2023 Minerals Yearbook

VANADIUM [ADVANCE RELEASE]

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VANADIUM

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In 2023, the United States did not produce any vanadium from primary ores and concentrates (table 1). The United States continued to be a major producer of vanadium products from secondary sources such as ash, petroleum residues, and spent catalysts. However, secondary producers continued to rely on supplies of imported feedstock for a large portion of their production. Unless otherwise specified, all statistics in this chapter are in metric tons (t) of vanadium content. In 2023, the United States' estimated domestic vanadium production from ash, residues, and spent catalysts was 6,500 t, a 48% increase from that in 2022. Total imports for consumption increased by 13% from that in 2022. The United States imported 2,280 t of ferrovanadium (FeV), 2,320 t of vanadium pentoxide (V_2O_5), and 151 t of other oxides and hydroxides of vanadium, collectively valued at $171 million (table 3). The United States imported 221 t of aluminum-vanadium master alloy valued at $15.7 million (table 4). Imports of vanadium chemicals were 793 t valued at $9.06 million (table 6). The United States exported 159 t of FeV, 28 t of V_2O_5, and 142 t of other oxides and hydroxides of vanadium, which were collectively valued at $6.24 million (table 3). Exports of aluminum-vanadium master alloy were 64.6 t (gross weight) valued at $3.65 million, and exports of vanadium metal were 38.0 t valued at $1.57 million (table 4). Exports of ash and residues were 1,540 t (gross weight) valued at $3.61 million (table 5). Estimated vanadium consumption in the United States was 8,000 t, a 6% increase from that in 2022 (table 1). Ferrovanadium consumption of 4,700 t accounted for 59% of the reported vanadium consumption (table 2). In 2023, estimated worldwide production of vanadium was 104,000 t, a slight increase from the 102,000 t in 2022 (tables 1, 7).

Vanadium's main use was as a hardening agent in steel because it is critical for imparting toughness and wear resistance. These properties are especially important in high-strength low-alloy steels. Vanadium-containing steels can be subdivided into microalloy or low-alloy steels that generally contain less than 0.15% vanadium and high-alloy steels that contain as much as 5% vanadium. Nonmetallurgical applications of vanadium included batteries, catalysts, ceramics, dyes, pigments, and other miscellaneous chemical applications.

Large-scale energy storage systems are growing in use owing to the increase in energy production by renewable energy sources such as solar and wind. Vanadium redox flow batteries (VRFBs) have almost unlimited energy storage capacity, zero emissions, very long cycle lives, and can remain unused for long periods of time without negative effects. These advantages have made VRFBs a beneficial solution in different energy management strategy scenarios (U.S. Vanadium LLC, 2022).

Production

Industry convention for describing the production of V_2O_5 included the terms primary production, joint production, and secondary production depending on the raw source material for production. Primary production takes place from mined ore as mineral concentrate derived from vanadiferous titanomagnetite (VTM) and sandstone-hosted vanadium (with or without uranium). When a VTM iron ore is used to produce iron, vanadium is contained in the crude steel and must be extracted whether the finished steel will contain vanadium or not. Joint production, therefore, refers to vanadium slags that are produced during steelmaking. Secondary vanadium production takes place from various industrial waste materials, such as vanadium-bearing fly ash, petroleum residues, and spent catalysts.

The major vanadium commodities are aluminum-vanadium master alloy, FeV, oxides and hydroxides of vanadium [such as vanadium trioxide (V_2O_3)], vanadium chemicals, V_2O_5, and vanadium-bearing ash, residues, and slag. V_2O_5 is the most widely produced oxide, and most V_2O_5 and V_2O_3 are processed further into FeV.

Energy Fuels Inc.'s White Mesa Mill (operated by EFR White Mesa LLC), near Blanding, UT, had the only vanadium coproduct recovery circuit in the United States. However, Energy Fuels had not recovered vanadium from its existing tailings pond solutions since 2020. In the first quarter of 2023, Energy Fuels sold 36 t of V_2O_5 (contained in FeV) from its existing inventory, and as of yearend 2023, Energy Fuels had approximately 410 t of V_2O_5 as finished goods inventory and an estimated 450 to 1,400 t of V_2O_5 in its tailings solution, which was available for future recovery. No vanadium production was planned for 2024, and the company was expected to monitor the vanadium market to guide future potential production. According to the company, Energy Fuels also continued its conventional and in situ uranium recovery at the same time as exploration, permitting, and evaluation of uranium properties in the United States. The White Mesa Mill had a production capacity of more than 3,630 metric tons per year (t/yr) of uranium concentrate (U3O8) (Energy Fuels Inc., 2024, p. 14–17, 28–29, 63).

In October, the Bureau of Land Management issued a Record of Decision and Plan of Operations approval for Nevada Vanadium Mining Co.'s Gibellini vanadium project in Eureka County, NV. The project was expected to have an average annual production of approximately 4,500 t of V_2O_5 (reported as 10 million pounds) over its 7-year mine life and would employ approximately 120 people. Additionally, the Plan of Operations included construction of a solar photovoltaic array and a VRFB that would power 100% of the project's electricity requirements (Bureau of Land Management, 2023; Mining Technology, 2023).

AMG Vanadium LLC, a wholly owned subsidiary of AMG Critical Materials N.V. (Netherlands), was a major producer of FeV and other ferroalloys from oil refinery spent catalysts and powerplant residues at its headquarters in Cambridge, OH, and at its facility in nearby Zanesville, OH, which recently had undergone a $300 million expansion project. AMG reported that the Zanesville facility exceeded target production volumes in the fourth quarter of 2023 and historical production averages achieved by the Cambridge operation (AMG Critical Materials N.V., 2024, p. 2; AMG Vanadium LLC, undated).

Bear Metallurgical Co. (BMC), a subsidiary of Yildirim Group (Turkey), continued as a producer and toll processor of high-grade FeV at its processing facility in Butler, PA. The facility also processed V_2O_5 into FeV (Project Blue Group Ltd., undated a).

Gladieux Metals Recycling LLC (GMR), a wholly owned subsidiary of Aleon Metals, operated a facility in Freeport, TX, that had an estimated production capacity of 5,000 t/yr of V_2O_5 and a recycling capacity of 55,000 t/yr of V_2O_5. GMR recycled spent hydroprocessing catalysts produced by petroleum refineries during diesel fuel, gasoline, and jet fuel production. In 2022, Largo Inc. signed a 10-year offtake agreement with GMR for the purchase of all standard and high-purity grade vanadium products from GMR's recycling facility (Aleon Metals, 2022, undated).

Riverside Specialty Chemicals continued production of high-quality vanadium chemicals at its manufacturing facility in Bear, DE. The plant produced ammonium metavanadate, high-purity V_2O_5, and vanadium electrolyte. The plant had a capacity of 75,700 liters per month (L/mo) of vanadium electrolyte (Project Blue Group Ltd., undated b).

U.S. Vanadium LLC (USV) operated its facility in Hot Springs, AR, where vanadium ash, residues, and other waste materials were converted into high-purity vanadium oxides and vanadium chemicals used by the aerospace, chemical, steel, and titanium industries. In addition, USV operated a vanadium feedstock roasting facility in Benton, AR, adjacent to the company's vanadium oxide production facility. According to the company, the Benton facility, purchased in 2021, enabled the company to more efficiently grind and roast vanadium feedstock in preparation for chemical processing into a wide variety of vanadium products, including high-purity vanadium oxides and ultra-high-purity electrolyte for use in VRFBs. In 2022, USV agreed to sell up to 3 megaliters (ML) of vanadium electrolyte a year for the next 5 years to Enerox GmbH (Cell Cube) (Austria) (U.S. Vanadium LLC, 2021, undated; Murray, 2022).

Consumption

Reported consumption statistics were derived by the U.S. Geological Survey (USGS) from voluntary surveys of U.S. operations. Consumption data prior to 2007 included statistics derived from only one survey, during which more than 50 companies with a broad range of metal consumption were canvassed on a monthly or annual basis. It is important to note that reported consumption data after 2007 included a second annual voluntary survey of domestic vanadium-processing companies. Combined reported consumption data and stocks from both surveys, as well as estimates to account for nonrespondents, are included in tables 1 and 2.

Reported vanadium consumption in the United States was estimated to be 8,000 t in 2023, a 6% increase compared with the 7,510 t in 2022 (tables 1, 2). Most vanadium was consumed in the form of FeV, which was used to introduce vanadium into steel to provide additional strength and toughness. In 2023, 4,700 t of FeV was estimated to have been consumed, representing 59% of the total amount of the reported vanadium consumed (table 2). FeV was available as alloys containing either 45%-to-50% or 80% vanadium. The 45%-to-50%-grade FeV is produced by silicothermic reduction of V_2O_5 in slag or other vanadium-containing materials. Most of the 80%-grade FeV was produced by aluminothermic reduction of V_2O_5 in the presence of steel scrap or by direct reduction in an electric arc furnace.

Metallurgical applications, primarily as an alloying agent for iron and steel, continued to dominate U.S. vanadium use in 2023. Nonmetallurgical applications of vanadium included batteries, catalysts, ceramics, dyes, pigments, and other miscellaneous chemical applications. Catalyst and pigment consumption data were withheld to avoid disclosing company proprietary data (table 2). A variety of vanadium chemicals were used in catalysts to manufacture a variety of industrial chemicals and to clean industrial process waste streams. V_2O_5 was used as a catalyst in the sulfuric acid industry and was used as a corrosion inhibitor for equipment in the petrochemical industry (Yang and others, 2021, p. 19).

A redox flow battery operates on the principle of storing and generating electricity through oxidation and reduction reactions between specific materials. Redox flow batteries come in various types and sizes depending on the solvent and form of the specific material used. VRFBs use a liquid vanadium electrolyte composed of vanadium dissolved in a stable, nonflammable, water-based solution to store energy in large separate storage tanks. Lithium-ion batteries, however, store electrochemical energy in solid forms of lithium. One of the main advantages of the VRFBs is that they provide design flexibility because their power generation and energy storage components are separate. This allows for any storage capacity to be matched with any power output capacity. By pairing variable renewable energy sources, such as wind turbines or solar arrays or panels, excess renewable energy can be captured and utilized later, giving VRFBs a strategic advantage in applications where balancing the grid would be necessary. Trial VRFB projects have begun where VRFBs were used as electric vehicle charging stations. VRFBs can be added to existing charging infrastructure in urban areas. In remote areas, VRFBs can be paired with solar energy systems as standalone charging systems (Gunjan and others, 2022, p. 1, 5, 8–9; Khan, 2024; Invinity Energy Systems, undated).

It is important to note the reporting differences used for vanadium electrolyte switches between the equivalent megawatt hour (MWh), the number of liters of electrolyte, and the contained amount of vanadium. For example, 1 MWh of stored energy is equal to approximately 68,000 L of vanadium electrolyte or 9.89 t of V_2O_5. A proportion of V_2O_3 can also be included in this number depending on whether a chemical or electrical method of production was used. The exact specification of the elements contained in the electrolyte varied between VRFB manufacturers. The manufacturer of the vanadium electrolyte worked closely with VRFB manufacturers to ensure that its electrolyte was suitable (McGahan, 2023).

In 2023, cost and equipment and raw material availability continued to be barriers for entry of VRFBs into the battery market. The vanadium used in the VRFBs accounted for approximately 30% to 50% of the cost of the battery, requiring between 3 and 6 kilograms of vanadium per kilowatthour (kWh) of energy storage. VRFBs required large electrolyte tanks and pumping systems and therefore were suited primarily for stationary applications. Lithium-ion batteries have been proven to be versatile in not only stationary applications but also in electric vehicles and consumer electronics. This versatility and their low capital cost continued to make lithium-ion batteries the dominant technology over VRFBs (Gunjan and others, 2022, p. 8–9).

According to researchers, VRFBs were one of the most recyclable types of batteries. VRFBs are composed mainly of alloys and plastics that can be easily recycled. The actual vanadium electrolyte comprised approximately one-third of the total VRFB system and does not degrade. A study by U.S. Vanadium on a decommissioned VRFB showed that approximately 97% of the vanadium from the vanadium electrolyte was successfully recovered. This high level of recyclability and reusability of VRFBs makes it a viable option in many stationary energy storage applications (U.S. Vanadium LLC, 2021).

VRFB manufacturers continued to look at a variety of models to lease electrolytes to end users to shield them from fluctuating vanadium costs and to reduce initial upfront costs. There also continued to be competition from a variety of alternative battery technologies with different chemistries. Examples of alternative flow battery chemistries included iron-chromium, zinc-bromine, and zinc-cerium (Gilani, 2023; Blackridge Research & Consulting, 2024).

As of December 2023, some of the U.S.-based manufacturers establishing VRFB production lines (all at different levels of completion) included Ashlawn Energy, LLC (Binghamton, NY); ESS Inc. (Wilsonville, OR); Perennial Power Holdings, Inc. (New York, NY); Primus Power Corp. (Hayward, CA); StorEn Technologies Inc. (Greenville, SC); and ViZn Energy Systems Inc. (Columbia Falls, MT).

Prices

In 2023, the U.S. average monthly price for domestic FeV (78% to 82% vanadium content), as published by Argus Media, Argus Non-Ferrous Markets, ranged from $13.444 to $19.000 per pound of vanadium content, compared with $16.300 to $32.150 per pound in 2022. The 2023 annual average for U.S. FeV (78% to 82% vanadium content) was $16.417 per pound. In 2023, the European average monthly price for FeV (78% to 82% vanadium content) ranged from $25.886 to $39.934 per kilogram, compared with $31.379 to $59.250 per kilogram in 2022. The 2023 annual average for European FeV (78% to 82% vanadium content) was $32.751 per kilogram. The average monthly price in China, 98% V_2O_5 content, ranged from $5.490 to $9.796 per pound in 2023, compared with $7.564 to $13.102 per pound in 2022. The 2023 annual average price in China, 98% V_2O_5 content, was $7.497 per pound.

Foreign Trade

Vanadium entered international trade in the form of FeV, V_2O_5, waste and scrap, vanadium metal (including aluminum-vanadium master alloy), and vanadium-bearing ash, residues, and slag. It is difficult to calculate the total quantity of vanadium entering international trade owing to multiple factors. First, not all countries published data for all forms of vanadium; second, when countries did publish trade data, some data were not distinguished correctly between different vanadium forms. Data can be quoted in terms of either gross weight, V_2O_5 content, or vanadium content. The data in this chapter are quoted in either gross weight or vanadium content, unless otherwise noted. It is important to note that the U.S. Census Bureau has withheld some of the data from individual countries in some of their trade reports. Where data were withheld by the U.S. Census Bureau, it was noted in the footnotes of each table. In table 1, USGS estimates have been included for data suppressed by the U.S. Census Bureau.

World Review

Most of the world's supply of vanadium was derived from either joint product steel slag production or from primary ore production. Production from these two sources is shown in table 7. In 2023, the leading vanadium-producing nations from these two sources, in descending order of vanadium content, remained China (67%), Russia (19%), South Africa (8%), and Brazil (5%).

World vanadium reserves were estimated to be 16 million metric tons. Increased recovery of vanadium from fly ash, petroleum residues, slag, and spent catalysts was not included in the reserve estimate and would significantly extend the life of the reserve if included (Polyak, 2024).

According to Project Blue Group Ltd. (2024), global vanadium consumption was estimated to be approximately 116,000 t (vanadium content) in 2023, unchanged from that in the previous year.

Australia.—Australian Vanadium Ltd. (AVL) signed a new agreement to purchase land for its vanadium-processing plant at Tenindewa, 60 kilometers (km) east of Geraldton in Western Australia. Under the new agreement, AVL was granted a license to access the land immediately for the purpose of drilling, engineering, surveying, and excavation. The project's mine site is located approximately 40 km south of Meekatharra in Western Australia. The crushing, milling, and beneficiation of the vanadium-bearing magnetite ore was expected to take place at the mine site. The resulting concentrate would be brought to the proposed vanadium-processing plant, where the final processing to high-quality vanadium products would be completed (Australian Vanadium Ltd., 2023, p. 1–3).

In December, AVL completed construction of its first commercial VRFB electrolyte manufacturing facility in Western Australia. The facility was expected to produce high-purity electrolyte to support up to 33 MWh per year of VRFB energy storage. Production was expected to commence in 2024. AVL reported that the V_2O_5 initially used for the electrolyte manufacturing facility would be sourced from USV's Arkansas facility until its Australian Vanadium project had commenced

V_2O_5 production. The electrolyte manufacturing technology also was licensed from USV. The vanadium electrolyte produced at the facility was expected to be used with AVL's subsidiary, VSUN Energy, as well as with a variety of other supply agreements, including Western Australia's regional power provider, Horizon Power (Carroll, 2023a).

In June 2023, Vecco Group Pty Ltd. (Brisbane, Queensland) commenced operations at its vanadium electrolyte production facility. According to the company, Vecco's Townsville vanadium electrolyte facility was the first commercial-scale vanadium electrolyte production facility in Australia. Its initial annual energy storage capacity was expected to be 175 MWh, and there were plans to expand to 350 MWh. The vanadium electrolyte facility was expected to integrate with the Debella mining project that was being built near Julia Creek, approximately 650 km west of Townsville. Vanadium production at Debella was expected to commence in 2024, with production of approximately 5,500 t/yr of V_2O_5 over a mine life of more than 50 years. Vecco was expected to use imported vanadium ore at the electrolyte facility until the Debella project commenced. The vanadium electrolyte facility was partially funded by the Queensland government through its Industry Partnership Program (Carroll, 2023b; Vecco Group Pty Ltd., undated).

Sumitomo Electric Industries, Ltd. (Osaka, Japan) received its first order in June 2023 from Vecco Group for a VRFB with a capacity of 750 kWh in Australia. The VRFB, with installation planned in December 2023, would be used as a trial project for Energex Ltd., part of Energy Queensland Ltd. (EQL), a Queensland-government-owned corporation. In September 2022, the Queensland government's Department of Energy and Climate released a plan with new commitments of 70% renewal energy targets by 2032, and 80% by 2035. To help achieve this goal, EQL planned to install numerous VRFBs in its power distribution network to support the required increase in renewable generation (Sumitomo Electric Industries Ltd., 2023; Queensland Treasury, 2024).

Brazil.—Largo Inc. (Toronto, Ontario, Canada), a vertically integrated vanadium producer and owner of the Maracás Menchen Mine, produced 9,681 t of V_2O_5 in 2023, 7% less than the 10,436 t of V_2O_5 produced in 2022. The Maracás Menchen Mine is located 813 km northeast of Brasilia. Largo expected to produce between 9,000 and 11,000 t of V_2O_5 during 2024 (Largo Inc., 2024, p. 2; undated).

Canada.—In December 2023, VanadiumCorp Resource Inc. reported that the vanadium-electrolyte-processing facility equipment for its Val-des-Sources facility in Quebec was complete and ready for inspection at the manufacturer's United Kingdom facility. Once VanadiumCorp engineers conducted the equipment inspection, the equipment would be released for immediate shipping to the facility in Quebec for reassembly. The Val-des-Sources electrolyte facility was expected to have a capacity of 350,000 liters per year of high-purity vanadium electrolyte with a total capital cost of approximately $1.25 million. The facility was scheduled to be completed in the first quarter of 2024. VanadiumCorp announced that the preengineering scoping for its second vanadium electrolyte facility in Quebec was complete. This second facility would have a capacity of approximately 4 megaliters per year, providing approximately 76 MWh of VRFB energy storage per year. The necessary economic, engineering, and environmental studies were expected to be complete by the second quarter of 2024 (VanadiumCorp Resource Inc., 2023).

China.—China invested heavily in VRFB manufacturing and deployment in 2023 and remained the world's leading vanadium electrolyte producer, with an estimated 91% of the market share. China also consumed a large amount of the vanadium electrolyte that it produced for its own VRFB installations. China accounted for nearly 90% of the MWh capacity of VRFBs, compared with 5.6% for Japan and 2.2% for the United States. Project Blue expected China's VRFB market dominance to continue because the country would have at least nine new VRFB facilities under construction in 2024. It was estimated that global vanadium consumption in VRFBs in 2023 was approximately 4,320 t (vanadium content), with about 90% of the consumption in China (McGahan, 2023; Sardain, 2024).

Some of the China-based companies that produced vanadium electrolyte included Beijing Xingchen New Energy Technology Co. Ltd., Chengyu Vanadium and Titanium Technology Co., Dalian Rongke Power Co. Ltd., Pangang Group Xichang Steel and Vanadium Co. Ltd., Vanmo Tech Co. Ltd., and Zhonge Energy Storage Technology Co., Ltd.

In September, Beijing Xingchen New Energy Technology commenced full-scale production at its VRFB manufacturing facility. The facility is in Changzhou Wujin National High-tech Zone in the Wujin District, Changzhou, Jiangsu (vanadiumprice.com, 2023).

Czechia.—EVRAZ NIKOM, a.s. (now Czech Vanadium, a.s) had one processing facility, located in Mnsek pod Brdy, 30 km southwest of Prague. It processed vanadium oxide produced by EVRAZ Vanady Tula (Russia) into ferrovanadium (Czech Vanadium, a.s., undated).

Finland.—Neometals Ltd. announced that it would not proceed with its proposed vanadium recovery project in Finland, citing financial reasons. Neometals and its project partner, Critical Metals Ltd. (Sweden), had been evaluating the feasibility of recovering high-purity V_2O_5 from high-grade vanadium-bearing slag in Scandinavia (Sardain, 2023).

Germany.—AMG Titanium (a subsidiary of AMG Critical Materials N.V.) continued construction at its vanadium electrolyte plant in Nuremberg. The facility was expected to start up in the second half of 2024 and have 6,000 cubic meters of vanadium electrolyte capacity (approximately 100 MWh) (AMG Critical Materials N.V., 2024, p. 3).

Kazakhstan.—Ferro-Alloy Resources Ltd.'s (FAR) (United Kingdom) two main operations were the high-grade Balasausqandiq vanadium project and its processing facility that recovered vanadium, molybdenum, and nickel from third-party concentrates. Both operations were located at the Balasuasqandiq deposit in Qyzylorda Province in southern Kazakhstan. FAR reported 311 t of V_2O_5 produced in 2023 compared with 306 t of V_2O_5 in 2022 at its processing facility, where FAR processed secondary materials (spent catalysts) to produce V_2O_5. FAR also reported that its Balasausqandiq vanadium project would be developed in two phases, Phase 1 and Phase 2. Phase 1 would produce approximately 5,600 t of V_2O_5, and Phase 2 could produce up to 22,400 t of V_2O_5 after commissioning (Ferro-Alloy Resources Ltd., 2024).

Russia.—EVRAZ Nizhny Tagil Metallurgical plant (NTMK), an integrated metallurgical complex located in Nizhny Tagil in the Sverdlovsk oblast, continued to be one of the world's leading processors of VTM. NTMK processed material mined at the EVRAZ Kachkanarskii Gorno-Obogatitelnyi Kombinat, an iron-ore mine, approximately 140 km away. EVRAZ Vanady Tula, located 180 km south of Moscow, was a leading European producer of V_2O_5, FeV-50, and FeV-80, which were alloy additions used to manufacture extra high-strength steel for various applications and titanium alloys. Vanady Tula processed vanadium slag from EVRAZ NTMK into FeV and V_2O_5 (EVRAZ plc, undated; Mashprom, undated; Project Blue Group Ltd., undated c, d).

South Africa.—Bushveld Minerals Ltd.'s operations consisted of three mineral assets— the Brits Mine, the Mokopane Mine, and the Vametco Mine—and two processing facilities—Vametco and Vanchem. The Vametco Mine and processing facility were located in Brits, North West Province. The Vametco processing facility produced Bushveld nitro-vanadium, a proprietary steel-alloying vanadium carbon nitride product. The Vanchem processing facility consisted of three roasting kilns, a vanadium chemical facility, two FeV-processing facilities, and a V_2O_5-processing plant. Vanchem produced FeV, V_2O_5, a variety of vanadium chemicals, and had the ability to produce V_2O_3. The Mokopane Mine was expected to be the primary source of feedstock for Bushveld's Vanchem facility. In 2023, Bushveld produced 2,306 t of nitro-vanadium at its Vametco facility and 1,408 t of vanadium (798 t of FeV, 416 t of V_2O_5 flake, and 195 t of vanadium chemicals) at its Vanchem facility, for a total of 3,714 t of vanadium at both facilities. In 2022, Bushveld produced 2,705 t of nitro-vanadium at its Vametco facility and 1,137 t of vanadium (657 t of FeV, 288 t of V_2O_5 flake, and 193 t of vanadium chemicals) at its Vanchem facility, for a total of 3,842 t of vanadium at both facilities (Bushveld Minerals Ltd., 2023, 2024, undated b).

Construction was completed at Bushveld Electrolyte Company's (BELCO) electrolyte manufacturing plant in August 2023. Samples of the electrolyte were distributed by BELCO to customers for qualification and compatibility testing. BELCO's samples were successfully qualified by three international battery companies, and it was in discussions with multiple companies for supply contracts. The plant had an annual capacity of 8 ML of vanadium electrolyte. Each liter of vanadium electrolyte was expected to contain between 82 and 92 grams of vanadium, with the plant using approximately 1,100 t of vanadium oxide equivalent during full production. BELCO was owned by Bushveld Energy Ltd. (55%) and the Industrial Development Corporation of South Africa (45%) (Bushveld Minerals Ltd., 2023, undated a).

Glencore plc's (Switzerland) Rhovan vanadium facility, 30 km northwest of Brits, produced approximately 8,850 t of V_2O_5 in 2023, compared with approximately 8,980 t of V_2O_5 in 2022. In August, Glencore announced that the necessary approvals were in place to begin construction of a 25-megawatt solar photovoltaic powerplant at its Rhovan vanadium facility. Glencore set a target of a 15% reduction in emissions by 2026 and was continuing to work on plans to make the facility more efficient and reduce its carbon in the future (Creamer Media Mining Weekly, 2023; Glencore plc, 2024, p. 5).

Outlook

Because almost all vanadium is used in the production of steel, vanadium consumption trends are greatly influenced by trends in steel production, and the use of vanadium in a wider range of steels is expected to continue to gradually increase. The outlook for vanadium consumption in nonferrous alloys is largely dependent on trends in consumption for titanium alloys in business, commercial, and military aircraft.

VRFB batteries have a low environmental impact in terms of battery disposal and have high energy capacity limits owing to the ability of the system to have very large tanks for the electrolyte solution storage. However, VRFB implementations continues to have some major disadvantages, including the high cost of the electrolyte used in the battery and the system complexity of the batteries. There will be continued competition from a variety of alternative battery technologies, and VRFBs will have to continue to refine their technology and secure stable vanadium supplies to ensure that they can keep costs down (Gilani, 2023; Project Blue Group Ltd., 2024).

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TABLE 1
SALIENT VANADIUM STATISTICS[1]

(Metric tons, vanadium content, unless otherwise specified)

	HTS codes and Schedule B numbers[2]	2019	2020	2021	2022	2023
United States:						
Production from primary ores and concentrates		460	17	--	--	--
Production from ash, residues, and spent catalysts[e]		3,000	2,900	3,200	4,400	6,500
Consumption, reported		9,900	7,920	8,030	7,510	8,000 e
Imports for consumption:						
Aluminum-vanadium master alloy	8112.99.2000	222	101	35	104	221
Ash and residues[3, 4, 5]	2620.40.0030, 2620.99.1000	2,120	1,550	1,680	2,240	3,140
Chloride oxides and hydroxides of vanadium	2827.49.1000	532	176	207	175	363
Ferrovanadium[6]	7202.92.0000	2,280	1,360	2,170	2,650	2,280
Hydrides and nitrides of vanadium	2850.00.2000	54	57	200	352	245
Oxides and hydroxides, other	2825.30.0050	105	67	69	222	151
Sulfates	2833.29.3000	74	34	408	117	2
Vanadates	2841.90.1000	73	104	15	92	29
Vanadium chlorides	2827.39.1000	1	11	16	68	154
Vanadium metal	8112.92.7000	45	(7)	(7)	28 r	20
Vanadium ores and concentrates[5]	2615.90.6090	108	2	4	492	674
Vanadium pentoxide (anhydride)	2825.30.0010	3,620	1,670	1,710	1,980	2,320
Total imports		9,230	5,130	6,520	8,520 r	9,590
Exports:						
Aluminum-vanadium master alloy[5]	8112.99.2000	29	14	72	28	36
Ash and residues[3, 5]	2620.50.0000, 2620.99.1000	1,280	503	930	1,130	861
Ferrovanadium	7202.92.0000	295	210	173	154 r	159
Oxides and hydroxides, other	2825.30.0050	750	51	235	309	142
Vanadium metal	8112.92.7000	27	1	4	8	38
Vanadium ores and concentrates[5]	2615.90.6090	95	92	81	185	82
Vanadium pentoxide (anhydride)	2825.30.0010	423	50	17	143	28
Total exports		2,900	920	1,510	1,950 r	1,350
Stocks, yearend:						
Ferrovanadium		197	206	209	184	169
Other[8]		60	63	62	64	63
World, production from ore, concentrates, slag[9]		92,800	105,000	105,000	102,000	104,000

[e]Estimated. [r]Revised. -- Zero.

[1]Table includes data available through November 5, 2024. Data are rounded to no more than three significant digits; may not add to totals shown. Includes U.S. Geological Survey estimates.

[2]Harmonized Tariff Schedule of the United States (HTS) codes are imports and Schedule B numbers are exports.

[3]Includes both HTS codes 2620.40.0030 and 2620.99.1000.

[4]Includes U.S. Geological Survey estimates for data suppressed by U.S. Census Bureau.

[5]Reported by the U.S. Census Bureau as metric tons of vanadium pentoxide equivalent. Data were converted to vanadium content by multiplying reported data by 0.56.

[6]Some data suppressed by the U.S. Census Bureau; not included in ferrovanadium total.

[7]Less than ½ unit.

[8]Includes chlorides, vanadates, vanadium-aluminum alloy, other vanadium alloys, vanadium metal, vanadium pentoxide, and other specialty chemicals.

[9]May include estimated data.

TABLE 2
U.S. REPORTED CONSUMPTION OF VANADIUM, BY END USE AND FORM[1]

(Kilograms, vanadium content)

	2022	2023[e]
End use:		
Steel:		
Carbon	1,210,000	1,300,000
Full alloy	1,770,000	1,900,000
High-strength low-alloy	W	W
Stainless and heat resisting	86,000	95,000
Tool	W	W
Total	3,060,000	3,400,000
Cast irons	W	W
Alloys (including steels and superalloys)	2,620,000	2,900,000
Chemical and ceramic:		
Catalysts	W	W
Pigments	W	W
Miscellaneous and unspecified[2]	1,830,000	1,700,000
Grand total	7,510,000	8,000,000
Form:		
Ferrovanadium	4,470,000	4,700,000
Other[3]	3,040,000	3,300,000
Total	7,510,000	8,000,000

[e] Estimated. W Withheld to avoid disclosing company proprietary data; included with "Miscellaneous and unspecified."
[1]Table includes data available through November 5, 2024. Data are rounded to no more than three significant digits; may not add to totals shown. Includes U.S. Geological Survey estimates.
[2]Includes electrical steel and unspecified steel.
[3]Includes chlorides, other specialty chemicals, other vanadium alloys, vanadium-aluminum alloy, vanadium metal, vanadium pentoxide, and vanadates.

TABLE 3
U.S. IMPORTS AND EXPORTS OF FERROVANADIUM, VANADIUM PENTOXIDE (ANHYDRIDE), AND OTHER OXIDES AND HYDROXIDES OF VANADIUM[1]

(Kilograms unless otherwise specified)

	Ferrovanadium[2]			Vanadium pentoxide (anhydride)[3]			Other oxides and hydroxides of vanadium[4]		
Country or locality	Gross weight	Vanadium content	Value	Gross weight	Vanadium content	Value	Gross weight	Vanadium content	Value
Imports for consumption:									
2022	3,460,000	2,650,000	$165,000,000	2,830,000	1,980,000	$64,400,000	337,000	222,000	$9,100,000
2023:									
Austria	1,140,000	911,000	30,800,000	--	--	--	--	--	--
Brazil	--	--	--	1,540,000	1,350,000	35,000,000	110,000	71,400	2,350,000
Canada	1,470,000	1,170,000	44,800,000	3,430	1,660	185,000	--	--	--
China	--	--	--	2,410	1,410	109,000	--	--	--
Czechia	(5)	(5)	16,100,000	--	--	--	--	--	--
Germany	--	--	--	78,700	60,100	1,640,000	--	--	--
Japan	251,000	128,000	4,320,000	--	--	--	--	--	--
Latvia	122,000	65,700	2,220,000	--	--	--	--	--	--
South Africa	1,450	1,180	47,800	1,300,000	820,000	29,100,000	120,000	79,400	2,940,000
Taiwan	--	--	--	78,300	78,300	1,620,000	--	--	--
United Kingdom	--	--	--	6,000	5,980	147,000	--	--	--
Total	2,980,000	2,280,000	98,200,000	3,010,000	2,320,000	67,900,000	230,000	151,000	5,280,000
Exports:									
2022	225,000 r	154,000 r	5,370,000 r	XX	143,000	2,220,000	XX	309,000	2,930,000
2023:									
Argentina	198	149	8,900	--	--	--	--	--	--
Australia	--	--	--	NA	8,100	88,400	--	--	--
Austria	--	--	--	NA	906	8,750	NA	43,700	389,000
Belgium	--	--	--	NA	10,100	60,000	NA	29,500	262,000
Belize	--	--	--	--	--	--	NA	434	7,650
Canada	34,800	26,100	1,080,000	--	--	--	NA	22,600	228,000
China	2,000	1,500	50,000	--	--	--	--	--	--
Colombia	301	226	15,700	--	--	--	--	--	--
Germany	--	--	--	--	--	--	NA	433	3,850
Guyana	--	--	--	--	--	--	NA	284	2,530
India	--	--	--	NA	3,680	35,000	--	--	--
Israel	762	572	4,430	--	--	--	--	--	--
Japan	--	--	--	NA	3,570	33,900	--	--	--
Korea, Republic of	--	--	--	--	--	--	NA	45,200	402,000
Mexico	11,500	7,020	406,000	--	--	--	--	--	--
Netherlands	191,000	124,000	3,140,000	--	--	--	--	--	--
Russia	--	--	--	NA	38	5,470	--	--	--
Thailand	--	--	--	NA	24	3,120	--	--	--
Vietnam	--	--	--	NA	1,770	6,360	--	--	--
Total	241,000	159,000	4,710,000	XX	28,200	241,000	XX	142,000	1,300,000

[r]Revised. NA Not available. XX Not applicable. -- Zero.

[1]Table includes data available through July 2, 2024. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes Harmonized Tariff Schedule of the United States (HTS) code and Schedule B number 7202.92.0000.

[3]May include catalysts that contain vanadium pentoxide. Includes HTS code and Schedule B number 2825.30.0010.

[4]Includes HTS code and Schedule B number 2825.30.0050.

[5]Data suppressed by U.S. Census Bureau; not included in "Total."

Source: U.S. Census Bureau.

TABLE 4
U.S. IMPORTS AND EXPORTS OF ALUMINUM-VANADIUM MASTER ALLOY
AND VANADIUM METAL, INCLUDING WASTE AND SCRAP AND VANADIUM ORES AND CONCENTRATES[1]

(Kilograms unless otherwise specified)

	Aluminum-vanadium master alloy[2]			Vanadium metal, including waste and scrap[3]			Vanadium ores and concentrates[4]		
Country or locality	Gross weight	Vanadium content	Value	Gross weight	Vanadium content	Value	Gross weight	Vanadium content[5]	Value
Imports for consumption:									
2022	149,000	104,000	$6,870,000	33,600 r	27,900 r	$1,930,000 r	1,690,000	879,000	$7,190,000
2023:									
Belgium	--	--	--	2	1	5,950	--	--	--
Canada	--	--	--	37	37	3,650	1,430,000	743,000	6,160,000
China	333,000	218,000	15,300,000	1,450	1,220	94,800	9	3	3,400
France	--	--	--	27	23	10,200	--	--	--
Germany	14	14	35,400	19,200	18,700	1,100,000	--	--	--
Japan	1,760	1,410	96,900	4	4	2,520	--	--	--
Korea, Republic of	--	--	--	54	49	4,390	--	--	--
Mexico	439	439	20,300	--	--	--	767,000	460,000	3,610,000
Russia	1,200	1,200	191,000	--	--	--	--	--	--
United Kingdom	10	10	36,200	--	--	--	--	--	--
Total	336,000	221,000	15,700,000	20,800	20,000	1,220,000	2,200,000	1,200,000	9,770,000
Exports:									
2022	50,400	XX	2,510,000	XX	7,860	362,000	XX	331,000	1,220,000
2023:									
Australia	2,500	NA	96,400	--	--	--	--	--	--
Belgium	161	NA	6,230	--	--	--	--	--	--
Canada	--	--	--	--	--	--	NA	15,900	224,000
Colombia	4	NA	3,510	--	--	--	--	--	--
France	6,170	NA	581,000	NA	370	14,300	NA	519	6,750
Germany	628	NA	48,800	--	--	--	--	--	--
Japan	51,000	NA	1,940,000	NA	19,800	781,000	--	--	--
Latvia	--	--	--	--	--	--	NA	3,500	45,500
Lithuania	--	--	--	--	--	--	NA	127,000	444,000
Spain	84	NA	3,240	--	--	--	--	--	--
United Kingdom	3,660	NA	964,000	NA	17,500	779,000	--	--	--
Vietnam	477	NA	7,160	--	--	--	--	--	--
Total	64,600	XX	3,650,000	XX	37,700	1,570,000	XX	147,000	720,000

[r]Revised. NA Not available. XX Not applicable. -- Zero.
[1]Table includes data available through July 2, 2024. Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Aluminum-vanadium master alloy consisting of 35% aluminum and 64.5% vanadium. Includes Harmonized Tariff Schedule of the United States (HTS) code and Schedule B number 8112.99.2000.
[3]Includes HTS code and Schedule B number 8112.92.7000.
[4]Includes HTS code and Schedule B number 2615.90.6090.
[5]Reported by the U.S. Census Bureau as metric tons of vanadium pentoxide equivalent. To convert to vanadium content, multiply reported data by 0.56.

Source: U.S. Census Bureau; data adjusted by the U.S. Geological Survey.

TABLE 5

U.S. IMPORTS AND EXPORTS OF VANADIUM-BEARING ASH AND RESIDUES[1]

(Kilograms unless otherwise specified)

Country or locality	HTS codes and Schedule B numbers[2]	2022 Gross weight	2022 Vanadium content[3]	2022 Value	2023 Gross weight	2023 Vanadium content[3]	2023 Value
Imports for consumption:	2620.40.0030, 2620.99.1000						
Canada		(4)	(4)	$6,730,000	(4)	(4)	$6,610,000
China		--	--	--	666	457	2,800
Curacao		169,000	74,700	622,000	--	--	--
Kuwait		(4)	(4)	587,000	(4)	(4)	5,650,000
Russia		774,000	126,000	1,290,000	--	--	--
Vietnam		(4)	(4)	2,050,000	(4)	(4)	13,900,000
Total		944,000	200,000	11,300,000	666	457	26,200,000
Exports:	2620.50.0000, 2620.99.1000						
Australia		4,990	NA	3,000	--	--	--
Austria		--	--	--	152,000	NA	171,000
Belgium		345,000	NA	312,000	48,300	NA	230,000
Brazil		38,500	NA	4,200	--	--	--
France		147,000	NA	357,000	860,000	NA	1,450,000
Germany		85,400	NA	28,100	147,000	NA	188,000
Guadeloupe		19,100	NA	6,720	--	--	--
Italy		--	--	--	38,900	NA	200,000
Japan		410,000	NA	184,000	--	--	--
Korea, Republic of		126,000	NA	110,000	38,700	NA	56,700
Mexico		69,700	NA	888,000	65,800	NA	1,130,000
Netherlands		760,000	NA	698,000	186,000	NA	190,000
United Arab Emirates		5,770	NA	74,200	--	--	--
Total		2,010,000	XX	2,660,000	1,540,000	XX	3,610,000

NA Not available. XX Not applicable. -- Zero.

[1]Table includes data available through July 2, 2024. Data are rounded to no more than three significant digits; may not add to totals shown. Does not include U.S. Geological Survey estimates for data suppressed by U.S. Census Bureau.

[2]Harmonized Tariff Schedule of the United States (HTS) codes are imports and Schedule B numbers are exports.

[3]Data are in kilograms of vanadium pentoxide equivalent.

[4]Data suppressed by the U.S. Census Bureau; not included in "Total." See table 1 for U.S. imports and exports of vanadium-bearing ash and residues that includes U.S. Geological Survey estimates for suppressed data.

Source: U.S. Census Bureau.

TABLE 6
U.S. IMPORTS FOR CONSUMPTION OF MISCELLANEOUS VANADIUM CHEMICALS[1]

(Kilograms unless otherwise specified)

		2022			2023		
Material and country or locality	HTS[2] codes	Gross weight	Vanadium content	Value	Gross weight	Vanadium content	Value
Chloride oxides and chloride hydroxides of vanadium:	2827.49.1000						
Colombia		132,000	82,400	$109,000	582,000	363,000	$504,000
Japan		92,300	92,300	1,500,000	--	--	--
Total		224,000	175,000	1,610,000	582,000	363,000	504,000
Hydrides and nitrides:	2850.00.2000						
Austria		--	--	--	398	297	17,300
China		18,800	15,000	64,500	17	17	7,160
Denmark		40	40	4,080	--	--	--
France		3	3	2,780	--	--	--
Germany		334,000	271,000	2,830,000	165,000	133,000	1,200,000
India		17,900	14,200	70,200	--	--	--
Ireland		17	14	20,400	9,840	7,770	47,400
Israel		--	--	--	4	3	3,800
Netherlands		--	--	--	12,000	9,470	46,900
South Africa		60,700	48,000	459,000	117,000	92,100	593,000
Sweden		4,400	3,960	172,000	2,430	2,320	97,100
United Kingdom		7	7	4,200	20	20	3,180
Total		436,000	352,000	3,630,000	306,000	245,000	2,010,000
Sulfates:	2833.29.3000						
Canada		1,870	1,170	4,270	--	--	--
China		2,650	1,760	25,500	2,650	1,690	27,500
Finland		122,000	114,000	1,740,000	--	--	--
Total		127,000	117,000	1,770,000	2,650	1,690	27,500
Vanadates:	2841.90.1000						
Austria		152,000	76,800	3,360,000	--	--	--
China		5,600	4,470	141,000	30,000	22,000	569,000
Germany		--	--	--	3,600	2,260	94,300
India		--	--	--	8	5	2,320
Japan		2,540	1,650	16,900	280	187	12,100
South Africa		--	--	--	5,000	3,850	85,400
United Kingdom		14,100	9,390	306,000	908	605	20,300
Total		174,000	92,400	3,820,000	39,800	28,900	783,000
Vanadium chlorides:	2827.39.1000						
Belgium		--	--	--	31	30	2,150
Canada		--	--	--	2,540	2,420	34,200
China		2,160	2,060	164,000	4,510	4,300	525,000
France		9,210	8,770	290,000	8,480	8,080	294,000
Germany		225	214	8,290	118	118	3,650
India		500	476	32,300	--	--	--
Japan		55,400	55,400	966,000	111,000	106,000	1,750,000
Singapore		1,000	952	80,100	--	--	--
Switzerland		--	--	--	34,900	33,500	3,120,000
Total		68,500	67,800	1,540,000	161,000	154,000	5,730,000

-- Zero.

[1]Table includes data available through July 2, 2024. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Harmonized Tariff Schedule of the United States (HTS).

Source: U.S. Census Bureau.

TABLE 7

VANADIUM: WORLD PRODUCTION, BY COUNTRY OR LOCALITY[1, 2]

(Metric tons, vanadium content)

Country or locality	2019	2020	2021	2022	2023
Brazil	5,923	6,622	5,779	5,844	5,421
China	60,000	70,200	70,300	66,900	70,000 e
Russia[3]	18,380	19,533	20,058	20,000 e	20,000 e
South Africa	8,030	8,584	8,799	8,871	8,667
United States	460	17	--	--	--
Total	92,800	105,000	105,000	102,000	104,000

[e]Estimated. -- Zero.

[1]Table includes data available through June 3, 2024. All data are reported unless otherwise noted; totals may include estimated data. Totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.

[2]Production from coproduct steel slag and primary ores only. Does not include secondary vanadium production.

[3]Includes metric tons of vanadium in vanadium slag produced in Russia but processed at varying recovery rates in Austria and Russia.