Alberto Cremona, Oliver Richter
Clariant Prodotti (Italia) SpA, Novara (I)
alberto.cremona@ngi.it

http://dx.medra.org/10.17374/CI.2026.108.2.67

VANADIUM PERSPECTIVES

Vanadium, a transition metal with particular physico-chemical properties, is a key critical element playing an important role in the production of steel, batteries, and catalysts. The present article aims at a concise update concerning main current and future uses, production, reserves, and recycling prospects.

Vanadium is a refractory metal which has seen continuous growth for application in high-strength steel, titanium alloys, batteries, and catalysts: the global market, although difficult to estimate due to absence of a harmonized custom code, was around US$ 2.8 billion in 2022 and is expected to reach nearly US$ 4 billion by 2028 growing at a CAGR of approximately 5% [1].
The crustal concentration of the element is relatively high, around 0.02%. It is the first metal of group V of the periodic table, and the electronic configuration of the atom ground state is $[Ar]3d^3 4s^2$: the oxidation states from +2 to +5 are the most common and enable redox chemical reactions for different uses [2].
The metal is steel gray with a blue shade, and its compounds display a wide chromatic range justifying the name after Vanadis, the Scandinavian goddess of beauty. It is malleable, ductile, and soft in a pure form, although impurities usually have a hardening and embrittling effect; it has a high melting point (1910 °C), a good corrosion resistance at room temperature due to the formation of a protective oxide film on the surface, and stability against alkalis, sulfuric and hydrochloric acids [3].
Although no vanadium-specific industry group exists, the Vanadium International Technical Committee (Vanitec), established since 1972 and headquartered close to London (UK), is a global, not-for-profit organization whose members include the world's major vanadium stakeholders [4].
Vanadium is not traded on any commodity exchange and prices are opaquely settled in private negotiations: thus, in absence of benchmarks, indicative prices are published by trade organizations based on contracts negotiated between suppliers, consumers and traders [5].
Over the past two decades the market has swiftly reached a global size, shaped by major interests across the entire value chain: the present note aims at a concise overview about uses, production, market, and resources.

Uses

The global output of vanadium in 2024 (in terms of metal) was over 129,000 tons, representing a year-on-year growth over 7% at a slight deficit with respect to estimated consumption. Production has been maintaining a rising trend despite the impact of pandemics, inflation, stagnation, and regulations. In 2019, output surpassed 100,000 tons for the first time and a percentage increase over 25% was registered over 4 years: until 20 years ago annual production was less than 40,000 tons [6].
Vanadium from various sources is converted into vanadium pentoxide and trioxide, which are the feedstock to produce ferrovanadium (92% of consumption), the ferroalloys, and vanadium nitride (VN), with a smaller proportion used to produce high-purity vanadium compounds.
Global consumption in 2022 by sector was 89% steel, 4.3% energy storage, 3.9% chemicals & catalysts, and 2,8% titanium alloys: although its use in energy storage is small, the growth from 2021

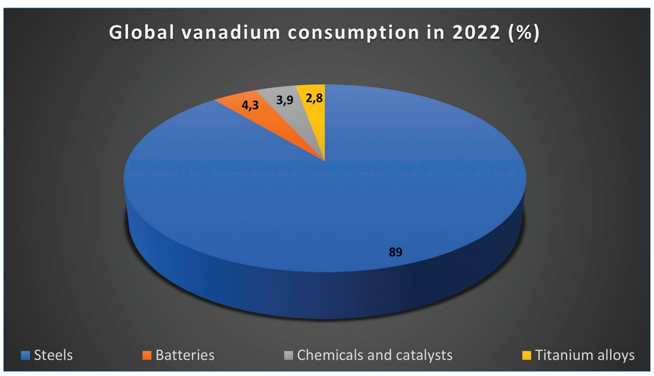

Fig. 1 - Global vanadium consumption, in % (from https://vanitec.org/)

to 2022 marked a 42% year-on-year increase and is forecast to continue (Fig. 1) [7]. High-strength low-alloy (HSLA) steels are by far the largest market and account for over 50% of consumption. In steel applications, even a low concentration around 0.1 wt% of vanadium imparts toughness, strength, wear resistance, anti-corrosion, and anti-oxidation properties: its properties were exploited on an industrial scale in automobile manufacturing since 1908 and today titanium alloys are the materials with the best strength-to-weight ratio. End-use markets include automotive, aerospace, construction, pipelines: therefore, consumption is also linked to building regulatory codes (e.g., new vanadium-bearing reinforcing bars (rebar) Chinese standards in September 2024) and the defense sector. The same fields will influence future demand, and steelmaking will continue to dominate driven both by consumption and content of high strength steels [8].
Decarbonization efforts are expected to promote use in two directions: use of a lower carbon steel and integration of clean energy with a rechargeable battery called vanadium redox flow battery (VRFB). VRFBs store surplus energy during peak electricity production, allowing discharge when renewable production is low. They were first successfully tested in the 1980s but spread only in the last decade due to several advantages including capacity, durability, sustainability, and safety compared with lithium batteries; capital costs and the requested high purity vanadium so far prevented significant diffusion but growth in the next years is expected to exert a significant impact also on metal prices [9].
Chemical end-uses are mature markets, and vanadium oxides are used as catalyst in the production of sulfuric acid, maleic and phthalic anhydrides, ethylene-propylene rubbers, polyethylene, flue gas desulfurization, and denitrification of stationary and mobile sources by selective catalytic reduction. Specific catalytic properties relate to its ability to stabilize in different oxidation states and to the reversible loss of oxygen with formation of metastable vacancies behaving as active sites: the heterogeneous catalysis of sulfuric acid, maleic, and phthalic anhydrides syntheses will be briefly described [10].
Sulfuric acid is one of the world's largest-volume industrial chemicals and its synthesis possesses an historic importance in chemistry and catalysis. Due to its vast applications, the global demand for sulfuric acid reflects industrial progress and global consumption stood around 300 million metric tons in 2023, with predominant use in production of phosphate and sulfate fertilizers. Sulfuric acid is mostly generated by burning sulfur dioxide from sour oil and gas processing in the "contact" process with conversion of SO_2 to SO_3 and subsequent absorption in H_2SO_4. The reaction scheme is the following:

$$SO_2 + 1/2O_2 \rightleftharpoons SO_3$$
$$SO_3 + H_2O \rightleftharpoons H_2SO_4$$

Platinum and iron oxide were the first catalysts to be used in the first step, but vanadium pentoxide catalysts were developed since the 1920s and have been employed exclusively ever since. In the late 1980s, cesium-promoted catalysts were introduced, allowing conversion at a lower temperature. The active phase, a mixture of vanadium pentoxide with alkali metal sulfates, is present under operation conditions in the liquid state in the pores of an inert support and the mildly exothermal reaction involves a redox cycle of the couple V^{5+}/V^{4+}.
Commercial catalysts usually contain 6-9 wt% V_2O_5 promoted by alkali-metal sulfates (usually K_2SO_4 with a K/V atomic ratio of 2-4) and deposited on diatomaceous-earth or precipitated silica gel.
The industrial reaction is divided into several adiabatic stages (in general four or five) with intermediate cooling. Gas containing between 9-11% v/v sulfur dioxide and about 10% v/v oxygen is passed through several converters in series in the temperature range 450-550 °C with an overall conversion higher than 99%. Typical poisons are water vapor, arsenic, and halogens and the average service life up to 10 years requires more than 2,000 metric tons of yearly vanadium demand [11-13].
Maleic anhydride (MA) global production totalled over 1.7 million metric tons in 2024, and its largest market is for unsaturated polyester resins, followed by 1,4-butanediol (BDO), specialty acids, lubricating oil additive, and biodegradable aliphatic polyesters. From the 1930s until the mid-1970s, MA was produced primarily by oxidation of benzene; since then, n-butane became the preferred path-

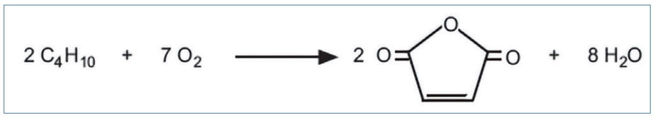

Fig. 2

way due to cost, toxicity, carbon selectivity, and product quality: by the mid-1980s it was the only feedstock in the USA.
Both routes employ vanadium-based catalysts and today the n-butane method by vapor-phase oxidation in a fixed-bed reactor has over 90% of the market, typically in upward flow configuration [14].
The highly exothermic reaction is reported in Fig. 2.
The complex chemistry involves the transfer of 14 electrons with extraction of eight H atoms and insertion of three O atoms accompanied by ring closure. Redox mechanisms are involved with both activated and surface lattice oxygen: surface available redox pairs are considered at a molecular level to differentiate between n-butane activation and the selective oxidation to the desired product.
The reaction occurs over a vanadium–phosphorus oxide (VPO) with a feed concentration around 2% v/v of butane in air, and the temperature is controlled around 380-420°C: at a space velocity around 1,700 h^{-1}, n-butane conversion around 85% is achieved with an overall MA molar yield between 60–65%. The VPO catalyst is composed of low surface-area (10-20 m^2/g) vanadyl pyrophosphate $(VO)_2P_2O_7$ with different promoters such as Fe, Cr, Ti, Co, Ni, Nb, Bi, and Mo.
The principal routes of catalyst deactivation are crystallization of the amorphous phase, accumulation of carbonaceous species, over-reduction, over-oxidation, and loss of phosphorus: to the purpose, a phosphorus-containing compound is added at parts per million levels directly to the oxidation reactor to provide phosphorus replenishing. Also poisoning by sulfur and chlorides might constitute a problem at parts per million level. The lifetime typically ranges between 3-5 years before replacement becomes necessary with a globally installed capacity reaching 1,600 tons vanadium [15-16].
Phthalic anhydride (PA) finds extensive application for plasticizers, alkyd resins, and unsaturated polyester resins: global production was about 3.8 million metric tons in 2022. The main differences of the various vapor phase processes are relative to catalysts, raw material, and reactor design and today over 90% of the world's PA capacity is produced by o-xylene oxidation, a process introduced in the mid-1950s followed by development of a vanadium pentoxide/titanium dioxide catalyst supported on an inert ceramic carrier [17].

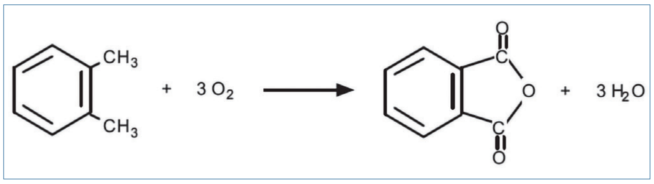

Fig. 3

The strongly exothermal reaction is represented in Fig. 3.
The industrial process is conducted in fixed bed tubular reactors slightly above ambient pressure, at temperatures from 390 to 450 °C, and o-xylene feed concentrations between 0.5 and 1.8 v/v % in air. Nowadays, each reactor comprises up to five catalysts layers each with a specific composition to reach an overall o-xylene conversion over 99.9% and molar selectivity around 83%.
The commercial catalyst is a shell type with the active mass coated at 6 to 20 wt% on hollow ceramic cylinders and vanadium content of the active mass ranges from 4 to 10 wt%. The active VOx species are formed on the anatase support during in-situ calcination, start-up, and break-in period and also depend on the interaction with several promoters such as Cs, Nb, P, and Sb: the reduced shell thickness obtained by molecular engineering allows an increase of selectivity, yield and stability.
Deactivation phenomena comprise poisoning, over-reduction of vanadium oxide species, coke formation, sintering and transformation of the TiO_2 anatase phase into the catalytically inactive rutile phase. Catalyst lifetime typically extends up to five years depending on the operative conditions and yearly vanadium demand is limited to less than 5 tons [18-20].
The last mention in catalysis is for the unique characteristics of Ziegler-type vanadium catalysts for olefin polymerization: although long known, during the last decades vanadium chemistry developed into a key component of organic synthesis due to the rich redox activity displayed by their complexes [21].

Fig. 4 - Cluster of vanadinite crystals from Mibladen mine (Morocco). Photograph by R.M. Lavinsky, distributed under a CC-BY 3.0 license

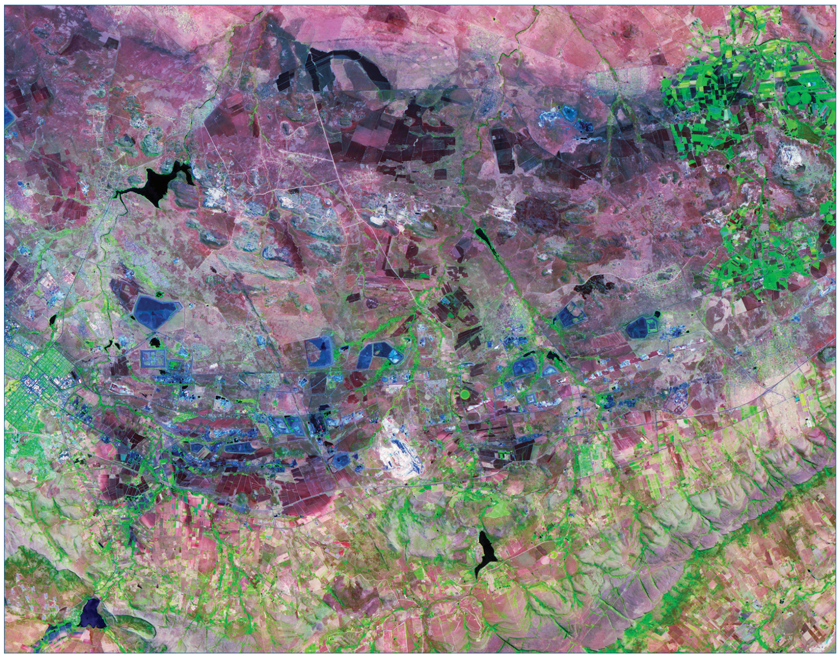

Fig. 5 - Satellite image of the Bushveld Igneous Complex (South Africa) in 2006. Courtesy of NASA/METI/AIST/Japan Space Systems and U.S./Japan ASTER Science Team

Production & Market

The diversity of vanadium sources is wide but, despite a relative diffusion, concentrated deposits are rare. It is associated as a secondary phase with iron, titanium, aluminum, zinc, lead, and uranium in about 150 minerals with the most economically relevant including magnetite (Fe_3O_4), vanadinite [$Pb_5(VO_4)_3Cl$] (Fig. 4), carnotite [$K_2(UO_2)_2V_2O_8 \cdot 3H_2O$], and patronite VS_4 [22].

The major extractive share (70% in 2022) is held by co-/by-production of slag produced in iron or steel processing. The slag is usually composed of oxides such as Fe_2O_3, CaO, SiO_2, and MgO and 10-20% vanadium pentoxide (V_2O_5). Due to its ancillary role, price or demand for vanadium does not affect supply in the short term and issues may arise by the complex relation between supply (as a co-/by-product from steelmaking) and demand (~90% of vanadium is used in steel manufacturing). Primary production (*i.e.*, direct mining of vanadium as the main product) held another 17% of the share and mining capacity is unresponsive to changes in demand on account of dependence on the steel market economics. The predominant ore (~90%) for the two routes is vanadiferous titanomagnetite, a deposit of magnetite (Fe_3O_4) in which the trivalent iron is occasionally substituted by vanadium or titanium. Co-/by-production deposits have a V_2O_5 grade between 0.2 and 1%, while higher-grade primary deposits may have V_2O_5 levels exceeding 2% [23-25].

Secondary production (13% share in 2022) involves the recycling of spent catalysts, residues from alumina or uranium production, or ash derived from burning vanadium-bearing coal or petroleum. A further estimated 100,000 tons of vanadium oxide per year are released in the environment by burning fossil fuels with sensible toxicological issues.

The three routes use similar multistep extraction and refinement techniques. After smelting the crushed ore, salt roasting takes place with a sodium compound to produce sodium metavanadate ($NaVO_3$), transforming insoluble low-valence vanadium into a soluble high-valence compound. After leaching with water and treatment with sulfuric acid, a polyvanadate ("red cake") precipitates and on fusing at 700 °C it gives a black, technical grade vanadium pentoxide that can be reduced in an electric furnace mostly in the presence of iron or iron ore to produce ferrovanadium (*e.g.*, FeV80 where the double digit number denotes the vanadium percentage content) [26].

Vanadium production is geographically concentrated. In 2023, China was by far the leading producer with two thirds of global production (about 66% with a low export share), followed by Russia (19%), South Africa (9%), and Brazil (6%) (Fig. 5). Until the 1980s, South Africa's output amounted to about 35% of world production and today remains the largest primary producer, with the Bushveld Complex one of the highest-grade deposits. Despite being a new player since the mid-2010s, Brazil is the world's largest exporter, while the USA are world's major secondary producer due to massive oil refining capacity. Vanadium production does not significantly contribute to the economy: in 2020, the vanadium market represented about 0.09% of the total South Africa exports, 0.06% for Brazil, 0.03% for Russia and less than 0.002% for China [27].

In 2024, Asia/Pacific accounted for a dominant demand driven by rapid industrialization and infrastructure development: China is also a top importer of the metal and accounts for over 60% of worldwide consumption due to its enormous rise in steel and construction sectors, followed by Europe (12%), North America (10%), Japan (4%), and India (3%).

In the last years the market saw cycles of deficit followed by oversupply, with price fluctuations also influenced by environmental and trade policies: the highest peak occurred during 2018-2019 due to China's shift toward environmentally friendly mining practices and the introduction of new high-strength rebar standards.

Global reserves are estimated around 18 million tons, almost totally distributed in Australia (47.2%), Russia (27.8%), and China (22.8%): the major share lies in a country where several projects started already since 1999, but production is still negligible (Fig. 6). Geopolitical polarity contrasts with the reassuring burn-off time around 140 years (defined as the ratio between proven reserves and average annual mining rate at the current consumption rates) [28, 29].

In principle, the element can be substituted with difficulty in steel applications by titanium, niobium, or manganese, but it is irreplaceable in aerospace titanium alloys; platinum and nickel might represent alternatives for some catalytic applications.

Due to unique properties and deposit localizations, Japan (1983), European Union (2017), United States (2018), China (2023), Canada (2023), and Australia (2024) included vanadium in the list of critical materials. Today there is no production and trade for vanadium ores and concentrates in the EU, although until the 1980s Finland and Norway produced around 10% of world output. Remarkably, the EU leading import source of vanadium oxides in 2024 was still Russia with nearly 50% of the share, thus maintaining a role played during the past decade [30-32].

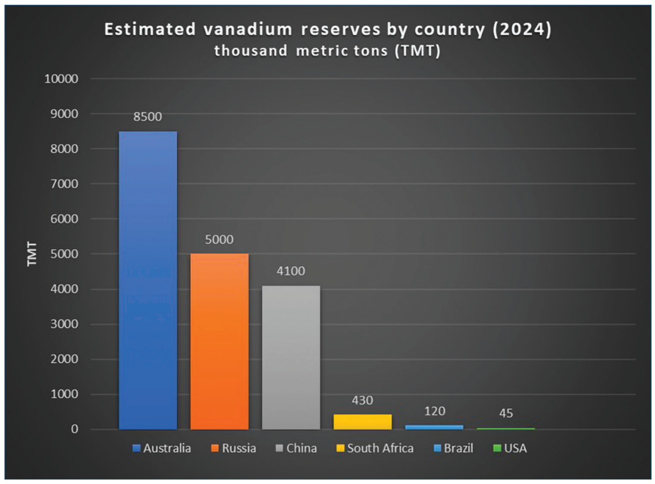

Fig. 6 - Vanadium reserves in thousand metric tons (from U.S. Geological Survey, Vanadium, Mineral Commodity Summaries, January 2025)

Recovery & Sustainability

Main secondary vanadium sources are steel scrap, chemical process catalysts, petroleum residues, utility ash, and vanadium-bearing pig iron slag. In the case of steel, the status is common with molybdenum, manganese, and nickel, a group of metals employed in the production of steel: operations exploit an efficient network of collectors and companies utilizing the steel scrap as a valuable raw material. However, most vanadium recycling can only be evaluated indirectly: vanadium-containing steel is normally undifferentiated by iron scrap and is not separated by the global pool since there are significant specific cost and energy challenges. Therefore, although as mentioned a global figure for secondary production of vanadium was estimated around 13% in 2022, recycling data vary widely and are unsuitable for productive planning: for example, in the EU an end-of-life recycling input rate of 44% was reported in 2017 and in China a recycling rate of 28% is obtained mainly from catalysts and colorants [33-36].

Spent vanadium catalysts represent a valuable secondary raw material due to higher concentrations and lower extractive costs than natural deposits. The sector is not limited to the spent catalysts comprising the metal in the original composition, but especially concerns over 150,000 tons of spent hydrotreatment catalysts generated annually and containing from 6 to 25 wt% V_2O_5 (conservatively around 10% of global vanadium output) along with other strategic metals, whose recovery, dictated by environmental concerns and economic opportunities, could significantly be increased by vertical integration in oil refineries. Several hydro- and pyro-metallurgical processes are applied in which the metals are recovered as mixed solutions and then separated through conventional separation techniques (solvent extraction, selective precipitation, and ion-exchange). Pyrometallurgical methods are similar to the usual extractive techniques and involve roasting with a sodium salt at 600-800 °C, leaching, removal of impurities by solvent extraction and/or ion exchange with final precipitation of V_2O_5. Hydrometallurgical processes involve leaching with alkaline (sodium hydroxide, sodium carbonate, ammonia) or acidic solutions (sulfuric, nitric, hydrochloric, oxalic acids): alkaline leaching is selective for vanadium but more expensive in terms of reagents [37, 38].

Flow vanadium batteries are of recent introduction and recycling operations have a limited degree, but the used metal should be easy to manage.

Under the growing pressure of political instabilities, specific recycling and sustainable recovery processes should be promoted to mitigate the widespread supply risk of this specialty element.

REFERENCES

[1] https://www.prnewswire.com (accessed on 07/07/2025).
[2] R.J.H. Clark, D. Brown, The Chemistry of Vanadium, Niobium and Tantalum, Pergamon, 1973, 494.
[3] F. Cardarelli, Materials Handbook, 3rd edition, Springer, 2018, 470.
[4] https://vanitec.org/ (accessed on 07/07/2025).
[5] Vanadium, Commodity Research Note, SP Angel, Q1 2018.
[6] J. Wang *et al., Journal of Cleaner Production*, 2024, **476**, 143721.
[7] Energy storage now the second largest consumer of vanadium, Press release, Vanitec, 1st June 2023.
[8] Largo Physical Vanadium, Project Blue, December 2022.
[9] Circular Business Model for Vanadium Use in Energy Storage, World Bank Group, 2023.
[10] M. Sutradhar *et al.*, Vanadium Catalysis, Royal Society of Chemistry, 2021, 3.
[11] Sulfuric acid, CEH, S&P Global, December 2023.
[12] H.F. Rase, Handbook of Commercial Catalysts - Heterogeneous Catalysts, CRC, 2000, 221.
[13] M.V. Twigg, Catalyst Handbook, 2nd Ed., Wolfe Publishing, 1989, 503.
[14] Maleic Anhydride, CEH, S&P Global, February 2025.
[15] G. Centi *et al., Chemical Reviews*, 1988, **88**, 55.
[16] J. Ihli *et al.*, *ACS Catalysis*, 2021, **11**, 8274.
[17] N. de Munck *et al.*, Industrial Arene Chemistry: Markets, Technologies, Sustainable Processes and Cases Studies of Aromatic Commodities, 1st Ed., J. Mortier (Ed.), Wiley-VCH, 2023, 1153.
[18] Phthalic Anhydride, CEH, S&P Global, July 2023.
[19] O. Richter, G. Mestl, *Catalysts*, 2019, **9**, 435.
[20] O. Richter *et al.*, Industrial Arene Chemistry: Markets, Technologies, Sustainable Processes and Cases Studies of Aromatic Commodities, 1st Ed., J. Mortier (Ed.), Wiley-VCH, 2023, 1203.
[21] R.R. Langeslay *et al., Chemical Reviews*, 2019, **119**, 2128.
[22] A.H. Ibrahim *et al., Recycling*, 2025, **10**, 6.
[23] K.E. Rodby *et al., Journal of Power Sources*, 2023, **560**, 232605.
[24] B. Yang *et al.*, Vanadium - Extraction, Manufacturing and Applications, Elsevier, 2021.

[25] F. Gao *et al., Mineral Processing and Extractive Metallurgy Review*, 2022, **43**, 466.
[26] D. Rappleye, R. Haun, *Journal of Sustainable Metallurgy*, 2021, **7**, 755.
[27] **https://scrreen.eu/wp-content/uploads/2024/01/SCRREEN2_factsheets_VANADIUM-update2.pdf** (accessed on 07/07/2025).
[28] Vanadium, Mineral Commodity Summaries, U.S. Geological Survey, January 2025.
[29] Outlook for Selected Critical Minerals - Australia 2021, Australian Government, 2021.
[30] D. Wu *et al., Resources, Environment and Sustainability*, 2025, **19**, 100188.
[31] M. Grohol, C. Veeh, Study on the Critical Raw Materials for the EU, Publications Office of the European Union, 2023.
[32] G.J. Simandl, S. Paradis, *Applied Earth Science*, 2022, **131**, 218.
[33] M. Petranikova *et al., Waste Management*, 2020, **113**, 521.
[34] J. Lee, *Journal of Materials Research and Technology*, 2021, **12**, 343.
[35] T.C. Goonan, Vanadium Recycling in the United States in 2004, U.S. Geological Survey, October 2011.
[36] H.U. Sverdrup, A.H. Olafsdottir, *Resources, Environment and Sustainability*, 2023, **13**, 100121.
[37] M. Marafi *et al.*, Handbook of Spent Hydroprocessing Catalysts, 2nd Ed., Elsevier, 2017, 311.
[38] R. Adavodi *et al., Separation and Purification Technology*, 2025, **363**, 132020.

Vanadio prospettive

Il vanadio, metallo di transizione dalle particolari proprietà fisico-chimiche, è un elemento chiave critico che svolge un ruolo importante nella produzione di acciaio, batterie e catalizzatori. Il presente articolo propone un sintetico aggiornamento su principali usi attuali e futuri, produzione, riserve e prospettive di riciclo.