage exploitation and to promote vanadium development in Brazil.** This may require gathering and distributing more extensive information for those regions considered to have significant vanadium potential, including Bahia and Ceará. Legacy CPRM geological data, reports, and studies should be broadly published online and in multiple languages. Brazil should also actively market these documents to expand their circulation, use, and impact.
- **Undertaking a comparative review of Brazil's exploration and mining policies/initiatives versus other vanadium-producing countries.** Such a review would take approximately 12 to 18 months and would analyze and prioritize how Brazil's government could encourage and accelerate vanadium exploration and mine development through potential legal, regulatory, and environmental, social, and governance (ESG) improvements. It should also include public-private partnerships and expertise from Brazilian universities in the area of mineral processing. Such improvements could include simpler licensing and permitting processes, lower royalties, preferential tax rates, and a coordinated approach to environmental policy. The ultimate objective of such policy improvements should be to encourage development and stability for investors seeking to develop Brazil's mineral sector generally, and vanadium in particular. Brazil's 2021 Pro-Strategic Minerals Policy[2], which focuses on simplifying the environmental licensing process by facilitating a dialogue between different national environmental agencies, is a right step in this direction.

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[2] Through the Pro-Strategic Minerals policy, the Government of Brazil has issued a list of specific critical minerals it aims to boost production of, and that are deemed of special interest to the country. Resolution No. 2 of June 18, 2021, defines the list of strategic minerals for the country. https://www.in.gov.br/web/dou/-/resolucao-n-2-de-18-de-junho-de-2021-327352416. Through the Pro-Strategic Minerals policy, the Government of Brazil is focusing on easing the environmental licensing process by facilitating, for example, the dialogue between the environmental agency responsible for conducting the environmental licensing process and authorities such as the managing bodies of Conservation Units, the National Indian Foundation (Funai), the National Institute for Colonization and Agrarian Reform (Incra) and the National Institute of Historic and Artistic Heritage (Iphan).

- **Developing downstream vanadium redox flow batteries (VRFBs) to capture more of the value chain.** Brazil could consider becoming a VRFB producer by leveraging the experience of Largo Resources, its main vanadium producer. Largo Resources manufactures VCHARGE, a VRFB system, in the United States. The Government of Brazil may wish to encourage Largo Resources to expand its battery manufacturing activities into Brazil by offering credit guarantees, higher capital allowances, and tax reductions. This would then allow Largo Resources to use the vanadium mined in Brazil to produce domestic VRFBs, or manufacture VRFBs for export, rather than exporting the run-of-mine commodity itself.

Summary: Global Vanadium Demand and Potential for Development in Brazil

- ***Green Uses of Vanadium***: *Vanadium is used in renewable energy technology, specifically in vanadium redox flow batteries.*
- ***Market Demand for Vanadium***: *Global vanadium markets should see a long-term supply-demand balance, albeit with short-term volatility. The steel industry will continue to be the main driver of global vanadium demand, although demand from energy storage is expected to provide an added source of demand for the commodity in coming years. The market is expected to remain in deficit from 2021 to 2023, followed by a surplus in 2024 to 2029, and then a deficit in 2030, according to Roskill. Increased market prices for vanadium should be expected, although this may be dependent on the rise in demand in battery storage technology.*
- ***Opportunities in Brazil***: *Vanadium is considered a strategic mineral under Brazil's Pro-Strategic Minerals Policy, which is designed to streamline environmental approvals and permitting procedures to accelerate production. Brazil does not have significant vanadium resources and reserves (0.9 percent of global reserves and resources). The country is the fourth largest producer of vanadium, but it only accounts for 6 percent of the global production. Brazil's vanadium production is relatively low cost due to the high grade of local vanadium deposits. Brazil has one mine producing vanadium (Maracás Menchen operated by Largo Resources), and one project at an advanced stage of development (Pitombeiras operated by Jangada Mines). Capacity is currently being expanded at Maracás Menchen and there are plans for a possible ferrovanadium plant, while the Pitombeiras project is expected to come onstream by 2024.*

1. INTRODUCTION

1.1. Purpose of this Report

This report analyzes global vanadium resources, supply and demand dynamics, technological and industrial drivers, current and future mineral producers and processors, and vanadium market economics. The report also examines Brazil's position within the current vanadium market, and its potential positioning in the future, thereby enabling MME and CPRM to make informed decisions about future policy actions that may be in the interests of Brazil's vanadium industry and resources.

1.2. Organization of this Report

This report is organized into eight main sections and two annexes:

- **Section 1: Introduction** – Presents the purpose of this report, provides a background on vanadium, and summarizes market trends and outlook for vanadium.
- **Section 2: Vanadium Physical Characteristics** – Provides information on vanadium uses, applications, and various vanadium types.
- **Section 3: Vanadium Resources** – Provides information on global vanadium resources and reserves, as well as more detailed data on the countries with the largest recognized reserves (Argentina, Bolivia, and Chile).
- **Section 4: Vanadium Supply** – Gives an overview of the global production of vanadium ores, recent supply trends, and forecasts for future supply.
- **Section 5: Vanadium Demand** – Explains global vanadium demand trends based on end-user markets and forecasts for future demand.
- **Section 6: Market Balance and Vanadium Prices** – Provides information on the expected market balance, pricing, and outlook for vanadium.
- **Section 7: Economic Competitiveness** – Summarizes production and cost information of existing mines and 12 mining projects to benchmark and assess the economic competitiveness of the sector and other mines and exploration projects in Brazil.
- **Section 8: Conclusions and Key Recommendations** – Summarizes the Deloitte team's analysis of the vanadium market, including project financing and potential global opportunities. This section also presents key recommendations for the Government of Brazil to inform future policy actions with respect to the vanadium industry.
- **Annex 1** – Provides a description of mining and beneficiation of VRFBs.
- **Annex 2** – Provides a list of current vanadium projects.

1.3. Background and Context

The steel industry dominates vanadium demand, accounting for 91 percent of total demand in 2020. Global vanadium consumption increased by 2.1 percent to 112.2 kt in 2020, mainly due to record steel production in China. Over the longer term, the shift from high-carbon fossil fuels to low-carbon energy systems – including the move toward wind, solar, hydrogen, and battery technologies – is expected to increase the use of vanadium for VRFB-related renewable energy storage applications. VRFBs are a type of rechargeable flow battery that uses a vanadium electrolyte and are expected to take a growing share of the renewable energy storage market due to their unique advantages for long-duration energy storage applications.

Annex 1 provides a detailed description of VRFBs.

Brazil has some of the largest and most diverse mineral deposits in the world. Most of its mining activities and revenues focus on several core commodities such as iron ore, gold, copper, and bauxite. While the production of these resources will remain core to Brazil's economic development, there is growing market demand and opportunities for vanadium and other Brazilian critical minerals.

Brazil currently produces six percent of the world's vanadium but has 0.9 percent of global reserves and resources as reported by S&P Global Intelligence. Brazil is currently a relatively small (albeit low cost) producer and exporter of vanadium. Largo Resources, the only producer of vanadium in the country, is currently expanding capacity by 12 percent to 13.2 kt/y V_2O_5. In addition, Jangada Mines, a UK-based company, is expected to bring its Pitombeiras project into production by 2024. These new projects and expansions notwithstanding, Brazil is likely to remain a relatively small global producer of vanadium for the foreseeable future.

1.4. Summary of Market Trends and Outlook for Vanadium

1.4.1. Vanadium Reserves and Resources

According to the U.S. Geological Survey (USGS), China holds 40 percent of global vanadium reserves[3], with Russia holding 22 percent, Australia 18 percent, and South Africa 15 percent. Vanadium is extracted from several different types of mineral deposits and from fossil fuels. The principal source of vanadium is magnetite (iron oxide) deposits (often in conjunction with titanium), which contain 0.2 to 1.0 percent V_2O_5. Vanadium is principally used to produce steel alloys. Vanadium adds strength, hardness, and high-temperature stability to steel and makes steel suitable for the construction, transportation, and aerospace industries.

1.4.2. Vanadium Supply and Demand

Vanadium production is concentrated in China (60 percent), Russia (17 percent), South Africa (seven percent), and Brazil (six percent). In 2020, approximately 72 percent of global vanadium was recovered through co-production (iron ore with vanadium) and 18 percent was recovered from primary production - via the mining of vanadium-rich iron ores. Some secondary production also occurs, from various minor sources and recycling.

[3] Vanadium reserves are defined as the amount of vanadium that could be economically extracted or produced at the time of determination, as defined by a high level of mineral exploration. Resources, on the other hand, are the amount of vanadium in or on the earth's crust that could *potentially* be economically extracted based on geological evidence and have a lower level of exploration.

Historically, the global vanadium supply has primarily relied on vanadium slag production from co-producing steel plants.[4] The market's dependency on vanadium slag as a source of vanadium has started to decrease due to limited spare capacity at vanadium-producing steel plants. As a result, supply growth has now become more dependent on primary sources of vanadium and significant primary resources are being developed in Australia and Kazakhstan.

According to Roskill, vanadium demand in the steel market will grow at a compound annual growth rate (CAGR) of about 2.7 percent to 2030 but will be constrained by vanadium-producing steel slag mills operating at close to full capacity. In recent years, the vanadium market has benefited from the increased use of vanadium in steel, primarily due to higher rebar standards being introduced in China and across Asia. Aside from steel, vanadium is used in non-metallurgical applications including catalysts, ceramics, electronics, and vanadium chemicals. Vanadium is also used for energy storage, via VRFBs; this suggests the potential for significant upside demand, although energy storage remains only a small part of the overall vanadium market.

1.4.3. Vanadium Market Outlook

Steel consumption largely drives the vanadium market. As a result, the outlook for vanadium demand over the longer term is positive based on the projected growth of steel demand, particularly in Asian markets. The demand for renewable energy storage is also expected to drive demand for vanadium going forward, with the VRFB market forecasted to grow at a CAGR of over 50 percent a year from 2020 to 2030. Although this growth forecast is significant, the scale of vanadium use in the steel industry is such that VRFBs will still only account for about 10 percent of total demand by 2030.

Demand growth is largely expected to match supply from new vanadium mining projects. Nevertheless, the market balance and price path are likely to be uneven because the construction of new mines and downstream processing plants tend to result in changes in capacity that are difficult to predict. In addition, as prices rise, alternate steel alloys that are less expensive could be substituted for vanadium steel, providing some elasticity to demand.

The vanadium market moved into a short-term surplus in 2020, due to the reduction in steel demand that was associated with the COVID-19 pandemic, but it is expected to be in a structural net deficit over the next few years, with modest price increases at levels above the long-term average. China still has significant vanadium reserves and resources; data on Chinese vanadium production remains opaque, and therefore represents a price risk to any future market outlook. In addition, VRFBs remain only one type of a diverse and emerging group of storage technologies that will be developed and implemented over the coming years; as such, VRFB demand growth − while prospective − is not assured.

1.4.4. Economic Competitiveness

The Deloitte team analyzed data from existing vanadium mines and from 12 companies which have produced recent feasibility, pre-feasibility, and scoping studies as part of potential mine development initiatives. Based on this data, the Deloitte team found that the operating cost curve for existing mines is relatively flat – 88 percent of production operates at or below $8.00/lb for V_2O_5. The Deloitte team also found that, with new capacity having an average operating cost of about $4.00/lb, most of the analyzed projects appear viable from an operating perspective. Furthermore, many of the projects have an internal rate of return (IRR) of above 20 percent, which suggests strong potential average returns (see Figure 15).

[4] Vanadium slag is produced as a run-off when smelting pig-iron.

2. VANADIUM PHYSICAL CHARACTERISTICS

Vanadium is a medium hard, silvery gray, ductile transition metal. Vanadium metal in native form is rare, as its variable valency results in it easily reacting with oxygen, nitrogen, and carbon at high temperatures to form complicated compounds. Indeed, Vanadium is found in various chemical forms across about 65 different minerals.[5]

2.1. Vanadium Production

According to the USGS, global vanadium resources are currently concentrated in China, Russia, South Africa, and Brazil, with 60 percent of production occurring in China, and 17 percent in Russia. In terms of economic concentrations, vanadium is found mainly in magnetite (iron oxide) deposits, often in conjunction with titanium. It is also found in aluminum ore, within highly concentrated phosphorous-containing minerals, and in sandstones with high uranium content. Vanadium can also be recovered from carbon-rich deposits such as coal, oil shale, crude oil, and tar sands, as well as from oil-field sludge, fly ash, and other waste products.

Figure 1: Ferrovanadium

Source: Largo Resources.

Vanadium is used mostly to produce steel alloys. Vanadium adds strength, hardness, and high-temperature stability to steel and makes it suitable for applications in tool making as well as for the construction, transportation, and aerospace industries. Secondary uses for vanadium include applications in ceramics, glasses, and pigments, as well as catalysts for the chemical industry. Vanadium is also used in VRFBs for utility-scale electricity storage. Apart from continued growth within the steel market (which is growing at approximately 3 to 4 percent a year, with a particular focus in Asia), there is also potential for strong vanadium demand growth through the increasing use of VRFBs to store and dispatch power from variable renewable energy sources, such as solar and wind.

[5] Vanadium in its natural form is vanadium pentoxide (V_2O_5). In its native form is vanadium (V).

Annex 1 provides more information on VRFBs.

In 2020, the mining of vanadium-rich iron ores provided approximately 90 percent of global vanadium supply: 72 percent through co-production and 18 percent from primary production. Other production methods accounted for the remaining 10 percent. Commercial vanadium products developed by processing vanadium ores are mainly ferrovanadium, which is an iron-vanadium alloy added to steel (see Figure 1). Manufacturers also produce V_2O_5 and V_2O_3, which are used for non-metallurgical applications such as catalysts, glass, ceramics, and electronics.

Due to its importance in steelmaking, aerospace alloys, and chemical catalyst processes, vanadium is widely recognized as a critical mineral, by Australia, the United States, the European Union, United Kingdom, and Japan.

3. VANADIUM RESOURCES

The section presents data on global vanadium resources and reserves in countries such as Brazil, Australia, China, Sweden, and Finland.

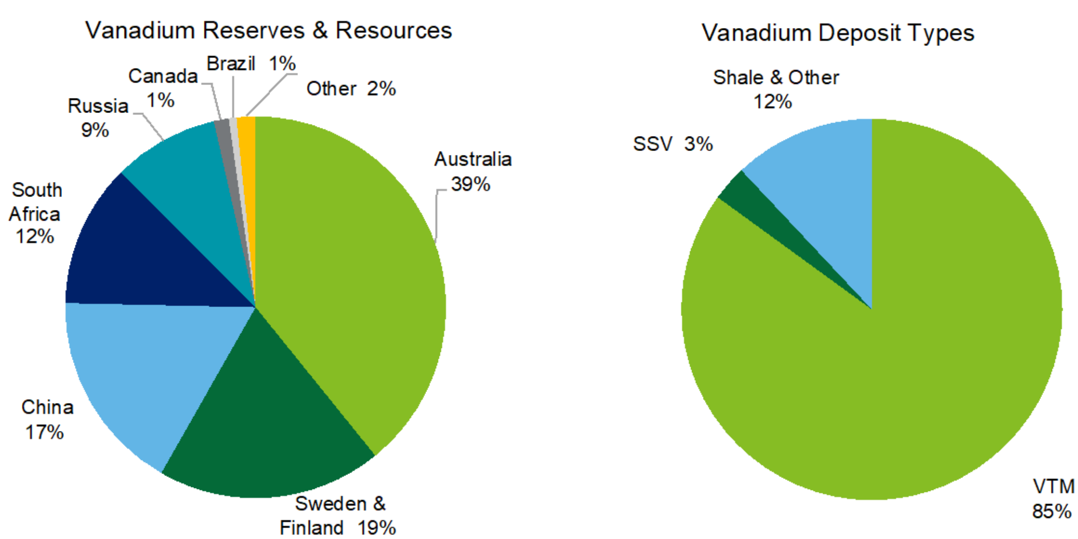
3.1. Vanadium Deposits

Vanadium is extracted from three main types of mineral deposits:

- **Vanadiferous titanomagnetite (VTM) deposits:** This is the principal source of vanadium (see Figure 2) and consists of magmatic accumulations of magnetite (iron oxide) and ilmenite (titanium mineral) and contains 0.2 to 1 percent V_2O_5. VTM deposits are abundant in countries that are leading vanadium producers (e.g., China, South Africa, and Russia).
- **Sandstone-hosted vanadium (SSV) deposits, with or without uranium**: These are the second most important economic source of vanadium; these deposits have average ore grades that range from 0.1 percent to greater than 1.0 percent V_2O_5. SSV deposits commonly have the highest grades of vanadium, but most are small deposits encompassing less than one million tonnes (Mt) of ore. Historically, the United States has been the main producer of vanadium from SSV deposits.
- **Vanadium-rich black shales:** Black shales regularly have grades exceeding 0.18 percent V_2O_5 and rising to as high as 1.7 percent. Although these resources occur worldwide and are reported to be large, they are currently of limited economic significance.

Vanadium is also present in fossil fuels, including crude oil and the crude residues (bitumen or asphalts) found in petroleum source rocks. Japan and the United States have recovered significant quantities of vanadium from petroleum residues. The combined reserves and resources are shown in Figure 2.

Figure 2: Global Reserves and Resources of Vanadium



Source: Deloitte estimates, based on data from USGS and S&P Global Intelligence.

3.2. Global Vanadium Resources

The USGS estimates that global vanadium reserves are 22.2 Mt, with additional vanadium resources exceeding 63.0 Mt. USGS notes that because vanadium is typically recovered as a by-product or co-product, demonstrated world resources of vanadium are not fully indicative of available supplies. China holds 40 percent of global vanadium reserves under this measure, with Russia holding 22 percent, Australia 18 percent, and South Africa 15 percent.

Table 1 shows the USGS reserves, along with other estimates for reserves and resources based on available data sourced from the S&P Global database and other sources. Most of the reserves and resources in the S&P Global figures are reported by individual mining companies and are governed by Australian JORC[6], Canadian CIM[7], and other similar national standards. The S&P Global numbers exclude some resources held by state and private enterprises and therefore should be viewed as commercially focused and indicative, rather than definitive.

The basis for USGS reserve calculations differs from the commercial data collated by S&P Global; it is derived from a variety of sources, including USGS evaluations, estimates compiled by individual countries, academic articles, company reports, presentations by company representatives, and trade journal articles. The USGS numbers should therefore be viewed as technically focused and inclusive. By comparing the S&P and USGS numbers, it is therefore possible to intuit a more comprehensive view of global vanadium supply versus relying on a single data-source. The data in Table 1 show significant vanadium resources located in Sweden and Finland; these resources, while large, are generally lower grade deposits than those currently in production.

Table 1: Global Vanadium Reserves and Resources Based on Reported Data 2020

Country	S&P	S&P Avg	S&P MII	S&P MII	USGS
	Reserves	Reserve	Resources	Resource	Reserves
	Mt contained V	Grade %V_2O_5	Mt cont. V	Grade % V_2O_5	Mt cont. V
China	-	-	0.588	0.93	9.500
Russia	-	-	-	-	5.000
South	0.953	0.86	5.781	0.48	3.000
Brazil	0.120	1.13	0.242	0.83	0.120†
United	-	-	0.359	0.55	0.045
Australia	1.889	0.54	19.881	0.32	4.000
Canada	-	-	0.708	0.40	-
Sweden &	-	-	10.589	0.23	-
Other	-	-	0.242	0.69	-
Kazakhstan	0.293	0.74	-	-	-
Total	**3.255**	**0.64**	**38.390**	**0.31**	**22.665**

Source: S&P Global data, USGS, and other company sources. Note: MII = Measured, Indicated & Inferred.
† This information is based on the old DNPM/ANM methodology.

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[6] The Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves ('the JORC Code') is a professional code of practice that sets minimum standards for Public Reporting of minerals Exploration Results, Mineral Resources and Ore Reserves.

[7] The Canadian Institute of Mining, Metallurgy and Petroleum (CIM) is a not-for-profit technical society of professionals in the Canadian minerals, metals, materials and energy industries. CIM's members are convened from industry, academia and government.

3.3. Brazilian Vanadium Resources

According to S&P Global data, Brazil has vanadium reserves of 0.12 Mt with an ore grade of 1.13 percent V_2O_5, and resources of 0.24 Mt with an average grade of 0.83 percent V_2O_5. These are potentially significant enough for Brazil to maintain and expand existing production, with grades higher than some competitor countries.

These reserves and resources numbers are from the existing operation of Maracás Menchen in Bahia operated by Largo Resources [TSE:LGO], and the Pitombeiras vanadium project in Ceará operated by Jangada Mines [LSE:JAN]. Maracás Menchen has 0.61 Mt of contained vanadium reserves and resources at a grade of 0.97 percent V_2O_5, while Pitombeiras has 0.04 Mt of vanadium resources at a grade of 0.45 percent V_2O_5.

3.4. Other Resource Areas

In addition to existing reserves in China, Russia, and South Africa, there are VTM deposits in Brazil, Chile, Canada, Australia, Madagascar, and Malaysia that could be potential sources of future vanadium production. Shale oil and tar sands containing vanadium are also present in North America and Australia.

Significant resource development is underway in Australia and Kazakhstan. Australia currently hosts the two largest reported undeveloped vanadium resources. The largest is Speewah Dome in Western Australia, owned by King River Resources [ASX:KRR], with a contained vanadium resource of 13.9 Mt at a grade of 0.30 percent V_2O_5. The second largest undeveloped resource is Julia Creek in Queensland, which is owned by QEM [ASX:QEM] and has a contained vanadium resource of 8.4 Mt at a grade of 0.31 percent V_2O_5. Exploration is continuing at both properties.

The most significant new primary project on the horizon is the Balasausqandiq vanadium deposit in Kyzylordinskaya oblast of southern Kazakhstan being developed by Ferro-Alloy Resources Group [LSE:FAR]. The project has a contained vanadium resource of 0.52 Mt at a grade of 0.64 percent V_2O_5.

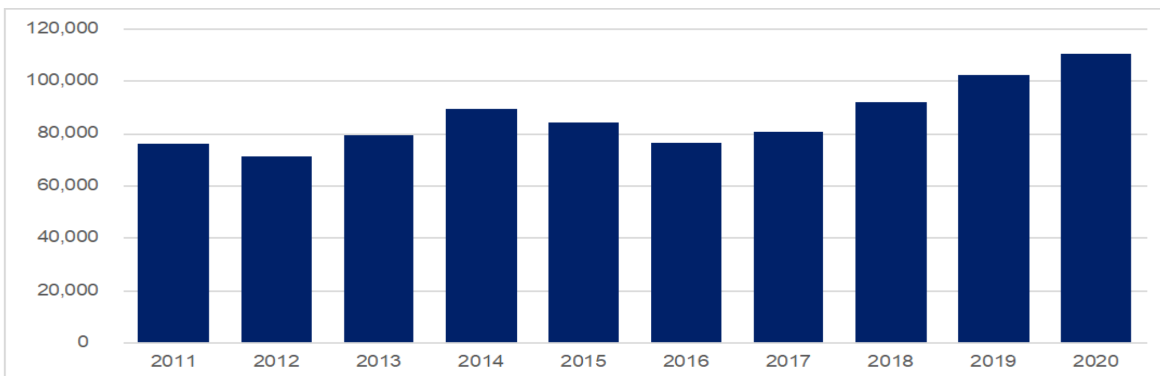
4. VANADIUM SUPPLY

This section provides more information on vanadium production, major producers, and the global supply outlook.

4.1. Global Production of Vanadium

Commercial estimates of global vanadium production show an increase to 116.1 kt in 2020 from 109.6 kt in 2019.[8] This increase was mainly due to higher slag production in China, driven by increased crude steel production. USGS, in contrast, estimated production in 2020 at 86.0 kt. **Error! Reference source not found.** illustrates how global vanadium production has grown over the past decade.

Figure 3: Global Vanadium Production (t) 2011-2020



Source: Vanitec.

The disparity between commercial and USGS numbers is not unusual: Vanadium is not a straightforward market to analyze. Supply mainly comes from three different sources:

- Co-production from iron ores containing vanadium (iron ores are smelted and a vanadium slag is produced);
- Primary production from vanadium-rich ore; and
- Secondary production from various minor sources and recycling.

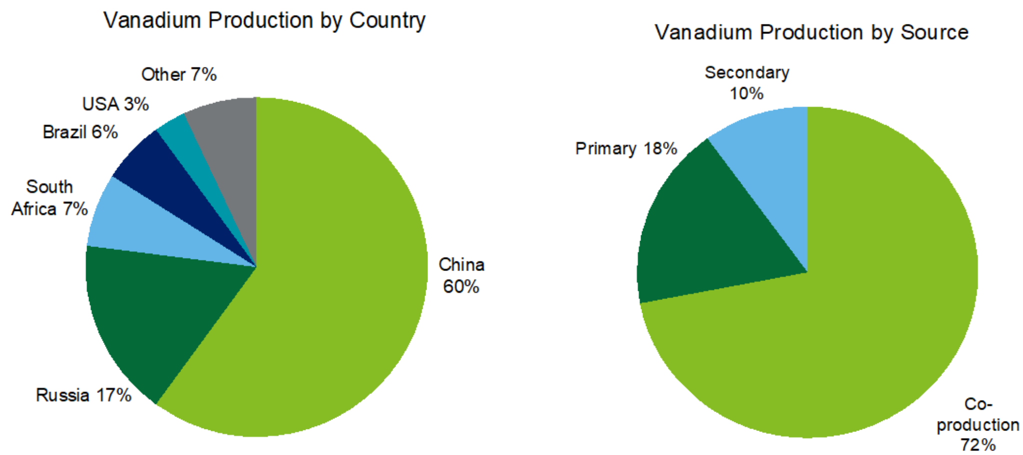
In 2020, approximately 72 percent of global vanadium was recovered through co-production and 18 percent was recovered from primary production (see

[8] Roskill, Bushveld Minerals.

Figure 4), both from the mining of vanadium-rich iron ores (magnetite and titaniferous magnetite). A further 10 percent of global vanadium was derived from secondary production. Production sources vary according to geographic origin, with some countries deriving vanadium from co-production and others from primary or secondary production.

China is currently the world's largest vanadium producer, accounting for 60 percent of global vanadium supply in 2020, and most of its vanadium is derived from co-production capacity. Russia is the second-largest producer (accounting for 17 percent of supply), and it also derives vanadium through co-production. South Africa is the third-largest vanadium producer (accounting for 7 percent of supply), but its output is derived from primary production. Brazil is also a primary producer, via vanadium output from the Maracás Menchen mine. Brazil's vanadium production accounted for about six percent of global supply in 2020.

Figure 4: Vanadium Production 2020



Source: Roskill, Bushveld Minerals.

The remaining vanadium-producing countries mainly use secondary production. For example, the United States produced about 3 percent of vanadium supply as a by-product of mining uriniferous sandstones from secondary sources in 2020, although this production has now ceased. Secondary production also takes place in Canada, Germany, and Japan.

4.1.1. Current Co-production of Vanadium

The main source of vanadium is derived from iron ore processed for steel production. To promote metallurgical consistency and quality, the vanadium contained in iron ore / crude steel must be extracted at an early stage, regardless of whether the finished product is anticipated to contain vanadium. Vanadium slags are produced as part of this extraction process.

Chinese vanadium slag producers are responsible for the largest quantity of vanadium derived from co-production. Chinese production of vanadium rose in 2020 due to increased slag production, which was driven by higher crude steel production and supported by the Government of China's stimulus measures for infrastructure spending. This increased slag production occurred despite steps by the Chinese government to rationalize its steel industry and cut pollution - criteria that may create supply constraints in the future.

In China and Russia, pig iron is produced via blast furnaces, but other countries employ different methods. In South Africa, for instance, iron is produced through a process that involves the pre-reduction of magnetite with powdered coal in a rotary kiln, followed by reduction in a submerged arc electric furnace. In New Zealand, vanadium-bearing co-product slag is generated during steel production from iron sands in a process like the one used in South Africa. The slag from South Africa contains up to 25 percent V_2O_5, whereas the slag from China and Russia contains between 14 percent and 22 percent. The V_2O_5 is then extracted from the slag by a roast-leach process.

4.1.2. Current Primary Production

Primary production accounted for about 18 percent of global vanadium supply in 2020. Vanadium derived from primary production rose year-on-year in terms of tonnage, even though its market share percentage decreased relative to 2019. Primary production has been growing in recent years and increased from around 13 kt in 2017 to about 20 kt in 2020. While the growth in primary production is modest relative to the overall volume of vanadium on the market, it has allowed a certain amount of decoupling of the vanadium price from the steel market to occur, as primary production is independent of the steel-making process.

4.1.3. Current Secondary Production

Secondary production accounted for approximately 10 percent of global vanadium supply in 2020. This type of production recovers vanadium from fly ash, petroleum residues, alumina slag, and from the recycling of spent oil refining catalysts.

4.1.4. Commercial Products

Figure 4 shows that two primary commercial products are developed by processing vanadium ores: ferrovanadium (an iron-vanadium alloy) and V_2O_5. Most vanadium is added to steel as ferrovanadium. Ferrovanadium is available in compositions containing 45-50 percent vanadium and 80 percent vanadium. The 45-50 percent grade is produced from slag and other vanadium-bearing residues, while the 80 percent grade is produced by the reduction of V_2O_5.

4.2. Vanadium Producing Companies

China is the largest global supplier of vanadium and has several significant producers. The largest is **Ansteel Group**, which owns Pangang Group and has capacity to produce 12,300 t/y of vanadium in the form of V_2O_5. Other producers include CITIC Jinzhou Metal, Chuanwei Group, and Jianlong (see

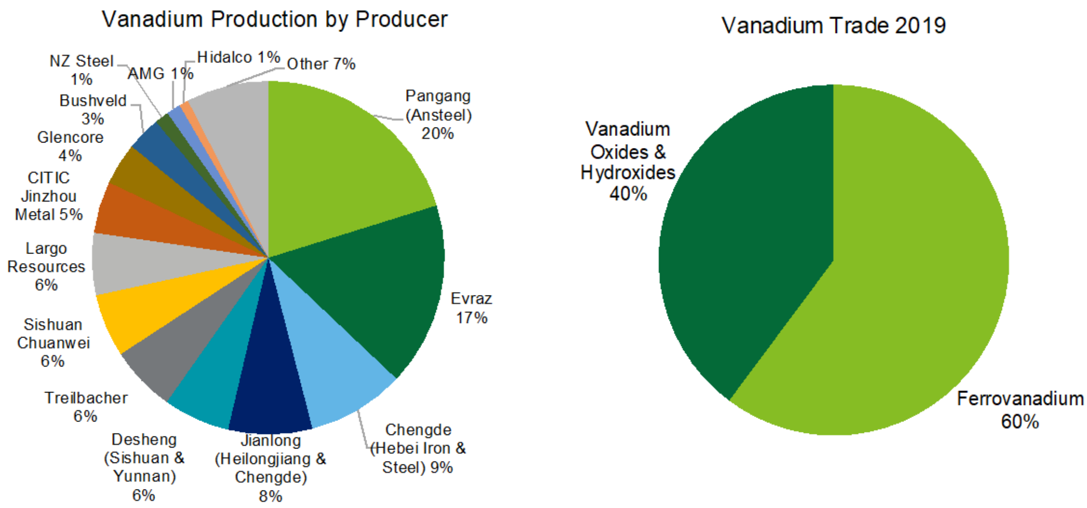
Figure 5).

EVRAZ is the largest vanadium producer outside of China. It is a vertically integrated steel, mining, and vanadium business with operations in Russia, Ukraine, the United States, Canada, Czech Republic, Italy, Kazakhstan, and South Africa. The company has a fully integrated production process that supplies the global steel industry with over 13,000 t/y of vanadium in different forms, such as ferrovanadium, pentoxide or polyvanadate.

EVRAZ operates the Kachkanar Mountain mine, the only source of vanadium-bearing iron ore in Russia. The ore is processed to vanadium slag at EVRAZ's Nizhny Tagil steel plant (NTMK) and then the vanadium slag is processed further at Vanady Tula (EVT) to produce ferrovanadium and V_2O_5. The vanadium slag produced at NTMK is EVRAZ's primary source of vanadium slag. In August 2021, however, EVRAZ announced that it would invest $228 million in the construction of a new vanadium slag processing plant in Russia. The plant, to be located at the Uzlovaya Special Economic Zone in the Tula region, is scheduled to start production in 2025. EVRAZ also has operations at Nikom in the Czech Republic, where it focuses on conversion of V_2O_3 into ferrovanadium.

Bushveld Minerals and **Glencore** are two large vanadium producers with operations in South Africa. Bushveld Minerals was expected to produce about 3,500 t of vanadium in 2021 and is increasing capacity to 5,000-5,400 t by the end of 2022, while aiming to reach 8,400 t/y in the long term. Glencore operates the Rhovan-Bakwen opencast mine and smelter complex, located near Brits. In 2020, it produced 4,490 t of vanadium mainly in the form of ferrovanadium and V_2O_5.

Figure 5: Vanadium Producers 2020 and Vanadium Trade Data 2019



Source: Company data, Deloitte estimates, OEC Trade Data.

In Brazil, **Largo Resources** produced 6,606 t of vanadium at its Maracás Menchen mine in 2020, which represented a 12 percent increase over 2019. The vanadium is contained within a massive titaniferous magnetite deposit that has much higher grades than most other vanadium deposits in the world. The low level of contaminants in the deposit makes the extraction and processing of vanadium much easier.

Vanadium production commenced at the Maracás Menchen mine in August 2014. Since then, the company has continued to further ramp up its production and sales of V_2O_5 concentrate. Production increased in the first half of 2021 due to kiln upgrades and other improvements implemented in January of that year, which were anticipated to increase nameplate production capacity to 13,200 t/y of V_2O_5 (7,375 t of vanadium). Largo Resources is also proceeding with a project to produce V_2O_3 and construction of a new ilmenite concentration plant, as well as considering a ferrovanadium plant.

The V_2O_5 produced by Largo Resources is exported through Glencore, mainly to the Netherlands (where it is re-exported) and South Korea, with smaller quantities sent to Canada, India, Japan, France, and the United States. Brazil also imports some ferrovanadium, mostly from Austria, China, the Czech Republic, and Russia. In Austria, **Treibacher**, a large industrial company in the chemical and metallurgical sectors, is the most significant producer of ferrovanadium in Europe.

4.3. Vanadium Supply Outlook

Historically, vanadium supply has primarily come from vanadium slag production from co-producing steel plants; however, there is now limited spare capacity at vanadium-producing steel plants, and supply growth has slowed from this source. New supply growth is now tending to come from primary production and, to a lesser extent, secondary production. This has resulted in more vanadium price volatility; a trend that is expected to continue.

4.3.1. Outlook for Co-Production of Vanadium

Co-production of vanadium slag has increased slightly in recent years, but the rate of supply growth has been diminishing, particularly from China, because the steel plants producing vanadium slag are operating close to full capacity. This situation is expected to continue going forward with limited new co-production capacity being planned. Chinese steel production has continued to rise, but the new steel output is being produced from imported iron ore, most of which is non-vanadium bearing.

In China, capacity utilization from vanadium slag producers was estimated at 80 to 90 percent in 2020, with the top five producers operating close to full capacity. Russia was also operating close to full capacity, at approximately 90 percent,[9] notwithstanding the new EVRAZ vanadium slag processing plant scheduled to start production in 2025.

4.3.2. Outlook for Primary Vanadium Production

Primary vanadium producers in South Africa and Brazil are expected to continue to increase and diversify the supply away from its traditional dependence on co-production. Production will also increase from new primary production in Kazakhstan and Australia. In contrast, primary production in China (derived from stone coal production) is expected to be limited by environmental restrictions.

Despite the expected increase in primary vanadium production, many of the recently announced greenfield projects are of a multi-commodity nature. This means they have relatively low vanadium grades and require significant capital. This said, there are several key projects that are likely to achieve production:

- The most promising new primary project on the horizon is the Balasausqandiq vanadium deposit, which is located in Kyzylordinskaya oblast of southern Kazakhstan and being developed by Ferro-Alloy Resources Group [LSE:FAR]. The Balasausqandiq deposit is not a typical vanadiferous titanomagnetite deposit; it is a sedimentary deposit with high vanadium grades and negligible iron. As a result, the deposit is expected to result in low-cost production, with a forecast production cost of $1.54/lb V_2O_5.

  FAR plans to increase output from the Balasausqandiq deposit in stages to match market demand and avoid oversupplying the market. Stage 1 will have capacity of about 5,600 t/y of V_2O_5 (mostly in the form of ferrovanadium), while stage 2 will raise capacity to 22,400 t/y of V_2O_5. Nevertheless, the orebody could eventually support capacity of 55,000 t/y of V_2O_5 (about 30,700 t/y vanadium). FAR is already producing vanadium by processing purchased vanadium-containing secondary materials. A bankable feasibility study is expected before the end of 2022, and this project alone has the potential to absorb new demand for five to eight years if fully developed.

- Australia is also expected to become a primary producer over the next few years. TNG [ASX:TNG] is currently planning construction at the Mt Peake project in Northern Territory. Atlantic, part of the Salim Group of companies, is also considering restarting the Windimurra vanadium project in Western Australia. Windimurra is a fully approved vanadium operation that has invested more than $493.2 million (A$700 million) in plant and infrastructure. When in production, the mine is expected to produce approximately 7,600 t/y of high-purity V_2O_5 flake.

[9] Bushveld Minerals.

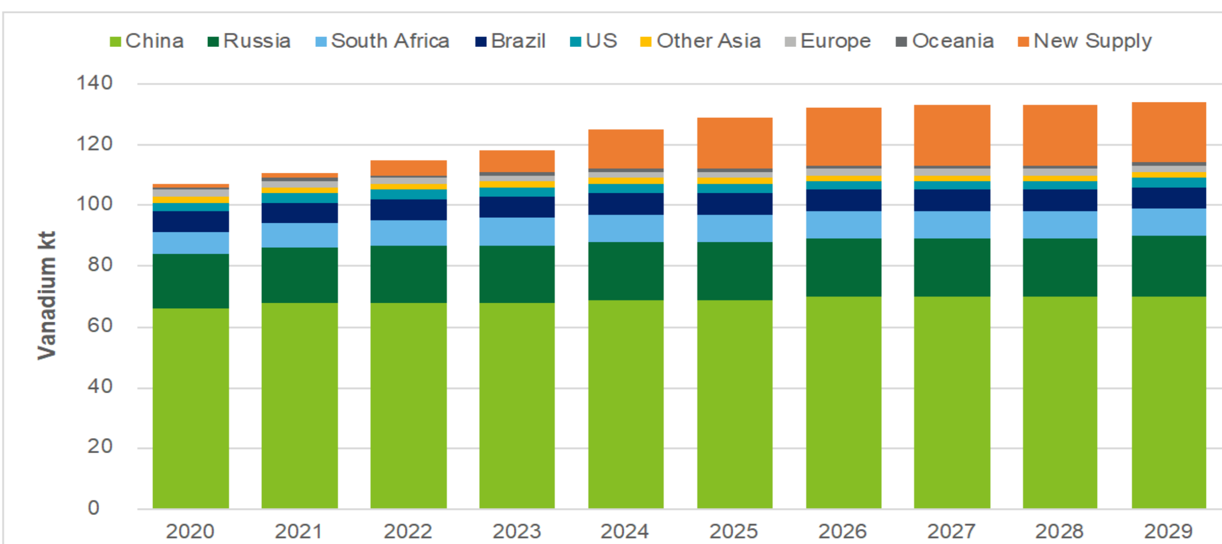
- Technology Metals Australia [ASX:TMT] has completed a feasibility study at Gabanintha in Western Australia. Three other feasibility studies are also underway: Audalia Resources [ASX:ACP] is conducting one at Medcalf in Western Australia; Australian Vanadium [ASX:AVL] is conducting one for its Australian Vanadium Project (also located in Western Australia); and Richmond Vanadium Technology [unlisted] is undertaking one for the Richmond project in Queensland.
- In Brazil, Jangada Mines [LSE:JAN] completed a feasibility study at the Pitombeiras vanadium project in Ceará in April 2022. The mining operation will focus on the extraction of a direct shipping ore comprised of iron ore with a high vanadium content. The company is also assessing the possible extraction of titanium dioxide. Annual production of 186 kt/y V_2O_5 concentrate is anticipated with a mine life of nine years.

4.3.3. Outlook for Secondary Vanadium Production

Vanadium production from secondary sources is forecast to continue rising in the medium term, even though it remains a higher-cost form of production than primary and co-production. However, secondary production is limited—not by processing capacity, but by the availability of the necessary feedstock and high production costs. The supply of secondary materials is derived from spent catalysts associated with processing crude oils and oil sands, as well as from manufacturing various acids, fly ash, residues from the combustion of oils and coals, and some residues from alumina production, particularly in India.

The market saw an increased supply of recycled catalyst material following regulations implemented by the International Maritime Organization in 2020 to limit sulfur content in marine fuels. To comply with the new regulations, refiners had to increase the use of catalytic cracking to convert (remove the sulfur) from refinery residues, the main raw material used to produce residual bunker fuels. These catalysts are recycled for secondary vanadium production.

Figure 6: Projected Vanadium Production by Country (kt)



Source: Roskill (2020), Australian Department of Industry, Science, Energy and Resources (2021).

Overall, Roskill forecasts that vanadium production will continue rising to around 140 kt/y by 2029 (

Figure 6), with most of the growth coming from new sources of supply.

5. VANADIUM DEMAND

The sections that follow provide more information on vanadium consumption, substitution risks, demand outlook, and associated trade data.

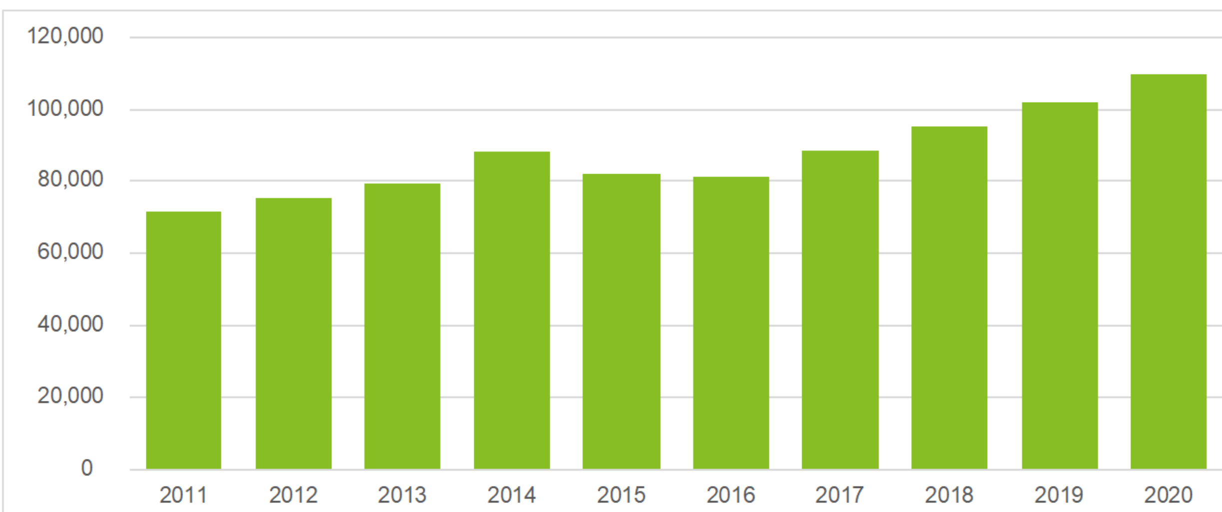
5.1. Global Consumption

Global vanadium consumption rose 2.1 percent to 112.2 kt in 2020 from 109.8 kt in 2019 (see Figure 7),[10] mainly due to record steel production in China that – in turn − was driven by increased government infrastructure spending. This more than offset weaker vanadium demand from the North American and European steel and aerospace industries, which declined in 2020 due to the COVID-19 pandemic and associated plant shutdowns.

Vanadium demand is dominated by the steel industry, which accounted for 91 percent of total demand in 2020 (see Figure 7). Steel production in China increased by seven percent year-on-year to a record 1,065 Mt in 2020, up from 996 Mt in 2019. Strong iron ore demand in China resulted in higher demand for vanadium, some of which came from domestic vanadium titaniferous magnetite ore, but the upswing also caused China to become a net vanadium importer for a period in 2020.

EVRAZ reported that global vanadium demand rose by 16 percent in the first half of 2021, with a strong recovery in global steel output. Demand in China alone increased by 20 percent, driven by higher rebar production and growing demand for vanadium-based energy storage.

Figure 7: Global Vanadium Consumption (t) 2011-2020



Source: Vanitec.

[10] Roskill, Bushveld Minerals.

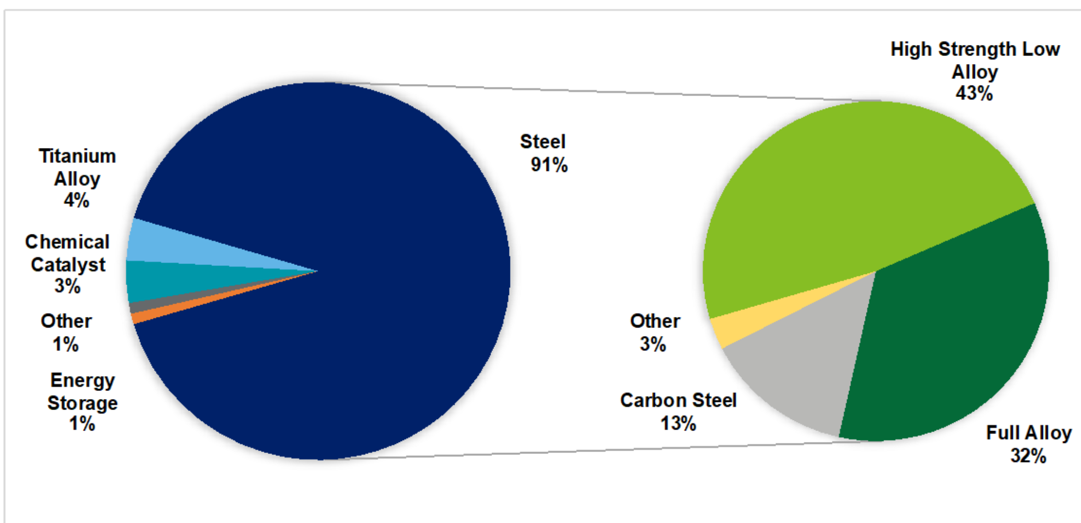
5.2. Vanadium Uses

The dominant use of vanadium is in steel to impart strength, toughness, and wear resistance. The formation of vanadium-rich carbides and nitrides strengthens steel; the addition of only a few kilograms of vanadium per tonne of steel increases its strength by as much as 25 percent. Apart from its strengthening characteristics, vanadium also inhibits corrosion and oxidation.

The construction sector is the largest consumer of steel products. Vanadium micro-alloyed high-strength rebar (reinforced steel rod) is a safe, reliable, and cost-effective solution for reinforced concrete construction, particularly in the world's earthquake-prone regions. Currently, some 85 percent of vanadium used in China is used in rebar.

In recent years, the vanadium market has benefited from its increased intensity of use in steel, particularly due to higher composition standards for rebar in Asia. Developed economies, such as Japan and those in Europe and North America, have a higher vanadium intensity than developing countries. In February 2018, China revised its steel rebar standards to limit the use of inferior strength steels in its construction industry. China surpassed the world average in its intensity of use in 2020, supported by its enhanced compliance on rebar standards.

Figure 8: Vanadium End-use



Source: Vanadium Resources, Ferro-Alloy Resources Group.

Figure 8 shows that high-strength low-alloy (HSLA) steels represent 43 percent of total steel produced using vanadium. HSLA steels containing vanadium are widely used for the construction of auto parts, buildings, bridges, cranes, pipelines, rail cars, ships, truck bodies, and armor plating for military vehicles. HSLA steels are also used in the oil and gas industry to meet demand for pipelines with higher strength and greater low-temperature toughness.

Titanium alloy accounts for roughly four percent of vanadium demand. When combined with titanium, vanadium produces a stronger and more stable alloy, and when combined with aluminum, it produces a material suitable for jet engines and high-speed airframes. Vanadium is also used in tool steels in various combinations with chromium, niobium, manganese, molybdenum, titanium, and tungsten.

Non-metallurgical applications of vanadium include catalysts, ceramics, electronics, and vanadium chemicals, which account for about four percent of vanadium demand. The most important industrial vanadium compound, V_2O_5, is used as a catalyst to produce sulfuric acid. Vanadium dioxide is used in the production of glass coatings that block infrared radiation.

Vanadium is also starting to be used in renewable energy technology, such as VRFBs, with energy storage accounting for about one percent of vanadium demand. Although it is at an early stage of development and has competing applications, the VRFB market is viewed as a strong potential growth market for vanadium.

VRFBs are discussed in more detail in Annex 1.

5.3. Substitution Risks

One risk to vanadium demand at higher price levels is substitution. Steels that contain various combinations of other alloying elements can be substituted for steels that contain vanadium. Certain metals, such as manganese, molybdenum, niobium, titanium, and tungsten, are interchangeable to some degree with vanadium as alloying elements in steel.

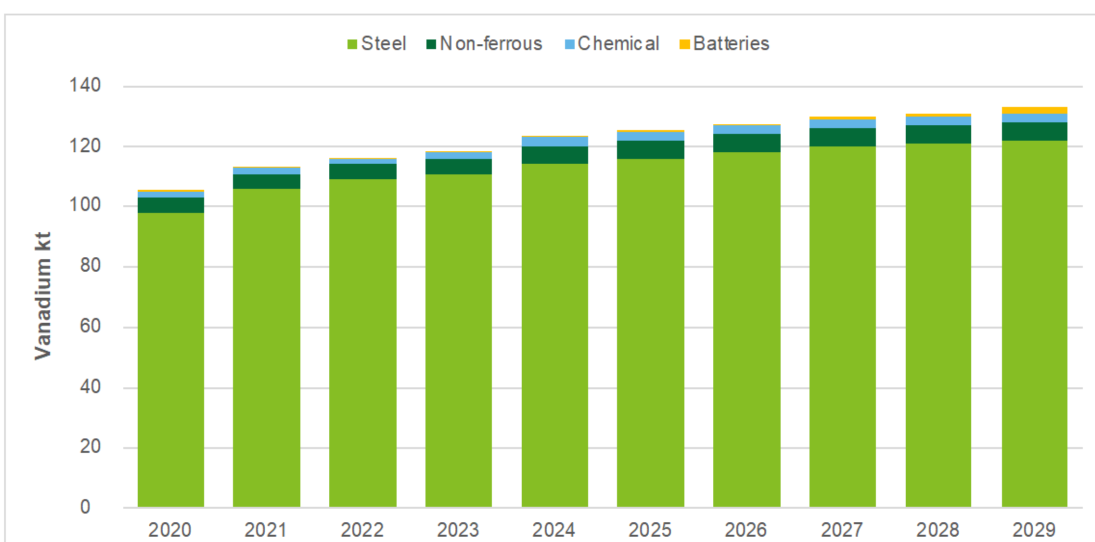
In practical terms, however, there is only a limited degree of substitution possible among these metals. Replacing vanadium with other mineral commodities requires significant technical adjustments to the steel production process to ensure that product specifications and quality are not compromised. As such, vanadium substitution is usually not considered a viable response to short-term changes in market conditions or price fluctuations, due to the considerable effort involved in implementing process changes.

Platinum and nickel can replace vanadium compounds as catalysts in some chemical processes. However, no acceptable substitutes exist for vanadium in aerospace titanium alloys because they have the best strength-to-weight ratio of any current engineered material.

5.4. Vanadium Demand Outlook

According to Roskill, vanadium demand in the steel industry will grow at a CAGR of about 2.7 percent through to 2030, with global vanadium demand from steel reaching approximately 136 kt by 2030. Figure 9 illustrates how forecasted demand for vanadium is anticipated to continue to be driven by the steel industry for the foreseeable future.

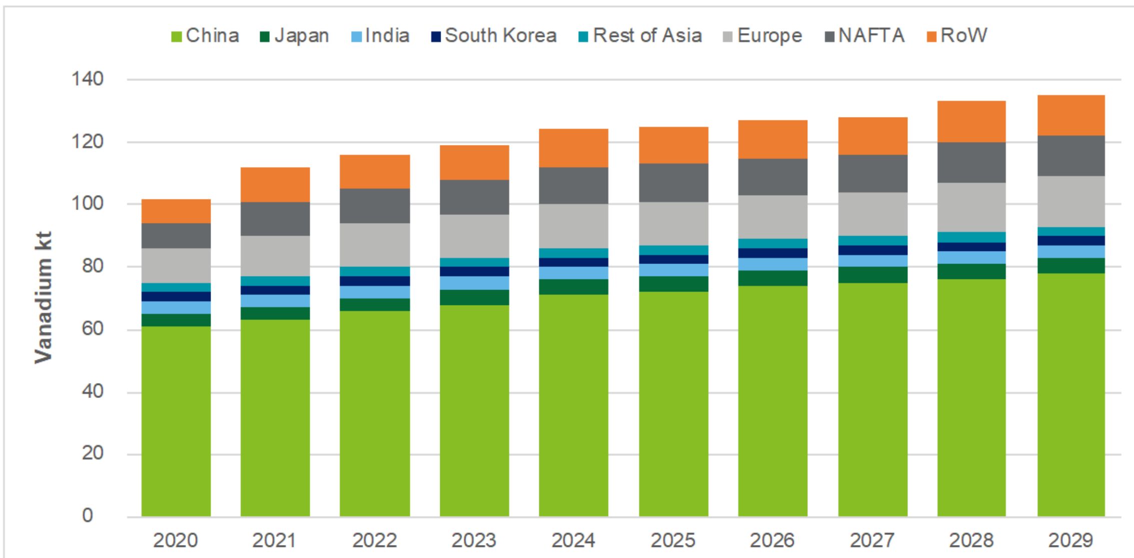
Figure 9: Projected Vanadium Consumption 2020-2029



Source: Roskill (2020), The Australian Government Department of Industry, Innovation, and Science.

While vanadium demand will be underwritten by its growing intensity of use in steel, the energy storage industry does offer demand upside, albeit from very low levels. According to Roskill, vanadium demand from VRFBs will grow at a CAGR of approximately 57 percent through to 2030, growing from 163 t in 2020 to 14,585 t in 2030, or some 10 percent of total forecast vanadium demand. Longer-term potential demand could be even greater. For example, the World Bank Group forecasts that by 2050, vanadium demand from energy storage alone could be twice as large as total global vanadium production in 2018.

Figure 10: Vanadium Consumption by Country 2020-2029



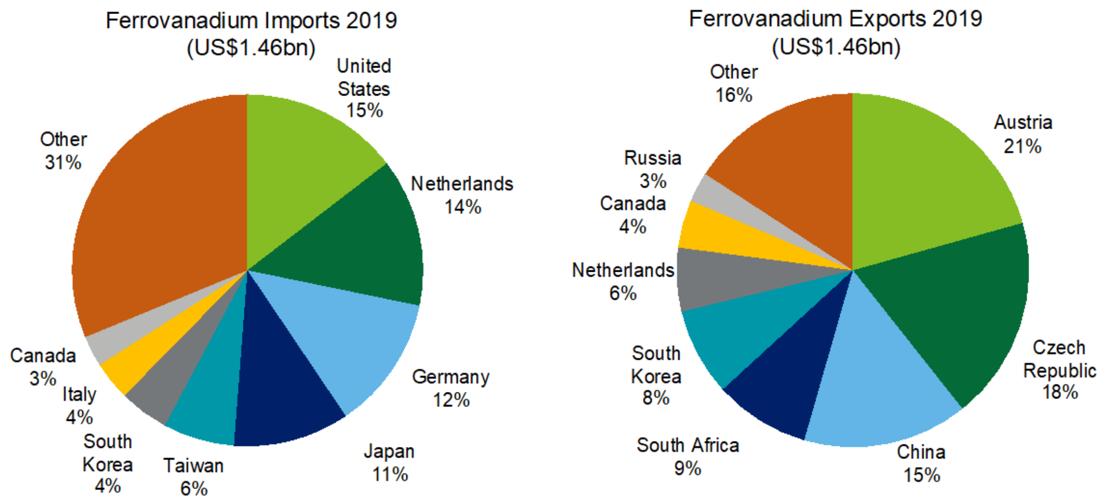
Source: Roskill (2020), The Australian Government Department of Industry, Innovation, and Science.

Figure 10 shows that China is anticipated to continue to dominate the vanadium market over the next decade. China will consume nearly 80 kt/y of vanadium, around 60 percent of global vanadium supply, by 2029. Consumption in other countries, including Japan and those in North American and Europe, will also increase.

5.5. Vanadium Trade Data

Trade in V_2O_3 and hydroxides totaled $965 million in 2019 and the trade in ferrovanadium totaled $1.46 billion (see Figure 11). Austria, Czech Republic, and China accounted for over 50 percent of exports. The major importers were the United States, Netherlands, Germany, and Japan, accounting for over 50 percent of imports.

Figure 11: Ferrovanadium Imports and Exports 2019



Source: OEC Trade Data.

6. MARKET BALANCE AND VANADIUM PRICES

This section analyzes the possible market balance for vanadium given the supply and demand assessments discussed in the two previous sections. It also provides a consensus price forecast.

6.1. Market balance

The vanadium market moved into a short-term surplus in the first half of 2020, as steel mill shutdowns took place due to the COVID-19 pandemic. However, supply and demand dynamics for vanadium switched to a structural net deficit after the rapid recovery of steel production in China in the second half of 2020, followed by the demand increase from other steel producers globally in 2021. Some of the key reasons for the current supply deficit are:

- Chinese and Russian slag producers are at high-capacity utilization;
- The steel industry in China has been increasingly relying on imported iron ore, which is often non-vanadium bearing, limiting any new domestic vanadium-bearing iron ore capacity growth; and
- Environmental restrictions in China on steelmakers, co-production, and stone-coal vanadium producers, as well as a ban on vanadium slag imports, are likely to restrict domestic vanadium output.

Vanadium demand is anticipated to decrease in the short to medium term. This is because Chinese authorities have implemented a series of measures to cool down the domestic property market and the resulting decline in steel production is likely to impact vanadium demand. Another factor that may negatively impact demand in the nearer term is concerns of weaker global demand for goods due to constrained supply chains (including automotive demand, which is also impacted by the tight semiconductors market). In the U.S., many steel mills conducted routine maintenance exercises in the second half of 2021, capping production. In the non-ferrous sector, demand from the aerospace industry remains subdued, although it is recovering from recent lows.

The longer-term outlook for vanadium demand is more positive, with various reports suggesting that consumption could increase by three to five percent annually until at least 2030.[11] Given that the market is largely driven by steel consumption (accounting for 90 percent of vanadium use), this forecast correlates with projected growth in the global steel markets of three to four percent a year between 2020 and 2030. However, increased intensity of use of vanadium in Asian steel markets, and strong growth from VRFBs, are expected to further boost vanadium demand.

There are several forecasts for growth of the VRFB market, but generally it is anticipated to grow at a CAGR of over 50 percent a year from 2020 to 2030. This is a significant rate of growth, but the early-stage nature of the VRFB market means that it will still only account for about 10 percent of vanadium demand by 2030 (see Annex 1).

Overall, demand growth is largely expected to match supply from new vanadium mining projects, which could begin in the short to medium term. The market balance and price path are likely to be uneven, as the construction of new mines and downstream processing plants tends to result in 'lumpy' changes in capacity. The market discipline (the pace at which a company operates the mine to slowly ramp up production to match demand) of new producers with large projects, such as the Balasausqandiq project owned by Ferro-Alloy Resources, will be important.

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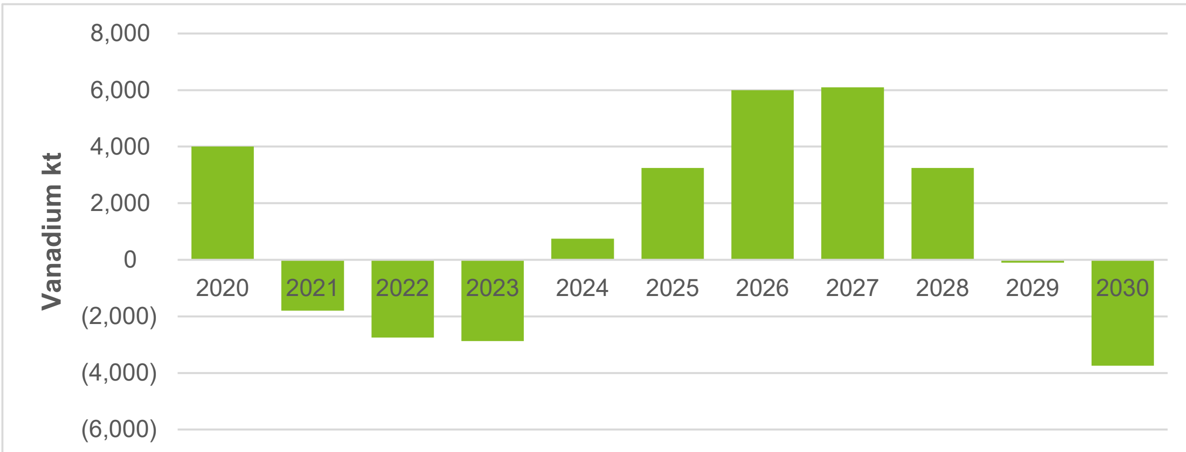
[11] Roskill, Bushveld Minerals.

Roskill expects the market to remain in deficit from 2021 to 2023, followed by a surplus from 2024, and only moving back to a deficit at the end of the decade (see Figure 12). Roskill assumes that all new projects announced will come into production.

Figure 12: Vanadium Market Balance 2020-2030



Source: Roskill Vanadium Outlook to 2030 (June 2021).

6.2. Vanadium Price

The 15-year average of the traded V_2O_5 price is about $8.00/lb. Vanadium prices are cyclical in nature; market imbalances have driven prices above $30.00/lb for V_2O_5 twice over the past 15 years, with the most recent spike beginning in 2018 and V_2O_5 prices rising to $28.00/lb in November 2018 (see

Figure 13) – the result of growth in Chinese steel production and regulatory requirements for increased vanadium content in Chinese rebar.

With global demand impacted by the COVID-19 pandemic and the market moving into surplus, V_2O_5 prices averaged just $5.90/lb in 2020. As global markets began to recover in the first half of 2021, the price started to rise. Global steel production increased 12.4 percent year-on-year during this period, and real vanadium demand was believed to have been stronger than apparent demand due to the simultaneous rebuilding of vanadium inventories This resulted in an extremely strong vanadium market in the beginning of 2021, with an 80 percent price increase to $9.60/lb, before declining slightly in the second half of the year. Vanadium is generally viewed as competitive at prices up to about $10.00/lb. Any major movement above this price limit results in substitute materials entering the steel market. A similar price level is also considered as the economic limit to VRFBs in the battery storage markets, although innovative finance techniques (such as separately leasing the vanadium content in a VRFB battery) are starting to provide lower-capital options to end users to mitigate the immediate impact of commodity prices. Largo Resources' clean energy division is piloting such a vanadium leasing structure on purchased VRFBs.[12] Subject to regulatory approval, the company is also seeking a separate listing in Canada to hold physical vanadium though a qualifying transaction with Column Capital.[13]

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12 https://www.largoinc.com/Our-business/clean-energy-storage/default.aspx

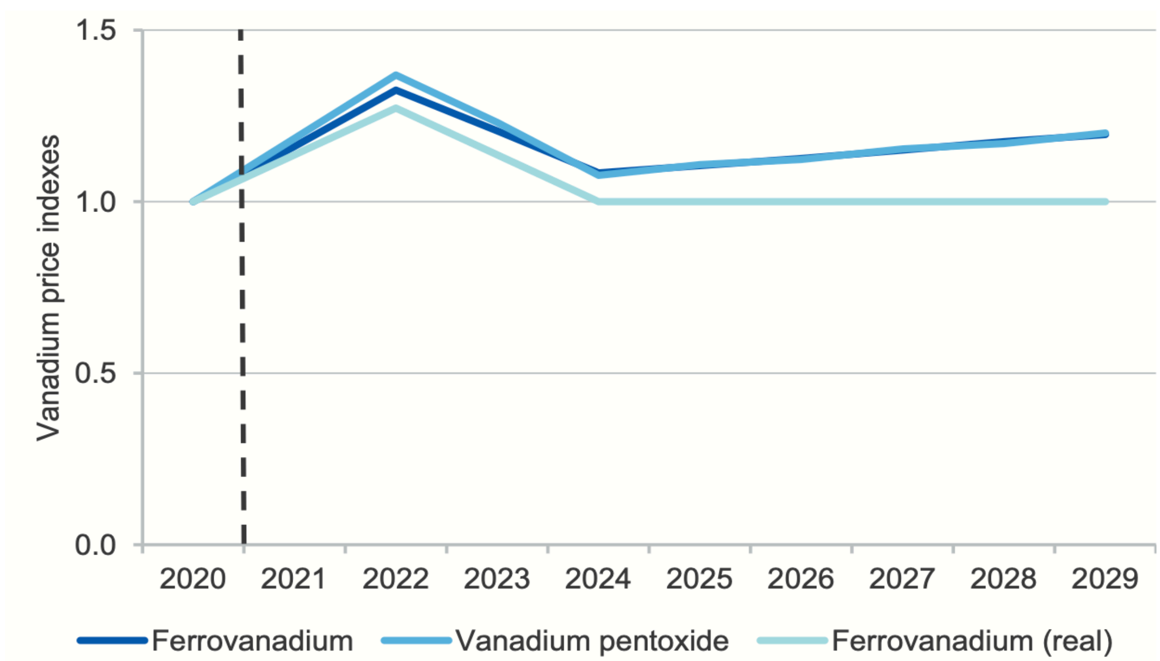
13 https://www.businesswire.com/news/home/20220413006095/en/Largo-Provides-Update-on-Proposed-Qualifying-Transaction-for-New-Physical-Vanadium-Holding-Company-Largo-Physical-Vanadium-Corp.

Figure 13: Vanadium Pentoxide Price ($/lb V_2O_5)

Source: London Metal Bulletin.

Overall, Roskill believes that vanadium prices will remain above the long-term forecast for the next two years (see Figure 14). Some downside risks have increased on the demand side, but tight supply should keep providing support to the market.

Figure 14: Vanadium Price forecast 2020-2029



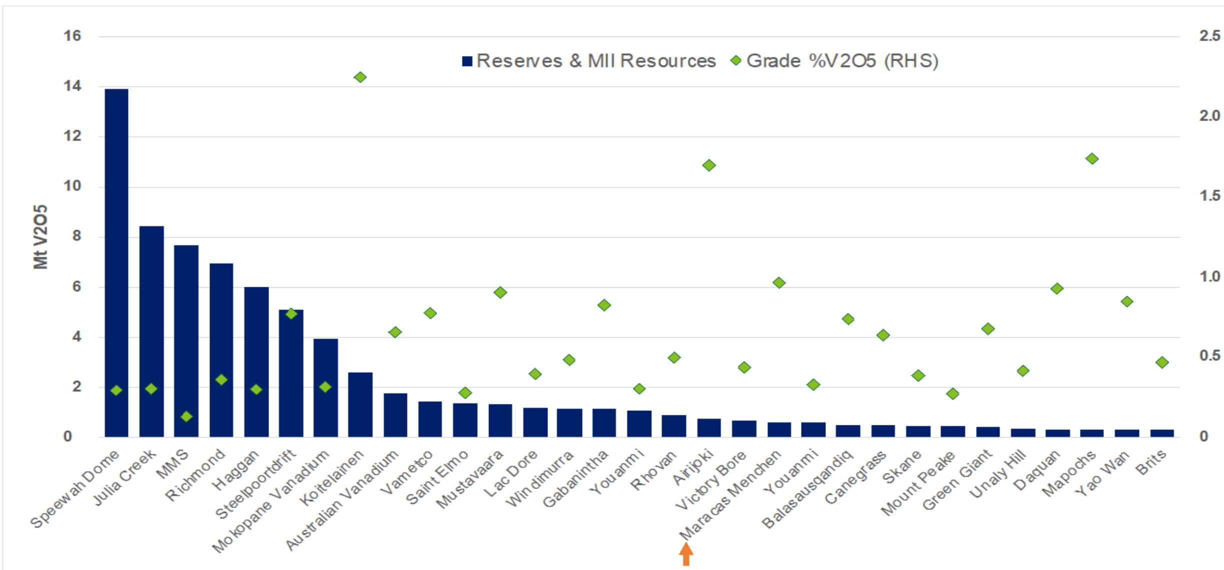
Source: Roskill (2020), Australian Department of Industry, Science, Energy and Resources (2021).

7. ECONOMIC COMPETITIVENESS

The Deloitte team used S&P Global data to evaluate the competitiveness of the vanadium industry. We identified data from 46 active projects and four operating mines, and information from feasibility reports published by exploration, development, and operating companies. Companies, investors, providers of finance, and governments may find it useful to examine existing mine and project data to benchmark potential vanadium projects.

Annex 2 lists these mines and projects.

Figure 15: Contained Vanadium Reserves and Measured, Indicated, & Inferred Resources



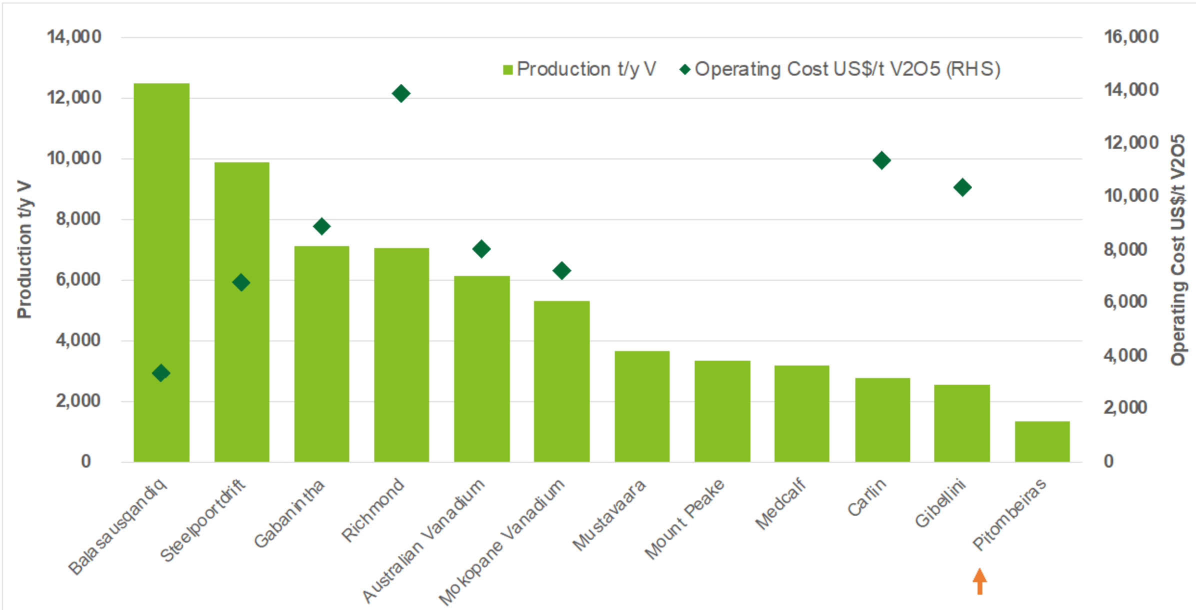
Source: S&P Global data, Deloitte.

Figure 15 shows the contained vanadium reserves and resources of all projects where data is available. Most projects have a grade between 0.25 percent to 1.0 percent V_2O_5; however, projects with largest contained reserves and resources tend to have the lowest grades. That includes the Maracás Menchen mine in Brazil, which is highlighted in the figure with an arrow.

Of these projects, the Deloitte team has collected data and analyzed information from 12 companies which have produced publicly available feasibility, pre-feasibility, and scoping studies. These reports were published at different times over the past five years using varying price assumptions and, as a result, are not uniformly comparable. Price assumptions, for example, varied from $6.30 to $11.32/lb for V_2O_5. Most of the valuation assessments were carried out at an 8.0 percent discount rate.

Figure 16 shows the projected production levels and operating costs of these 12 projects (the cash costs at the mine). Ideally, costs including transportation to the port or other point of sale should be included to make a better cost comparison, but this data is often not available. The average project operating cost is about $4.00/lb for V_2O_5, although data is not available for several projects. This is because the operating costs are presented per tonne of ore processed and these projects produce multiple products (including iron and titanium). It is worth noting the potentially large planned capacity and low operating cost of Balasausqandiq, Ferro-Alloy Resource Group's project in Kazakhstan.

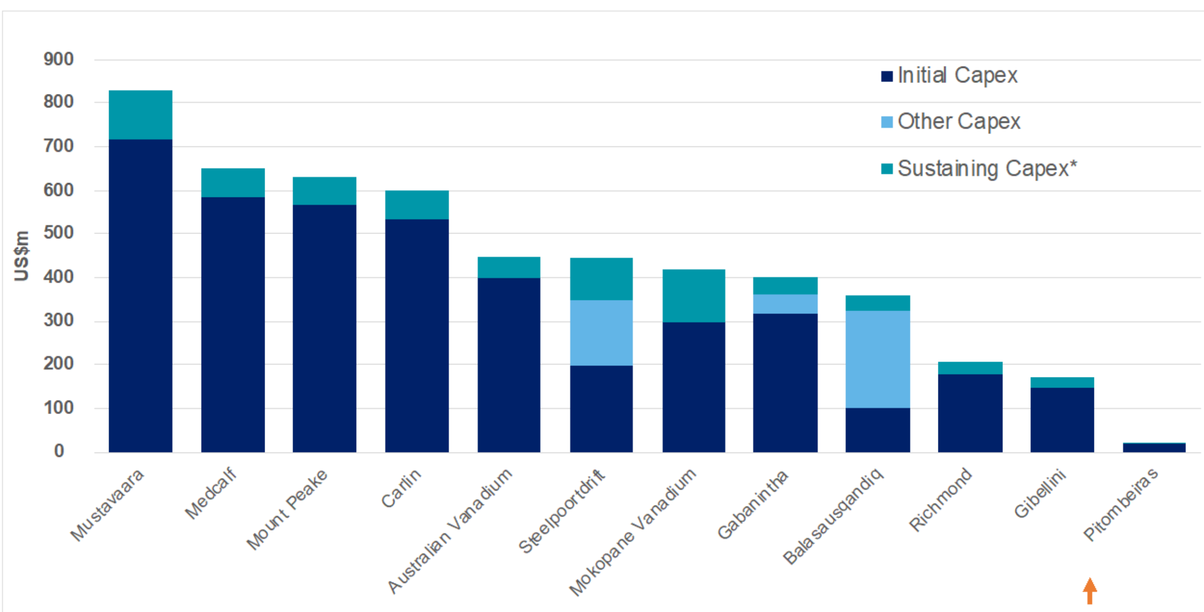
Figure 16: Projected Production Capacity (kt/y) and Operating Costs ($/t)



Source: Company data, Deloitte.

Figure 16, Figure 17, and Figure 18 also include the Pitombeiras project in Brazil, operated by Jangada Mines, which is highlighted with an arrow. Figure 16 highlights that Pitombeiras is a relatively small producer of vanadium and Figure 17 shows that it has a low capital expenditure (CAPEX) requirement.

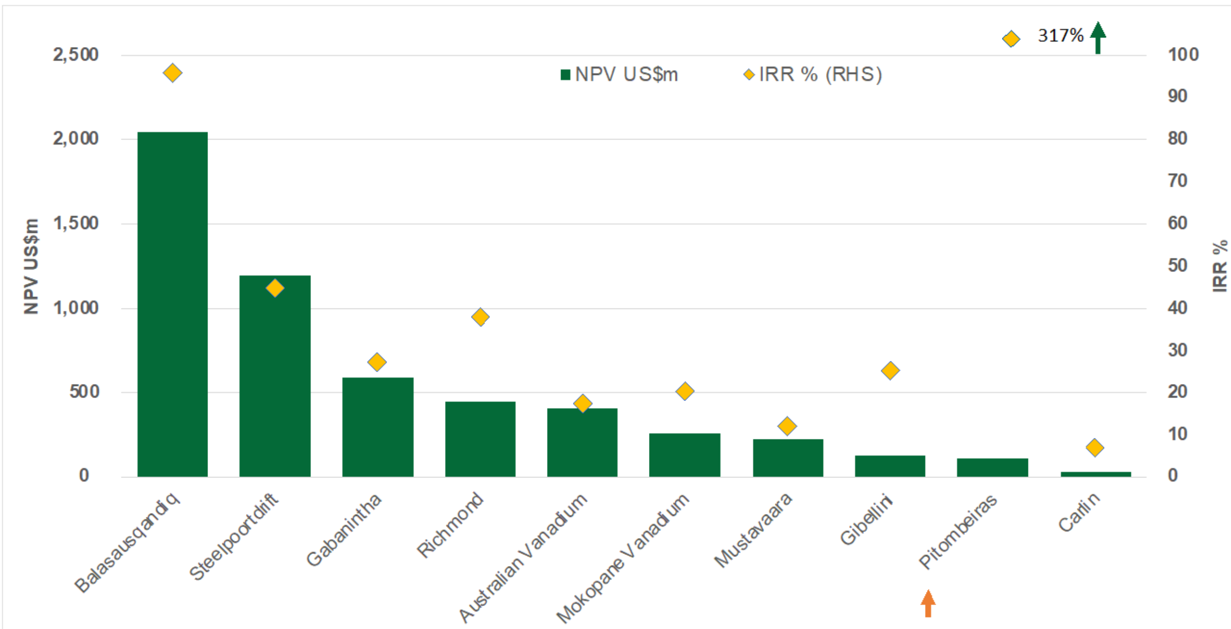
Figure 17: Vanadium Projects: Planned LOM Capital Expenditure ($m)



Source: Company data, Deloitte, *includes some estimates.

Another key factor in the economics of a mining project is the CAPEX required to establish and operate the mine. This includes the initial CAPEX, other CAPEX for later expansions, and sustaining CAPEX (usually for the replacement of plant and machinery). Figure 17 shows the total CAPEX for selected projects. Companies usually focus on the initial CAPEX, but it is important to look at the mine-life CAPEX to enable robust project comparisons.

Figure 18: Vanadium Projects: Net Present Value ($m) and IRR Post Tax %



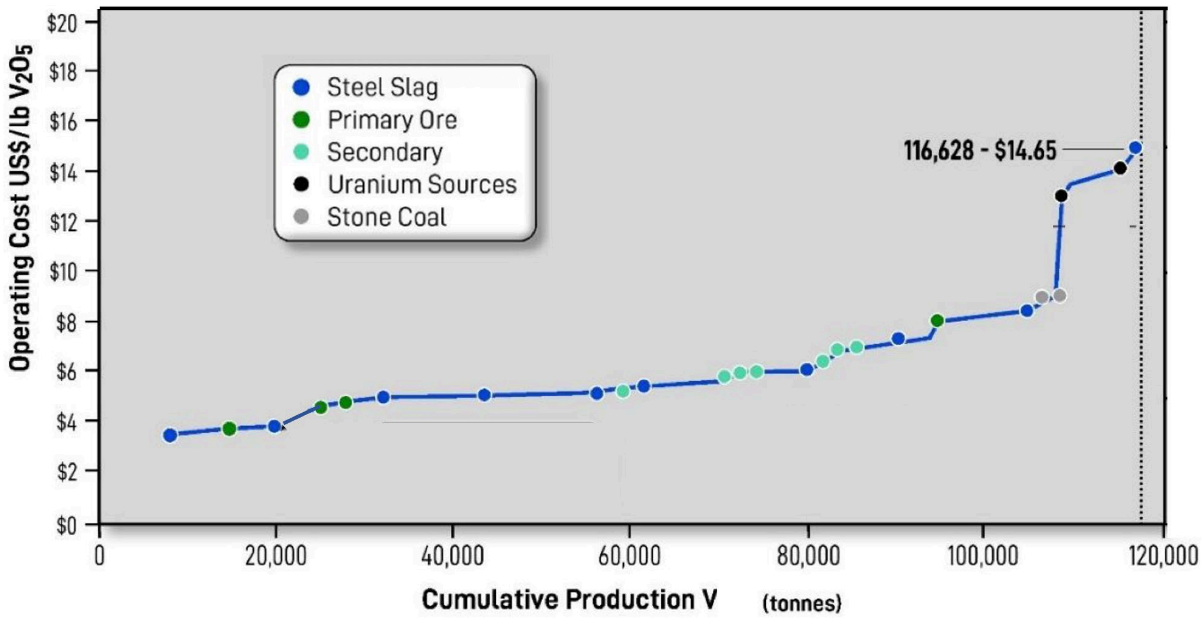
Source: S&P Global data, Deloitte

The ultimate measure of economic viability is project net present value (NPV) and the IRR. These are shown in Figure 18, but are not fully comparable because of the varying assumptions used. Also, not every project reported post-tax values. However, many of the projects have an IRR of above 20 percent suggesting strong prospective returns.

Figure 19 shows the relatively flat operating cost curve for existing mines, where 88 percent of production operates at or below \$8.00/lb for V_2O_5. Most of the new projects analyzed by the Deloitte team, which have an average operating cost of about \$4.00/lb, appear viable on an operating basis.

Pitombeiras is currently a relatively small vanadium project, with a low production and low CAPEX requirement. However, it reports a very high IRR due to its low level of capital expenditure required.

Figure 19: Vanadium Cost Curve – Price $/lb V2O5



Source: TTP Squared.

8. MARKET ANALYSIS

8.1. Global Vanadium Market Outlook

The vanadium market is a relatively small commodity market (0.8 percent the size of the copper market by value) with a relatively small number of producers, the majority being co-producers of vanadium as part of their iron-ore production process. With 60 percent of global production coming from China, mainly co-produced, the outlook for vanadium is very dependent on China and its steel industry.

China consumes vanadium primarily within its domestic steel industry and that capacity appears to be nearly fully utilized; therefore, its vanadium industry is likely to be capacity constrained going forward. Nevertheless, because of the endemic lack of transparency and reliable reporting on its vanadium reserves and resources, China will continue to have considerable influence over vanadium markets in the future. China briefly became a net importer during 2020, but the risk to other producers is that China could expand its vanadium capacity in coming years; as such, the market will continue to watch trends in Chinese vanadium imports as a bellwether to future market conditions.

Several exploration and development companies are looking at developing primary projects in Australia, Sweden, Finland, and South Africa, which could begin over the next few years. The project with the largest potential capacity is Balasausqandiq in Kazakhstan, which could absorb five to eight years of new demand if fully developed. The project's pace of development and level of production could have a meaningful impact on the market balance and vanadium price out to 2030.

Brazil also has significant resources, with higher average grades than other geographic regions and strong potential for development. Pitombeiras, operated by Jangada Mines, is the only advanced-stage exploration project currently reported.

The global projects described above have the potential to absorb the continued rising demand for vanadium in steel as well as the expected increase in demand from other areas, including for the installation of VRFBs. Although multiple VRFBs have already been installed in utilities around the globe, it is likely to be only one of a diverse group of storage technologies that are developed and implemented over the coming years.

The vanadium price outlook is relatively stable. Future long-term prices are expected to be slightly above long-term historical trading ranges of $6.00 to $8.00/lb for V_2O_5. Vanadium prices could spike, as they have done during past mismatches in supply and demand; however, sustained higher price levels appear unlikely given the potential for substitution by other metals.

8.2. Economic Opportunities for the Brazilian Vanadium Sector

Brazil has skilled and knowledgeable personnel to develop its vanadium industry and the country also has a high-quality vanadium producer that is expanding capacity and has a high-return development project. The pipeline of vanadium assets currently appears limited however, because Brazil does not have large-scale vanadium-bearing resources compared with several other countries developing projects.

- One avenue of opportunity for Brazil could be in the downstream production of VRFBs. A subsidiary of Largo Resources, U.S.-based Largo Clean Energy (LCE), is planning to produce VRFBs using vanadium mined from Brazil.

9. RECOMMENDATIONS FOR BRAZIL

The global vanadium market is relatively small and is expected to be in deficit from 2021 to 2023, followed by a surplus in 2024 to 2029, and again a deficit in 2030, according to Roskill. It is therefore unlikely that new vanadium production is likely to benefit from sustained appreciation of commodity prices. As such, the Government of Brazil might want to consider supporting the further development of its vanadium industry, and encourage downstream opportunities, by:

- **Streamlining access to, and circulation of, up-to-date domestic vanadium resource data to domestic and international exploration companies to encourage exploitation and to promote vanadium development in Brazil.** This may require gathering and distributing more extensive information for those regions considered to have significant vanadium potential, including Bahia and Ceará. Legacy CPRM geological data, reports, and studies should be broadly published online and in multiple languages. Brazil should also actively market these documents to expand their circulation, use, and impact.
- **Undertaking a comparative review of Brazil's exploration and mining policies/initiatives versus other vanadium-producing countries.** Such a review would take approximately 12 to 18 months and would analyze and prioritize how Brazil's government could encourage and accelerate vanadium exploration and mine development through potential legal, regulatory, and environmental, social, and governance (ESG) improvements. It should also include public-private partnerships and expertise from Brazilian universities in the area of mineral processing. Such improvements could include simpler licensing and permitting processes, lower royalties, preferential tax rates, and a coordinated approach to environmental policy. The ultimate objective of such policy improvements should be to encourage development and stability for investors seeking to develop Brazil's mineral sector generally, and vanadium in particular. Brazil's 2021 Pro-Strategic Minerals Policy[14], which focuses on simplifying the environmental licensing process by facilitating a dialogue between different national environmental agencies, is a right step in this direction.
- **Developing downstream vanadium redox flow batteries (VRFBs) to capture more of the value chain.** Brazil could consider becoming a VRFB producer by leveraging the experience of Largo Resources, its main vanadium producer. Largo Resources manufactures VCHARGE, a VRFB system, in the United States. The Government of Brazil may wish to encourage Largo Resources to expand its battery manufacturing activities into Brazil by offering credit guarantees, higher capital allowances, and tax reductions. This would then allow Largo Resources to use the vanadium mined in Brazil to produce domestic VRFBs, or manufacture VRFBs for export, rather than exporting the run-of-mine commodity itself.

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[14] Through the Pro-Strategic Minerals policy, the Government of Brazil has issued a list of specific critical minerals it aims to boost production of, and that are deemed of special interest to the country. Resolution No. 2 of June 18, 2021, defines the list of strategic minerals for the country. https://www.in.gov.br/web/dou/-/resolucao-n-2-de-18-de-junho-de-2021-327352416. Through the Pro-Strategic Minerals policy, the Government of Brazil is focusing on easing the environmental licensing process by facilitating, for example, the dialogue between the environmental agency responsible for conducting the environmental licensing process and authorities such as the managing bodies of Conservation Units, the National Indian Foundation (Funai), the National Institute for Colonization and Agrarian Reform (Incra) and the National Institute of Historic and Artistic Heritage (Iphan).

ANNEX 1 – VANADIUM REDOX FLOW BATTERIES

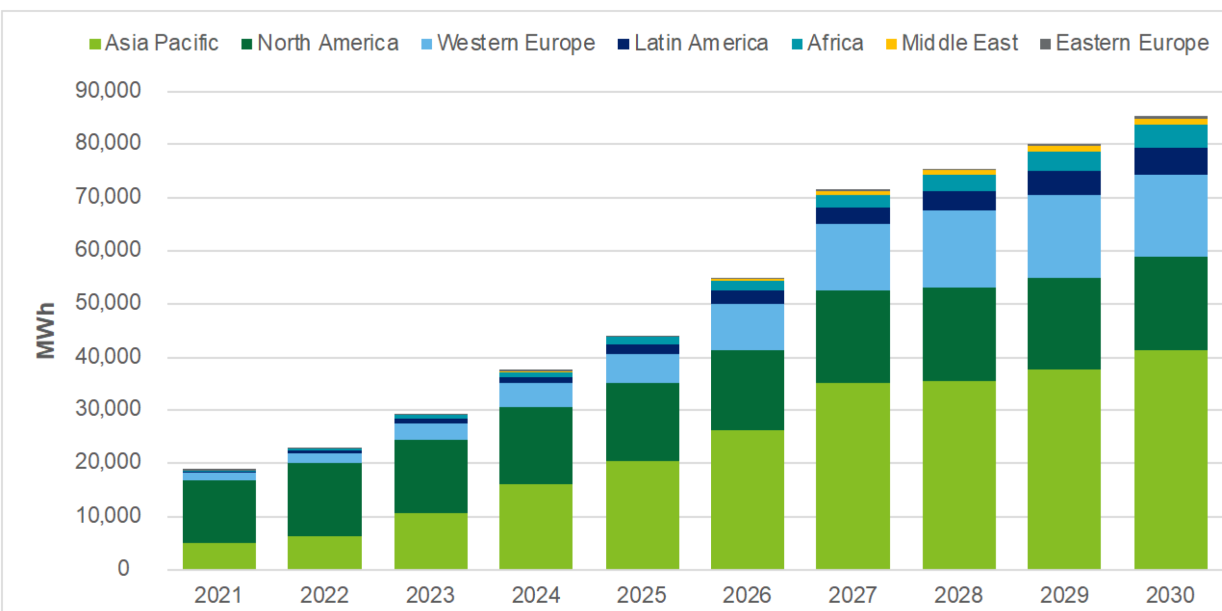
Stationary Energy Storage

Energy grid operators are increasingly adding renewables to their energy mix but are faced with finding solutions for intermittency. Electricity is much more difficult to store than other sources of energy and the variability of production of renewable energy sources creates misalignments between when electricity is produced and consumed. This is where stationary energy storage technologies come into play and become a key component in the future of energy infrastructure.

There are several storage methods, varying in the amount of energy stored, the length of storage time, and how quickly stored energy can be released. Some technologies are more appropriate for providing short bursts of electricity for power quality applications, such as smoothing the output of renewables. Other technologies are useful for storing and releasing large amounts of electricity over longer time periods.

Pumped-hydro systems still dominate electricity storage (with over 90 percent of installed storage capacity), but battery systems for stationary applications have started to grow rapidly. Wider deployment and the commercialization of new battery storage technologies has led to rapid cost reductions. Until recently, the new energy storage market mainly revolved around the production and consumption of lithium-ion batteries. However, lithium-ion batteries are not the best solution for all energy storage situations, especially long duration energy storage that requires a long life.

Figure 20: Annual Installed Long Duration Energy Storage Capacity by Region



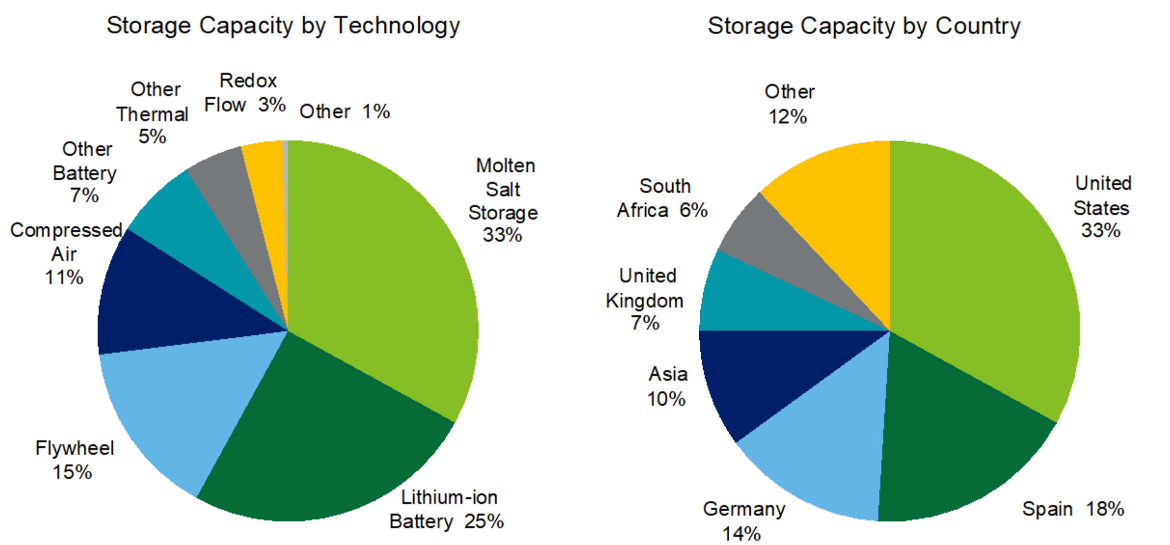
Source: Guidehouse Insights.

The International Renewable Energy Agency (IRENA)[15] forecasts that total electricity storage capacity could triple in energy terms by 2030 while Guidehouse Insights[16] suggests it could increase more than four-fold. The largest market for battery energy storage (BES) through 2030 may be the pairing of BES systems with the installation of new small-scale solar photovoltaic (PV) systems. Economies of scale, technology improvements, and optimizing of the manufacturing value chain will reduce material needs and drive cost reductions.

A stationary energy storage system can store energy and release it in the form of electricity when it is needed. In most cases, a stationary energy storage system will include an array of batteries, an electronic control system, inverter, and thermal management system within an enclosure. The primary commercially available technologies capable of long duration energy storage include lithium-ion batteries, compressed air energy storage (CAES), flow batteries, sodium sulfur batteries, and molten salt batteries. The two main flow battery technologies are vanadium redox flow and zinc bromine flow.

The growth in the electricity storage market to 2030 is not likely to be confined to just one type of BES. The very different requirements of the range of services that electricity storage can provide, and the varying performance characteristics of each group of electricity storage technologies means that a diverse group of storage technologies will be developed and implemented. IRENA believes that it is therefore likely that a range of technologies will find different market segments where they can compete on performance and cost. The electricity storage market in stationary applications will therefore remain a diverse one to 2030 and beyond.

Figure 21: Energy Storage Power Capacity (February 2020)



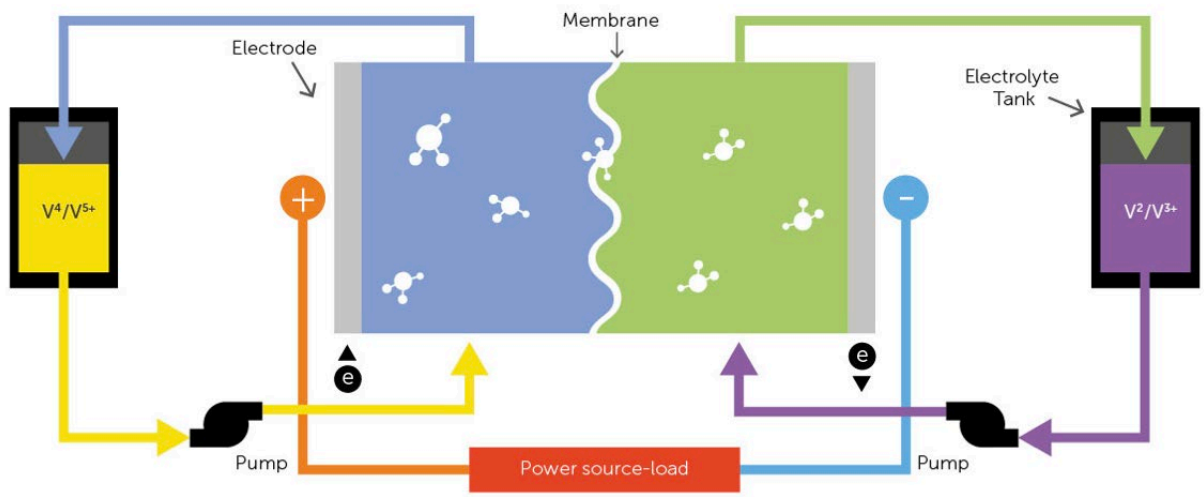
Source: On Location, US DOE Global Energy Storage Database. Excludes pumped hydro storage.

[15] IRENA, "Electricity Storage and Renewables: Costs and Markets to 2030," October 2017, https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets
[16] Guidehouse Insights, "Market Data: Utility-Scale Long Duration Energy Storage," accessed March 2022, https://guidehouseinsights.com/reports/market-data-utility-scale-long-duration-energy-storage

Vanadium Redox Flow Batteries

Flow batteries differ from conventional rechargeable batteries in that the electroactive materials are not all stored within the electrode but, instead, are dissolved in electrolyte solutions that are stored in tanks (one each on the anode and cathode sides). These tanks are separate from the main regenerative cell stack, and their contents are pumped into the cell stacks (reaction unit) as required during charging and discharging of the system. Using vanadium in a redox flow battery relies on the ability of this element to be present in four different oxidation states. VRFBs are the only redox flow battery that has been used in large-scale applications around the world for extended periods of time.

Figure 22: Vanadium Redox Flow Battery



Source: Bushveld Minerals.

VRFBs are expected to take a significant share of the stationary energy storage market, owing to unique advantages for long-duration stationary energy storage applications. Positive features of VRFBs include:

- Long lifespan cycles: the ability to repeatedly charge/discharge more than 35,000 times for a lifespan of over 20 years;
- 100 percent depth of discharge without material performance degradation;
- Low cost per kWh when fully used at least once daily;
- Operation close to ambient temperatures with no fire or smoke risk from thermal runaway;
- Vanadium is re-usable on decommissioning of a system;
- Flexibility for capturing the multi-stacked values of energy storage in grid applications; and
- No cross-contamination, since there is only one battery element, unique among flow batteries.

The disadvantages of the flow battery include its relatively low efficiency (compared with the lithium-ion battery) and its complex system architecture, potentially leading to a high cost for repair and maintenance if problems develop. There are a lot of moving elements compared to traditional batteries, with the circulation of the electrolyte solution requiring pumping, sensors, and flow management mechanisms. At the same time, system designs need to consider the risk of leaking of the acidic fluids requiring properly designed control measures in place. These issues also may reduce the applicability of the battery in certain stationary applications[17].

There are some 113 VRFBs installed worldwide, with 17 installed in China (15.8 MW, 48.0 MWh), 17 in the United States (7.4 MW, 33.2 MWh) and 15 installed in Germany (1.5 MW, 86.2 MWh). China has a further 1.5-2.0 GWh of VRFB projects underway.

Several vanadium producers and project developers already have joint ventures, strategic cooperation agreements, or purchased VRFB companies to develop and promote VRFB technology. A list of 33 VRFB companies can be found at: http://www.vanitec.org/vanadium-redox-flow-battery-vrfb-companies.

[17] IRENA, Electricity Storage and Renewables

ANNEX 2 – LIST OF VANADIUM PROJECTS

Table 2: Vanadium Project Resources by Contained Vanadium Mt

	Property Name	Country	Stage of Development	Company Operator	Meas., Inf. & Ind. Res. V Mt	Average Grade %V_2O_5
1	Speewah Dome	Australia	Prefeas/Scoping	King River Resources	13.91	0.30
2	Julia Creek	Australia	Reserve Devel.	QEM	8.44	0.31
3	MMS	Sweden	Prefeas/Scoping*	Unknown	7.68	0.13
4	Richmond	Australia	Feasibility Started	Richmond Vanadium	6.94	0.36
5	Haggan	Sweden	Prefeas/Scoping*	Aura Energy	6.04	0.30
6	Steelpoortdrift	South Africa	Prefeas/Scoping	Vanadium Resources	5.10	0.77
7	Mokopane Van.	South Africa	Feasibility Started	Bushveld Minerals	3.97	0.32
8	Koitelainen	Finland	Prefeas/Scoping	BMR Group	2.62	2.25
9	Aus. Vanadium	Australia	Feasibility Started	Australian Vanadium	1.76	0.66
10	Vametco	South Africa	Expansion	Bushveld Minerals	1.43	0.78
11	Saint Elmo	Australia	Prefeas/Scoping	Multicom Resources	1.38	0.28
12	Mustavaara	Finland	Prefeas/Scoping	Strategic Resources	1.32	0.91
13	Lac Dore	Canada	Prefeas/Scoping	Vanadiumcorp Res.	1.21	0.40
14	Windimurra	Australia	Preproduction*	Atlantic	1.14	0.49
15	Gabanintha	Australia	Feas. Complete	Technology Metals	1.13	0.83
16	Youanmi	Australia	Reserve Devel.	Venus Metals Corp.	1.08	0.30
17	Rhovan	South Africa	Operating	Glencore	0.89	0.50
18	Airijoki	Sweden	Prefeas/Scoping	BMR Group	0.75	1.70
19	Victory Bore	Australia	Reserve Devel.	Surefire Resources	0.66	0.44
20	Maracas Men.	Brazil	Operating	Largo Resources	0.61	0.97
21	Youanmi	Australia	Reserve Devel.	Diversity Resources	0.61	0.33
22	Balasausqandiq	Kazakhstan	Feasib.	Ferro-Alloy Resources	0.52	0.74
23	Canegrass	Australia	Reserve Devel.	Flinders Mines	0.51	0.64
24	Skane	Sweden	Reserve Devel.	Province Resources	0.46	0.39

	Property Name	Country	Stage of Development	Company Operator	Meas., Inf. & Ind. Res. V Mt	Average Grade %V_2O_5
25	Mount Peake	Australia	Constr. Planned	TNG	0.44	0.28
26	Green Giant	Madagascar	Prefeas/Scoping	NextSource Materials	0.40	0.68
27	Unaly Hill	Australia	Prefeas/Scoping	Surefire Resources	0.36	0.42
28	Daquan	China	Prefeas/Scoping*	Fit Plus Holdings	0.32	0.93
29	Mapochs	South Africa	Operating*	Private Interest	0.32	1.74
30	Yao Wan	China	Target Outline	Sparton Resources	0.32	0.85
31	Brits	South Africa	Reserve Devel.	Bushveld Minerals	0.31	0.47
32	Afton	USA	Exploration	Forum Energy Metals	0.30	1.10
33	Toolebuc	Australia	Reserve Devel.*	Liontown Resources	0.25	0.30
34	Coates	Australia	Target Outline	Australian Vanadium	0.20	0.51
35	Carlin	USA	Prefeas/Scoping	Phenom Resources	0.17	0.59
36	Kongshan	China	Operating	Xichuan Vanadium	0.16	1.42
37	Medcalf	Australia	Feasibility Started	Audalia Resources	0.15	0.47
38	Xiangxi	China	Adv. Exploration*	Unknown	0.14	0.79
39	Gibellini	USA	Prefeas/Scoping	Silver Elephant Mining	0.10	0.25
40	Guojiaping	China	Adv. Exploration*	Jingxi Nuclear Industry	0.10	0.86
41	Silasselka	Finland	Adv. Exploration	Strategic Resources	0.09	0.61
42	Bisoni McKay	USA	Prefeas/Scoping	Silver Elephant Mining	0.06	0.34
43	Iron-T	Canada	Adv. Exploration*	Private Interest	0.06	0.42
44	Pitombeiras	Brazil	Feasibility Started	Jangada Mines	0.04	0.45
45	Uitvalgrond	South Africa	Reserve Devel.*	Bushveld Minerals	0.03	1.50
46	Abenab	Namibia	Prefeas/Scoping	Golden Deeps	0.02	0.66
47	Bei An	China	Reserve Devel.	Xiushui Bei An Mining	0.02	0.87
48	Abenab	Namibia	Adv. Exploration*	Unnamed Owner	0.01	1.25
49	Sunday Compl.	USA	Preproduction	Western Uranium	0.01	1.87

Source: S&P Global data. * On Hold, Inactive, or Care & Maintenance

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