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2021 Minerals Yearbook

VANADIUM [ADVANCE RELEASE]

U.S. Department of the Interior
U.S. Geological Survey

June 2025

U.S. Geological Survey, Reston, Virginia: 2025

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Vanadium

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In 2021, 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 imported feedstock for a large portion of their production. In 2021, U.S. estimated production from ash, residues, and spent catalysts was 3,200 metric tons (t) of vanadium content, a 10% increase from that in 2020 (table 1). Production and trade quantities discussed in this chapter are all based on vanadium content, unless otherwise noted. Total imports for consumption increased by 17% from those in 2020 (table 1). The United States imported 2,170 t of ferrovanadium (FeV), 1,740 t of vanadium pentoxide (V_2O_5), and 69 t of other oxides and hydroxides of vanadium, collectively valued at $137 million (table 3). The United States imported 35 t of aluminum-vanadium master alloy valued at $2.87 million (table 4). Imports of vanadium chemicals were 640 t valued at $9.19 million (table 6). The United States exported 173 t of FeV, 17 t of V_2O_5, and 235 t of other oxides and hydroxides of vanadium, collectively valued at $8.90 million (table 3). Exports of aluminum-vanadium master alloy were 129 t (gross weight) valued at $4.31 million, and exports of vanadium metal were 3.66 t valued at $154,000 (table 4). Exports of ash and residues were 1,660 t (gross weight) valued at $3.45 million (table 5). Reported vanadium consumption in the United States was 8,030 t of vanadium content, essentially unchanged from the revised reported consumption in 2020 (table 1). In 2021, estimated worldwide production of vanadium was 105,000 t, unchanged from that in 2020 (tables 1, 7).

Vanadium's main use was as a hardening agent in steel, in which 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. Catalysts are the leading nonmetallurgical use for vanadium.

Large-scale energy storage systems are growing in use owing to the increase in energy production by renewable energy sources. Although not suitable for electric vehicles and consumer electronics owing to their size, vanadium redox flow batteries (VRFBs) are being used increasingly as an alternative to lithium-ion stationary storage. VRFB energy storage systems 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 solution in different energy management strategy scenarios (American Clean Power, undated).

Government Actions and Legislation

In 2019, domestic vanadium producers AMG Vanadium LLC and U.S. Vanadium LLC requested that the U.S. Department of Commerce launch an investigation under section 232 of the Trade Expansion Act of 1962 into whether the quantities of vanadium imports into the United States threatened to impair national security. The two applicants claimed that the U.S. industry had been negatively affected by "unfairly traded low-price imports, limited export markets due to value-added tax regimes in other vanadium producing countries, and the distortionary effect of Chinese and Russian industrial policies." On May 28, 2020, the Secretary of Commerce initiated an investigation into vanadium imports. A report was completed on February 22, 2021, and based on the findings, the Secretary concluded that the present quantities and circumstances of vanadium imports did not threaten national security as defined in section 232 (U.S. Department of Commerce, Bureau of Industry and Security, 2020a, b, 2021).

Production

Industry convention for describing the production of V_2O_5 usually applies the terms primary production, joint production, and secondary production according to the raw material source for production. Primary production takes place from mined ore as mineral concentrates derived from vanadiferous titanomagnetite (VTM) and sandstone-hosted vanadium (with or without uranium). Joint production refers to vanadium slags that are produced during steelmaking. When a VTM iron ore is used to produce iron, vanadium is contained in the crude steel and must be extracted whether or not the finished steel will contain vanadium. 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; vanadium-bearing ash, residues, and slag; vanadium chemicals; and V_2O_5. V_2O_5 is the most widely produced oxide, and most V_2O_5 and vanadium trioxide (V_2O_3) are further processed into FeV.

In 2021, there were two active secondary vanadium producers (in Arkansas and Ohio) and one idle secondary producer, that had been upgrading its idled Texas facility. One vanadium converter located in Pennsylvania began toll converting small amounts of V_2O_5 into FeV after many years of being idle.

Energy Fuels Inc.'s White Mesa Mill, near Blanding, UT, had the only vanadium-uranium coproduct recovery circuit in the United States. The mill had produced approximately 20,400 t of V_2O_5 (11,400 t of vanadium content) during its

40-year operating history (Energy Fuels Inc., 2020a). However, the company produced only 17 t of vanadium content in 2020, before suspending production at the end of the first quarter owing to low prices. Energy Fuels announced that production could be stopped and started at minimal cost in response to any vanadium market changes. The company estimated that approximately 680 to 1,400 t of recoverable V_2O_5 (380 to 780 t of vanadium content) of inventory was in its tailings facility awaiting future recovery. The vanadium produced in 2019 and 2020 was a high-purity vanadium product containing 99.6% to 99.7% V_2O_5. The company did not produce any vanadium in 2021 (Energy Fuels Inc., 2020b, p. 27; 2021, p. 30, 32, 37).

In August 2021, Silver Elephant Mining Corp. completed the preliminary economic assessment for its Gibellini vanadium project in Eureka County, NV. The project was designed to be an open pit mine with a production capacity of approximately 4,700 metric tons per year (t/yr) of V_2O_5. The mine and heap-leach-processing facility was expected to produce approximately 52,000 t of V_2O_5 during its 11-year mine life. The company expected the results of the Environmental Impact Statement in early 2022 (Silver Elephant Mining Corp., 2021).

U.S. Vanadium LLC (USV) operated its facility in Hot Springs, AR, where vanadium ash, residues, and other raw materials were converted into high-purity vanadium oxides and vanadium chemicals used by the chemical, steel, and titanium industries (U.S. Vanadium LLC, undated). USV completed a $2 million expansion of its capacity to produce ultra-high-purity electrolyte used by VRFBs at its Arkansas facility. The new electrolyte production facility, in Benton, AR, was adjacent to the company's vanadium oxide production facility and, according to the company, could efficiently grind and roast vanadium feedstock in preparation for chemical processing into a wide variety of vanadium-based products. USV electrolyte capacity was approximately 4 million liters per year of electrolyte. In September 2021, USV and Enerox GmbH of Austria announced a purchase agreement for 580,000 liters of electrolyte. Enerox sold its VRBF systems under its brand name, CellCube, and was expected to install an 8-megawatthour microgrid system at its manufacturing facility in Illinois (U.S. Vanadium LLC, 2021, 2022).

AMG Vanadium, a wholly owned subsidiary of AMG Advanced Metallurgical Group N.V. (Netherlands), in Cambridge, OH, was a major producer of FeV and other ferroalloys from spent oil refinery catalysts and powerplant residues (AMG Vanadium LLC, undated). AMG Vanadium announced that its second spent catalyst recycling and ferroalloy production facility would be almost identical to its existing facility. The new facility was in Zanesville in Muskingum County, OH. The company expected the new $325 million facility to double the company's spent catalyst recycling capacity and FeV production capacity. The facility was expected to achieve full capacity in the fourth quarter of 2022 (AMG Advanced Metallurgical Group N.V., 2022, p. 2, 7, 11).

Gladieux Metals Recycling LLC continued modernizing and renovating its idle V_2O_5 facility in Freeport, TX. Gladieux purchased the facility out of bankruptcy from Gulf Chemical and Metallurgical Corp. in 2017. Gladieux was expected to produce V_2O_5 from vanadium-bearing wastes (spent catalysts) as its feedstock (U.S. Department of Commerce, Bureau of Industry and Security, 2021).

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 where 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 and estimates to account for nonrespondents are included in tables 1 and 2.

Reported vanadium consumption in the United States was 8,030 t of vanadium content, essentially unchanged from reported consumption in 2020 (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 2021, 5,320 t of FeV was consumed, representing 66% 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 is 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 2021. Nonmetallurgical applications included batteries, catalysts, ceramics, pigments, and other vanadium 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, 2020, p. 19).

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, allowing for any storage capacity to be matched with any power output capacity. However, cost, equipment, and raw material availability continued to be barriers for entry into the battery market. The vanadium used in VRFBs accounts for approximately 30% of the cost of the battery, requiring between 3 and 6 kilograms of vanadium per kilowatthour of energy storage (Bushveld Minerals Ltd., 2018, p. 25, 41; Invinity Energy Systems, undated).

Some of the U.S.-based manufacturers, all at different levels of establishing VRFB production lines, included Ashlawn Energy, LLC (Springfield, VA); Perennial Power Holdings, Inc.

(New York, NY); Primus Power Corp. (Hayward, CA); StorEn Technologies Inc. (Stony Brook, NY); UniEnergy Technologies, LLC (Mukilteo, WA); and ViZn Energy Systems Inc. (Columbia Falls, MT).

Largo Resources Ltd. (Canada) announced the launch of its new VRFB company, Largo Clean Energy (LCE), headquartered in Virginia. LCE acquired the VRFB technology from Vionx Energy Corp. and was expected to further develop and deploy a variety of VRFB systems to its customers. LCE entered its first battery sales contract with Enel Green Power Espańa (Largo Resources Ltd., 2021).

H2, Inc. (Seoul, Republic of Korea) launched a 20-megawatthour-capacity VRFB project in northern California in December 2021. The project was expected to be fully operational and participating in market opportunities through the California power grid by the end of 2023 after completion of a successful pilot phase. According to H2, the H2 VRFB project members developing the project included a South Korean state-run power generation company and the country's national research institutes, with the Government of the Republic of Korea financially backing the project (H2, Inc., 2021).

Prices

In 2021, the U.S. average monthly price for domestic FeV (80% vanadium content), as published by CRU Group, ranged from \$12.531 to \$17.300 per pound of vanadium content, compared with \$9.672 to \$13.453 per pound in 2020. The 2021 annual average for U.S. FeV (80% vanadium content) was \$15.771 per pound. In 2021, the European average monthly price for FeV (80% vanadium content) ranged from \$26.731 to \$38.900 per kilogram, compared with \$22.972 to \$28.581 per kilogram in 2020. The 2021 annual average for European FeV (80% vanadium content) was \$33.889 per kilogram. The average monthly price for Chinese V_2O_5, published by CRU Group, ranged from \$6.578 to \$9.250 per pound in 2021, compared with \$5.893 to \$9.517 per pound in 2020. The 2021 annual average for Chinese V_2O_5 was \$8.172 per pound.

Foreign Trade

Vanadium entered international trade in the form of FeV, V_2O_5, vanadium-bearing ash, residues and slag, and vanadium metal including aluminum-vanadium master alloy, waste and scrap. It is difficult to calculate the total quantity of vanadium entering international trade owing to multiple factors. First, not all countries publish data for all forms of vanadium; second, when countries do publish trade data, some data are 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 suppressed some of the data from individual countries in some of their trade reports. When data were suppressed by the U.S. Census Bureau, it has been 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. The leading vanadium-producing nations from these two sources, in descending order of vanadium content, remained China, Russia, South Africa, and Brazil.

World vanadium reserves, estimated at 24 million metric tons, are likely sufficient to meet vanadium needs into the next century at the present rate of consumption. Increased recovery of vanadium from fly ash, petroleum residues, slag, and spent catalysts was not included in the reserve estimate and was expected to significantly extend the life of the reserve. World reserves can be found in the "World Mine Production and Reserves" section of the vanadium chapter in the USGS Mineral Commodity Summaries 2022.

Global vanadium consumption was estimated to be 114,000 t (vanadium content) in 2021, an increase of 7% from that in 2020. The strong recovery from the steel sector in many regions outside of China was cited as the main reason for the increase in consumption (EVRAZ plc, 2022, p. 23).

Australia.—Neometals Ltd. announced that it expected to have a development decision by mid-2022 for its Barrambie vanadium-titanium project located approximately 80 kilometers (km) northwest of Sandstone in the State of Western Australia (Neometals Ltd., 2022, p. 2). Neometals also continued evaluation work on its Vanadium Recovery Project joint venture with Critical Metals Ltd. to construct a recycling facility to recover and process vanadium products from vanadium-bearing steel slag from Swedish steel producer, Svenskt Stal AB. The facility would include a 200,000-t/yr slag processing plant. In June 2021, Neometals began a pilot trial to recover vanadium from steel slag from three different Scandinavian sites. The pilot trial would confirm the technical feasibility of its hydrometallurgical process for recovering vanadium from steel slag. According to the company, Neometals has developed a unique alkaline leaching process that sequesters carbon dioxide as its reagent. Traditional leaching methods rely on high strength acids that generate environmentally problematic tailings (Neometals Ltd., 2021, p. 4–18, 25).

Australia Vanadium Ltd. (AVL) entered into two agreements to aid in the development of its high-grade vanadium-titanium-iron deposit in the State of Western Australia. AVL agreed to supply E22 Energy Storage Solutions (E22) (Madrid, Spain) with V_2O_5 for its global battery installations. The agreement also involved vanadium electrolyte leasing for E22's battery projects in Australia. AVL completed its bankable feasibility study for its Australian vanadium project in early 2022. The feasibility study confirmed average annual vanadium production of 11,200 t of vanadium as a 99.5% high-purity V_2O_5 flake during an anticipated mine life of 25 years. Construction was expected to commence in the fourth quarter of 2023, dependent on successful regulatory approval and financing (Australian Vanadium Ltd., 2022, p. 1–6).

In the fourth quarter of 2021, TNG Ltd. appointed a subsidiary (Clough Projects Australia Pty Ltd.) to continue to work with TNG's development team on its Mount Peake vanadium-titanium-iron project in the Northern Territory. In November, TNG completed a preliminary integrated design layout of the beneficiation plant, the processing facility, and the plant utilities. TNG also worked with METS Engineering on a process design study for a vanadium electrolyte production facility for TNG's VRFB business unit. TNG expected the integrated plant layout would continue to advance the project to develop a fully integrated single mining and processing operation to produce three high-purity products for export—V_2O_5, titanium dioxide pigment, and iron oxide (TNG Ltd., 2022, p. 1–5)

Brazil.—Largo Resources' Maracás Menchen Mine, located 813 km northeast of Brasilia, produced 10,300 t of V_2O_5 in 2021, a 13% decrease from 2020 production of 11,800 t of V_2O_5. Largo Resources produced 2,000 t of V_2O_5 in the fourth quarter of 2021, a 40% decrease from production in the first quarter of 2021. Largo Resources attributed this large decrease to abnormally elevated levels of rainfall experienced in November and December 2021. The company noted that it had implemented a water diversion channel system to mitigate any future effects of heavy rainfall. Largo Resources' production capacity of approximately 13,200 t/yr of V_2O_5 was expected to increase to approximately 15,900 t/yr of V_2O_5 owing to an expected expansion of operations to be completed by 2032 (Largo Resources Ltd., 2021; 2022, p. 1–2, 6; undated).

Largo Resources completed the construction and rampup of its V_2O_3 processing plant at its Maracás Menchen Mine in the fourth quarter of 2021. Largo Resources expected to begin shipping V_2O_3 to its customers in the first quarter of 2022. Largo Resources USA Inc., a subsidiary of Largo Resources, signed a 10-year offtake agreement with Gladieux for the purchase of all standard and high-purity grade vanadium products from Gladieux Freeport, TX, recycling facility (Largo Resources Ltd., 2022, p. 1–2).

China.—China exported 4,830 t of FeV (80% grade) in 2021, an 8% increase from that in 2020. China exported 3,820 t of V_2O_5 (98% grade) in 2021, a 16% decrease from that in 2020 (Argus Metals International, 2022a).

Chengde Iron and Steel Group Co. Ltd. and Chengde Jianlong Special Steel reduced their vanadium output from November 2021 through April 2022 following a new round of environmental protection measures in Hebei and Jiangsu Provinces and Inner Mongolia, Tibet, and Xinjiang Uyghur Autonomous Regions. Chengde was a subsidiary of China-based steel producer Hebei Iron & Steel Group Mining Co., Ltd. (Argus Metals International, 2022b).

In 2017, the China National Development and Reform Commission called for more investment in energy storage, specifically projects involving VRFBs. China's goal was to install more than 1,000 gigawatts of wind and solar power generation capacity by 2030. One such project was the vanadium energy storage project in Hubei Province. Owing to the success of its 2019 VRFB project, VRB Energy announced that it would deploy a new VRFB project at a 100-megawatt solar energy powerplant in Xiangyang, Hubei Province. The company announced that in addition to the large-scale VRFB project, it also expected to construct a VRFB manufacturing facility and a research and development institute for flow battery technology in Xiangyang. The first phase of construction began in August 2021 (Colthorpe, 2021; Sparton Resources Inc., 2021).

Some of the China-based VRFB companies included Big Pawer Electrical Technology Xiangyang Inc. Co. Ltd.; Dalian Rongke Power Co. Ltd.; LE System Co., Ltd.; Shanghai Shenli Technology Co., Ltd.; Shanxi Jinneng Century Technology Co., Ltd.; and VRB Energy. According to the company, Shanghai Shenli Technology was funded by the Ministry of Science and Technology of China and the Shanghai municipal government (Shanghai Shenli Technology Co., Ltd., undated).

Czechia.—EVRAZ Nikom had one processing facility, which was used to process V_2O_5 from Russia and China and V_2O_3 from Bushveld Minerals Ltd.'s Vametco Mine (South Africa) into FeV. The processing facility is located in Mnisek pod Brdy, 30 km southwest of Prague (EVRAZ plc, undated).

Kazakhstan.—Ferro-Alloy Resources Group (FAR) (United Kingdom) produced 260 t of vanadium content at its vanadium-processing plant in southern Kazakhstan from imported petroleum residues. FAR was expected to increase its vanadium production in 2022 by installing a third roasting oven in early 2022 (Ferro-Alloy Resources Ltd., undated).

FAR progressed on the development of its Balasausqandiq vanadium project in Qyzylorda Province, in the south of Kazakhstan. FAR expanded the feasibility study beyond the previously planned phase 1 to include phase 2 and an assessment of options to process additional valuable byproducts. According to the company, the deposit was a large black shale formation not composed of VTM and therefore could be processed by a low-cost method involving leaching in sulfuric acid made from sulfur already being removed as an impurity from oil and gas production in Kazakhstan. Phase 1 was expected to have the capacity to treat 1 million metric tons per year (Mt/yr) of ore to produce 5,600 t of V_2O_5, and phase 2 was expected to have the capacity to treat 4 Mt/yr of ore to produce 22,400 t of V_2O_5. FAR cited availability of vanadium-bearing concentrates and efficiency of recovery as two potential risks of the project. FAR was reviewing a variety of alternative supplies of vanadium-bearing concentrates and continuing to obtain long-term contracts with feedstock suppliers (Ferro-Alloy Resources Ltd., 2022, p. 4, 10–15, 18–19).

Russia.—EVRAZ Nizhny Tagil Metallurgical plant (NTMK), an integrated metallurgical complex located in Nizhny Tagil in Sverdlovsk Province, continued to be one of the world's leading processors of VTM. EVRAZ's vanadium slag production increased by 3% to 20,100 t of vanadium content in 2021. According to the company, the Vanady Tula facility, located 180 km south of Moscow, used a low-cost, highly efficient technology to process the vanadium slag produced by NTMK into FeV and V_2O_5. EVRAZ Vanady Tula's Research and Development (R&D) Center continued to focus on decreasing vanadium losses in byproducts. One of the R&D Center's goals for 2022 was to implement a vanadium recycling facility project. Another goal was to continue to focus on producing battery-grade vanadium oxides for the VRFB market (EVRAZ plc, 2022, p. 4, 48, 49, 82).

EVRAZ began construction of a $228 million vanadium processing facility at EVRAZ Uzlovaya, in Tula Province, with a design capacity of 8.6 t/yr of vanadium slag. The new vanadium processing facility would allow vanadium slag to be processed within EVRAZ, instead of having to send vanadium slag to other tolling parties. The company expected the plant to be commissioned in 2025 (EVRAZ plc, 2022, p. 27, 40).

South Africa.—Bushveld Minerals Ltd.'s facilities consisted of three mineral assets (the Brits Mine, the Mokopane Mine, the Vametco Mine) and two processing facilities (Vametco and Vanchem). Bushveld Minerals Ltd. produced 3,590 t of vanadium content in 2021, essentially unchanged from the 3,630 t of vanadium content produced in 2020. Bushveld Minerals Ltd. expected to produce between 4,200 and 4,400 t of vanadium content in 2022 on the expectation that a third kiln would come online in the second quarter of 2022 at its Vanchem facility (Argus Metals International, 2022c).

The Vametco Mine and processing facility are located in Brits, North West Province. Vametco produced 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 project was expected to be the primary source of feedstock for Bushveld Minerals Ltd.'s Vanchem facility (Bushveld Minerals Ltd., undated).

Glencore plc's (Switzerland) Rhovan vanadium facility, 30 km northwest of Brits, produced 9,300 t of V_2O_5 in 2021, compared with 8,850 t of V_2O_5 in 2020 (Glencore plc, 2022, p. 6).

Outlook

The World Steel Association forecast global steel consumption to increase by 0.4% in 2022, after increasing by 2.7% in 2021. The World Steel Association cited stronger than expected recovery from the global coronavirus disease 2019 (COVID-19) pandemic in both the European Union (EU) and the United States despite continued supply chain issues and COVID-19 pandemic outbreak. However, the strong recovery was offset by sharper-than-anticipated economic deceleration in China. The global outlook for 2022 continued to be uncertain owing to the conflict between Russia and Ukraine as well as rising inflation (World Steel Association, 2022). Because almost all vanadium is consumed in the production of steel, vanadium consumption trends are greatly influenced by trends in steel production; however, the use of vanadium in a wider range of steels is expected to gradually increase. The outlook for consumption in nonferrous alloys is largely dependent on trends in consumption for titanium alloys in business, commercial, and military aircraft.

The COVID-19 pandemic remained the overriding concern for many companies in 2021 and continued to cause great uncertainty not only in the vanadium market but in many global markets. However, many companies were able to resume pre-pandemic practices as restrictions eased, and many companies reported that they were relatively unaffected with no significant issues for production, supply, or shipments (EVRAZ plc, 2022, p. 187–188).

Consumption of vanadium by the steel industry has gradually recovered since 2020, despite a sharp decrease in the third quarter of 2021 caused by steel output restrictions imposed by the Government of China. State-owned steel mills in China had been ordered to cut steel output and exports in order to reach its carbon-reduction targets. China's steel production in 2022 is expected to be unchanged from 2021 and 2020 levels. Many steel mills in China, particularly those producing high-performance and specialty steels, have increased their usage of ferroniobium instead of FeV because ferroniobium prices have remained more stable than FeV in 2021 (Argus Metals International, 2021).

In addition to continued growth from the steel sector, one area of much anticipated growth in the consumption of vanadium is the energy storage market, specifically VRFBs. A rise in China's vanadium consumption from the VRFB is expected to increase to at least 9,100 t of V_2O_5 in 2022 compared with 3,640 t of V_2O_5 in 2021 (Argus Metals International, 2021). China alone is expected to account for almost one-half of the global increase in renewable electricity in 2021, followed by the United States, the EU, and India (International Energy Agency, 2021, p. 22). All EU countries have adopted national renewable energy action plans showing what actions they intend to take to meet their renewable energy targets. The EU has a goal to cut greenhouse gas emissions by at least 55% by 2030 (European Commission, undated). Most countries are seeking to meet renewable energy targets, and VRFB storage is proving to be a potential solution to the rapidly rising deployment of wind turbines and solar panels, with many countries having numerous implementations already underway (PRNewswire, 2022).

VRFBs have low environmental effects 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. The battery is also nonflammable. However, VRFB implementations continued to have major disadvantages including the high cost of the electrolyte used in the battery and the system complexity of the batteries. These factors make it difficult for VRFBs to compete with lithium-ion batteries. The market leader in flow battery chemistry is vanadium, but researchers continue to work on other chemistries that could potentially be less expensive. Companies are expected to continue to improve VRFBs to make them more competitive in the battery market.

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TABLE 1
SALIENT VANADIUM STATISTICS[1]

(Metric tons, vanadium content, unless otherwise specified)

	HTS codes and Schedule B numbers[2]	2017	2018	2019	2020	2021
United States:						
Production from primary ores and concentrates		--	--	460	17	--
Production from ash, residues, and spent catalysts[e]		2,600	2,600	3,000	2,900	3,200
Consumption, reported		8,000 r	9,280 r	9,900 r	7,920 r	8,030
Imports for consumption:						
Aluminum-vanadium master alloy	8112.99.2000	288	281	222	101	35
Ash and residues[3, 4]	2620.40.0030, 2620.99.1000	2,540 r	2,810 r	2,120 r	1,550 r	1,680
Chloride oxides and hydroxides of vanadium	2828.49.1000	71	477	532	736	318
Ferrovanadium[5]	7202.92.0000	2,810	2,970	2,280	1,360 r	2,170
Hydrides and nitrides, of vanadium	2850.00.2000	173	72	54	57	200
Oxides and hydroxides, other	2825.30.0050	148	98	105	67	69
Sulfates	2833.29.3000	4	9	74 r	34 r	408
Vanadates	2841.90.1000	349	389	73	104	15
Vanadium chlorides	2827.39.1000	81	45	1	11	16
Vanadium metal	8112.92.7000	54	28	45	(6)	(6)
Vanadium ores and concentrates	2615.90.6090	1 r	331 r	108 r	2 r	4
Vanadium pentoxide (anhydride)	2825.30.0010	3,400	4,600	3,620	1,670	1,740
Total imports		9,920 r	12,100 r	9,230 r	5,690 r	6,660
Exports:						
Aluminum-vanadium master alloy[7]	8112.99.2000	236	161	51	24	129
Ash and residues[3, 7]	2620.50.0000, 2620.99.1000	2,870	2,560	2,280	898	1,660
Ferrovanadium	7202.92.0000	229	575	295	210 r	173
Oxides and hydroxides, other	2825.30.0050	148	53	750	51	235
Vanadium metal	8112.92.7000	59	39	27	1	4
Vanadium ores and concentrates[7]	2615.90.6090	109	86	170	164	145
Vanadium pentoxide (anhydride)	2825.30.0010	126	563	423	50	17
Stocks, yearend:						
Ferrovanadium		166	188	197	206	209
Other[8]		61	62	60	63	62
World, production from ores, concentrates, slag[9]		87,700 r	89,800 r	92,800 r	105,000	105,000

[e]Estimated. [r]Revised. -- Zero.
[1]Table includes data available through September 9, 2022. 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 of the United States are exports.
[3]Includes HTS codes 2620.40.0030 and 2620.99.1000 and Schedule B numbers 2620.50.0000 and 2620.99.1000.
[4]Includes U.S. Geological Survey estimates for data suppressed by U.S. Census Bureau.
[5]U.S. Census Bureau has suppressed quantity data; not included in ferrovanadium total.
[6]Less than ½ unit.
[7]Gross weight.
[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, 2]

(Kilograms, vanadium content)

	2020[r]	2021
End use:		
Steel:		
Carbon	1,100,000	1,460,000
Full alloy	1,760,000	1,770,000
High-strength low-alloy	W	W
Stainless and heat resisting	87,900	88,000
Tool	W	W
Total	2,960,000	3,320,000
Cast irons	W	W
Alloys (including steels and superalloys)	2,630,000	2,640,000
Chemical and ceramic:		
Catalysts	W	W
Pigments	W	W
Miscellaneous and unspecified[3]	2,340,000	2,070,000
Grand total	7,920,000	8,030,000
Form:		
Ferrovanadium	4,860,000	5,320,000
Other[4]	3,060,000	2,710,000
Total	7,920,000	8,030,000

[r]Revised. W Withheld to avoid disclosing company proprietary data; included with “Miscellaneous and unspecified.”

[1]Table includes data available through September 9, 2022. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes U.S. Geological Survey estimates.

[3]Includes electrical steel and unspecified steel.

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

TABLE 3

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

	Ferrovanadium[2]			Vanadium pentoxide (anhydride)[3]			Other oxides and hydroxides of vanadium[4]		
Country or locality	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value
Imports for consumption:									
2020	1,890,000 r	1,360,000 r	$55,400,000 r	2,390,000	1,670,000	$36,700,000	101,000	66,500	$2,830,000
2021:									
Austria	784,000	588,000	18,300,000	--	--	--	--	--	--
Brazil	--	--	--	730,000	727,000	15,700,000	4,910	3,190	117,000
Canada	1,110,000	887,000	27,700,000	--	--	--	--	--	--
China	--	--	--	8,910	5,120	99,300	30	19	4,850
Czechia	(5)	(5)	24,400,000	--	--	--	--	--	--
Germany	--	--	--	54,500	32,800	963,000	2	2	8,070
India	961	769	29,100	--	--	--	--	--	--
Japan	40,000	16,300	474,000	--	--	--	--	--	--
Korea, Republic of	439	439	15,900	--	--	--	--	--	--
Latvia	239,000	127,000	4,070,000	--	--	--	--	--	--
Netherlands	--	--	--	10,000	9,950	264,000	--	--	--
Russia	638,000	507,000	16,400,000	394,000	358,000	3,690,000	--	--	--
South Africa	2,000	1,620	59,200	966,000	571,000	20,700,000	96,700	65,500	1,970,000
Taiwan	--	--	--	51,600	33,700	896,000	--	--	--
Ukraine	86,000	43,100	1,450,000	--	--	--	--	--	--
Total	2,900,000	2,170,000	92,800,000	2,220,000	1,740,000	42,300,000	102,000	68,700	2,100,000
Exports:									
2020	278,000 r	210,000 r	5,440,000 r	XX	49,700	497,000	XX	50,600	440,000
2021:									
Argentina	10,000	7,500	259,000	--	--	--	--	--	--
Australia	--	--	--	NA	520	24,700	--	--	--
Austria	--	--	--	--	--	--	NA	80,500	716,000
Brazil	20,000	15,000	516,000	NA	885	8,410	--	--	--
Canada	61,500	44,900	1,740,000	--	--	--	NA	58,200	628,000
Colombia	4,000	2,880	101,000	--	--	--	--	--	--
France	--	--	--	--	--	--	NA	545	4,850
Honduras	438	329	7,480	--	--	--	--	--	--
India	--	--	--	NA	9,470	90,000	NA	6,030	53,600
Italy	--	--	--	--	--	--	NA	14,400	43,900
Mexico	113,000	83,700	3,170,000	NA	50	5,820	--	--	--
Netherlands	28,200	17,000	638,000	NA	6,290	109,000	NA	45,200	402,000
Peru	1,220	912	40,000	--	--	--	--	--	--
Trinidad and Tobago	--	--	--	--	--	--	NA	30,400	321,000
United Kingdom	471	353	11,800	--	--	--	--	--	--
Total	239,000	173,000	6,490,000	XX	17,200	238,000	XX	235,000	2,170,000

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

[1]Table includes data available through June 29, 2022. 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]U.S. Census Bureau has suppressed quantity data; 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[1]

	Aluminum-vanadium master alloy[2]			Vanadium metal, including waste and scrap[3]			Vanadium ores and concentrates[4]		
Country or locality	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content (kilograms)	Value	Gross weight (kilograms)	Vanadium content[5] (kilograms)	Value
Imports for consumption:									
2020	152,000	101,000	$6,100,000	315	165	$74,800	6,770	3,760	$561,000
2021:									
Belgium	3,530	2,640	145,000	--	--	--	--	--	--
Canada	--	--	--	--	--	--	2,080	1,250	4,580
China	--	--	--	3	2	2,640	--	--	--
Czechia	--	--	--	4	4	4,730	--	--	--
Germany	5,160	4,230	784,000	972	517	242,000	--	--	--
Mexico	154	144	11,600	--	--	--	11,900	6,570	959,000
Russia	41,400	28,100	1,870,000	--	--	--	--	--	--
United Kingdom	8	8	26,500	--	--	--	--	--	--
Vietnam	76	75	35,000	--	--	--	--	--	--
Total	50,400	35,200	2,870,000	979	523	249,000	14,000	7,820	964,000
Exports:									
2020	24,400	XX	1,060,000	XX	846	35,600	XX	164,000	1,160,000
2021:									
Australia	--	--	--	NA	56	11,300	--	--	--
Austria	402	NA	15,500	--	--	--	--	--	--
Brazil	--	--	--	--	--	--	NA	227	2,950
Cambodia	--	--	--	--	--	--	NA	79,000	1,030,000
Canada	--	--	--	--	--	--	NA	155	5,130
China	518	NA	20,000	--	--	--	--	--	--
France	3,260	NA	122,000	--	--	--	--	--	--
Germany	2,010	NA	84,300	NA	3,600	143,000	--	--	--
Hong Kong	--	--	--	--	--	--	NA	812	10,600
Japan	109	NA	4,210	--	--	--	--	--	--
Lithuania	--	--	--	--	--	--	NA	4,430	57,600
Mexico	--	--	--	--	--	--	NA	9,810	127,000
Peru	27	NA	6,410	--	--	--	--	--	--
Poland	1,630	NA	62,800	--	--	--	--	--	--
Russia	99,700	NA	3,660,000	--	--	--	--	--	--
Sweden	98	NA	3,770	--	--	--	--	--	--
Switzerland	134	NA	5,170	--	--	--	--	--	--
Taiwan	157	NA	6,070	--	--	--	NA	34,800	452,000
Ukraine	--	--	--	--	--	--	NA	11,800	154,000
United Kingdom	21,400	NA	321,000	--	--	--	--	--	--
Vietnam	--	--	--	--	--	--	NA	4,310	56,000
Total	129,000	XX	4,310,000	XX	3,660	154,000	XX	145,000	1,890,000

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

[1]Table includes data available through June 29, 2022. 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]Data are in kilograms of vanadium pentoxide.

Source: U.S. Census Bureau.

TABLE 5
U.S. IMPORTS AND EXPORTS OF VANADIUM-BEARING ASH AND RESIDUES[1]

		2020			2021		
Country or locality	HTS codes and Schedule B numbers[2]	Gross weight (kilograms)	Vanadium content[3] (kilograms)	Value	Gross weight (kilograms)	Vanadium content[3] (kilograms)	Value
Imports for consumption:	2620.40.0030, 2620.99.1000						
Belgium		387,000	60,000	$482,000	--	--	--
Canada		(4)	(4)	7,160,000	(4)	(4)	$5,550,000
Netherlands		--	--	--	98,100	29,900	240,000
Oman		--	--	--	120,000	33,200	267,000
Saudi Arabia		--	--	--	70,300	4,490	36,100
Switzerland		--	--	--	43,400	5,170	41,600
Trinidad and Tobago		--	--	--	93,000	28,500	229,000
Total		387,000	60,000	7,640,000	425,000	101,000	6,360,000
Exports:	2620.50.0000, 2620.99.1000						
Belgium		238,000	NA	276,000	1,010,000	NA	1,940,000
France		48,400	NA	32,900	--	--	--
Germany		87,200	NA	118,000	284,000	NA	117,000
Guadeloupe		--	--	--	40,800	NA	14,400
Hong Kong		--	--	--	63,200	NA	36,000
India		--	--	--	20,000	NA	25,000
Italy		204,000	NA	371,000	19,900	NA	55,700
Mexico		22,300	NA	35,800	98,200	NA	1,140,000
Netherlands		264,000	NA	245,000	107,000	NA	106,000
Thailand		34,200	NA	28,700	--	--	--
United Arab Emirates		--	--	--	19,900	NA	10,000
Total		898,000	XX	1,110,000	1,660,000	XX	3,450,000

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

[1]Table includes data available through June 29, 2022. 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 quantity data suppressed by U.S. Census Bureau.

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

[3]Data are in kilograms of vanadium pentoxide.

[4]U.S. Census Bureau has suppressed quantity data; not included in "Total."

Source: U.S. Census Bureau.

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

Material and country or locality	HTS[2] code	2020 Gross weight (kilograms)	2020 Vanadium content (kilograms)	2020 Value	2021 Gross weight (kilograms)	2021 Vanadium content (kilograms)	2021 Value
Hydrides and nitrides:	2850.00.2000						
China		3,550	2,810	$17,700	--	--	--
Czechia		655	518	6,870	--	--	--
France		--	--	--	1	1	$2,190
Germany		27,900	22,800	258,000	176,000	143,000	1,220,000
Ireland		5,970	4,720	49,100	7,100	5,610	51,400
Japan		40	32	15,200	991	783	30,200
Korea, Republic of		--	--	--	7	5	23,500
Poland		1	1	9,000	19,500	19,500	36,800
Russia		3,830	3,030	15,000	--	--	--
South Africa		28,200	22,300	343,000	35,400	28,000	448,000
Sweden		860	679	30,100	4,550	3,870	160,000
Total		71,000	56,900	744,000	244,000	200,000	1,970,000
Sulfates:	2833.29.3000						
China		4,190	2,620	25,200	2,300	1,510	31,200
Finland		42,700	30,900	309,000	431,000	406,000	6,440,000
Japan		100	62	3,180	--	--	--
Total		47,000 r	33,600 r	337,000 r	433,000	408,000	6,480,000
Vanadates:	2841.90.1000						
Austria		57,100	28,900	572,000	50	22	2,500
China		2,660	2,130	66,700	13,400	10,600	255,000
Germany		11,800	6,220	165,000	7,480	4,560	124,000
India		7	3	2,080	7	3	6,140
Japan		107	73	5,980	372	207	17,800
Russia		5	2	2,200	7	5	3,560
South Africa		15,000	11,300	192,000	--	--	--
Switzerland		57,000	28,900	569,000	--	--	--
Taiwan		36,000	23,300	345,000	--	--	--
United Kingdom		7,380	3,560	115,000	--	--	--
Total		187,000	104,000	2,030,000	21,300	15,400	408,000
Vanadium chlorides:	2827.39.1000						
Belgium		2,630	2,510	35,500	--	--	--
China		--	--	--	8,000	7,620	76,800
France		8,550	8,140	282,000	8,430	8,030	242,000
Germany		--	--	--	400	381	15,800
Total		11,200	10,600	318,000	16,800	16,000	335,000

[r]Revised. -- Zero.
[1]Table includes data available through June 29, 2022. Data are rounded to no more than three significant digits; may not add to totals shown.
[2]Harmonized Tariff Schedule of the United States.

Source: U.S. Census Bureau.

TABLE 7
VANADIUM: WORLD PRODUCTION, BY COUNTRY OR LOCALITY[1, 2]

(Metric tons, vanadium content)

Country or locality	2017	2018	2019	2020	2021
Brazil	5,206	5,500	5,923	6,622	5,779
China	55,900 r	59,500 r	60,000 r	70,200 r	70,300 e
Russia[3]	18,636	17,052	18,380	19,533	20,058
South Africa	7,959	7,700	8,030	8,584	8,799
United States	--	--	460	17	--
Total	87,700 r	89,800 r	92,800 r	105,000	105,000

[e]Estimated. [r]Revised. -- Zero.
[1]Table includes data available through May 25, 2022. 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 vanadium in vanadium slag produced in Russia but processed at different recovery rates in Austria and Russia.