BMAC Battery Metals Association of Canada

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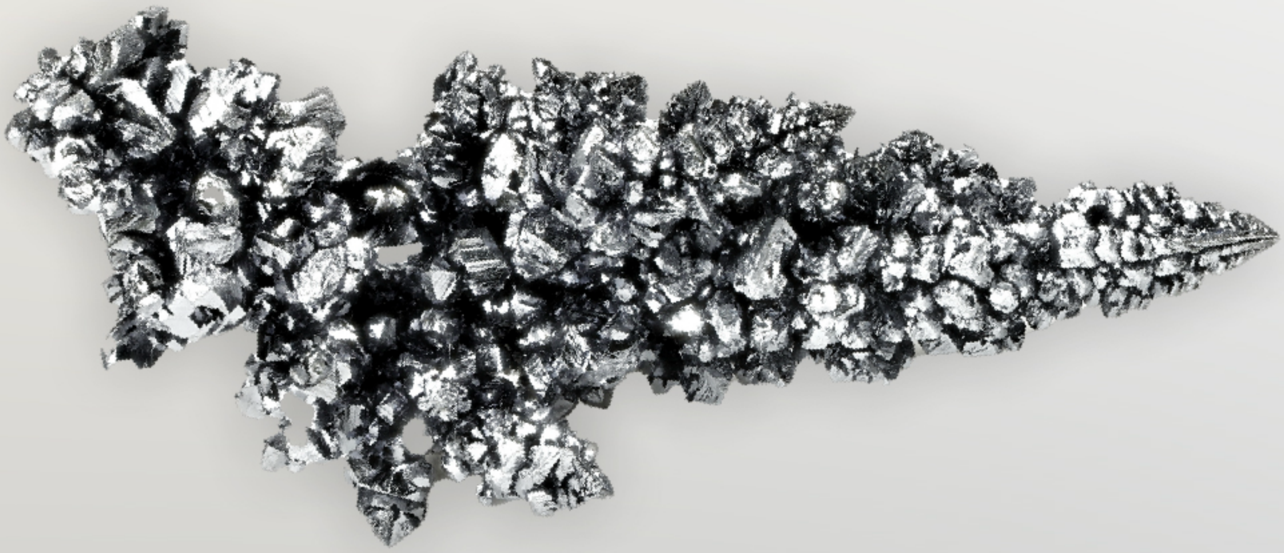
FOCUS ON

VANADIUM



FROM

ROCKS

TO

POWER

Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, & Beyond

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From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond

Focus on Vanadium

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About Us

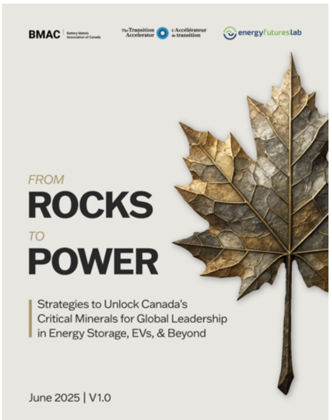
The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and connecting the segments of this value chain, ensuring Canada captures the economic potential of the sector and is able to attain its electrification targets. Together, our members collaborate to accelerate the development of the battery metals ecosystem in Canada.

The Transition Accelerator drives projects, partnerships, and strategies to ensure Canada is competitive in a carbon-neutral world. We're harnessing the global shift towards clean growth to secure permanent jobs, abundant energy, and strong regional economies across the country. We work with 300+ partner organizations to build out pathways to a prosperous low-carbon economy and avoid costly dead-ends along the way. By connecting systems-level thinking with real-world analysis, we're enabling a more affordable, competitive, and resilient future for all Canadians.

The Energy Futures Lab is an award-winning, Alberta-based not-for-profit that brings together a diverse network of innovators, influencers, and system actors from across Canada's energy landscape. Established in 2015, the Lab was created to address growing polarization around Canada's energy transition and respond to its most pressing challenges.

Through trusted leadership and creating non-partisan spaces for collaboration, the Lab convenes stakeholders and Rights and Title Holders to generate and test innovative, enduring solutions to complex, system-level issues. By empowering communities and change-makers to work across divides, the Lab fosters the conditions for meaningful progress toward a shared vision of a resilient and sustainable energy future.

About This Report

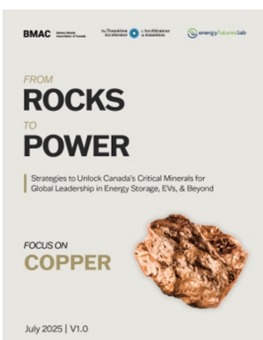


This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy storage value chains. By looking at specific opportunities and providing detailed justifications for its recommendations, *From Rocks to Power* offers a way out of our perpetual planning cycle and towards a new momentum for Canada's critical minerals sector—and our future economic prosperity.

Read the full report here »

Additional chapters are available for download below:

Copper »



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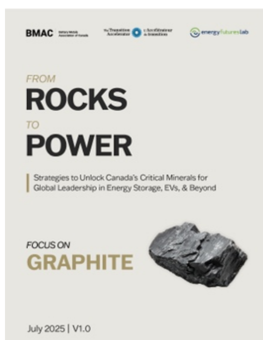

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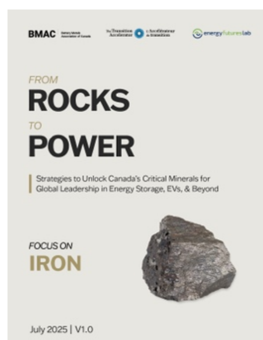

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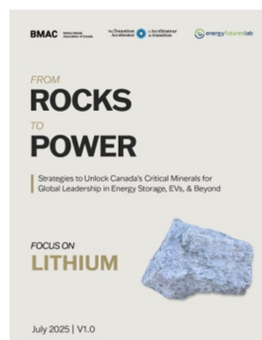

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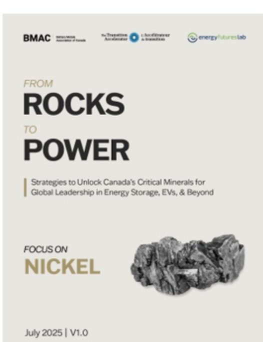

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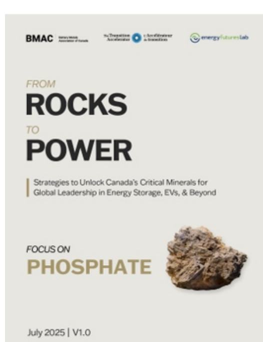

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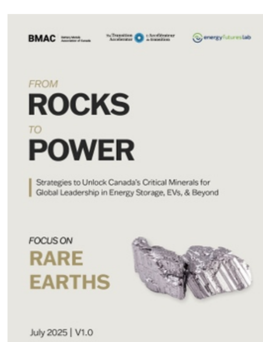

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Vanadium

1 The Canadian Vanadium Strategy

1.1 Vanadium in Canada

Table 1 Non-exhaustive selection of former and future vanadium extraction and processing projects in Canada

Selection of Former or Future Vanadium Extraction Projects				
Site Name	**Company**	**Province**	**Type**	**Status**
Alberta Vanadium Project	Suncor	AB	Petroleum Fly Ash	Unknown
Athabasca Oil Sand	Shell	AB	Petroleum Fly Ash	Unknown
Huzyk Creek	Vanadian Energy Corp	MB	Vanadadium-graphite	Exploration
Duddridge Lake	Searchlight Resources	SK	Carnotite	Exploration
BlackRock	Strategic Resources	QC	Titanoferous magnetite	FS 2022
Lac Doré	VanadiumCorp	QC	Titanoferous magnetite	PEA 2017, Resource Estimates 2020
Iron-T	VanadiumCorp	QC	Titanoferous magnetite	Exploration
Selection of Operational & Future Vanadium Processing Facilities				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Val-des-Sources (Demonstration)	VanadiumCorp	QC	Electrolyte	Operational since 2024
Sherbrooke (Commercial)	VanadiumCorp	QC	Electrolyte	2026
Saguenay Merchant Pig Iron Plant	Strategic Resources	QC	Ferrovanadium	2028+
Selection of VRFB Manufacturers operating in Canada				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Vancouver VRFB plant	Invinity	BC	VRFB	Operational since 2023
VRB Energy Vancouver	VRB Energy	BC*	VRFB	Founded in 2007

*VRB Energy is a Vancouver-based company with manufacturing and engineering subsidiaries in China

No vanadium is currently produced or separated in Canada, but several opportunities, such as the oil sands in Alberta, uranium ores in Saskatchewan or several titanomagnetite deposits in Quebec, are of interest for primary resources.

A 2005 study already showed that vanadium could be recovered from Suncor's and Syncrude's fly ash samples originating from oil sands operations in Alberta.[1] More recently, vanadium recovery attracted the attention of several oil sand companies from Alberta in the early 2020s, as Shell previously worked on a research project, and Suncor had plans to develop a commercial plant. With funding from Alberta Innovates and the Alberta Government, Shell previously led research in collaboration with the Athabasca Oil Sands Project, the University of Calgary and the University of Alberta to separate vanadium from oil sands-sourced bitumen, projecting to use it for VRFB.[2,3] Suncor previously planned to open a commercial-scale vanadium recovery facility, using by-products from coke-based boilers as a feedstock. The projected operation, dubbed Alberta Vanadium Project (AVP), was reported to require a total investment cost of $36 million, of which Emissions Reduction Alberta would provide $7 million of government funding.[4] It is unclear if those projects are cancelled or paused at the moment.

The Duddridge Lake deposit north of La Ronge, Saskatchewan, has the potential to co-produce vanadium with uranium, cobalt, and copper.[5]

In Quebec, VanadiumCorp is developing two mining projects containing vanadium-bearing titanomagnetite, the Lac Doré and Iron-T properties. The main Lac Doré project has notably 1.49 billion pounds of indicated and measured V_2O_5 concentrate from the mineral resource estimate, and mine development is projected to start in 2029 with a scoped production life of 40 years.[6] This company also plans to venture into the **vanadium electrolyte manufacturing** segment by opening **two plants in Quebec**: one located in Val-des-Sources has been operational since April 2024 and is expected to produce 300,000 litres of electrolytes per year, while a second plant in Sherbrooke is planned to produce 4 millions litres of electrolytes per year in 2026, with goals to produce 26 million litres per year by 2028.[7] The company secured a $500,000 grant for the Val-des-Sources plant from PRIMA Québec.[8]

VRB Energy is a Vancouver-based company founded in 2007 and with manufacturing and engineering subsidiaries in China. It is majority-owned by Ivanhoe Electric, a U.S.-based critical mineral exploration and development company. VRB Energy previously agreed to build in 2021 **100 MW/500 MWh energy storage station** integrated with a solar power station in Hubei, China.[9] As of 2025, it appears that its headquarters have been relocated from Vancouver to Tempe, Arizona. They plan to open two additional factories in China and one in Arizona.

Invinity has built an **8.4 MWh VRFB facility paired with a 21 MWp solar PV plant** deployed by Elemental Energy in Chappice Lake, Alberta in September 2023.[10] This plant was used for solar shifting, which is storing excess energy by solar generation during the daytime and discharging electricity into the evening or when the demand is high. This $45M project was funded by Elemental Energy, the Cold Lake First Nation, the National

Bank of Canada with additional support from Emissions Reduction Alberta and Natural Resources Canada.[11]

Moreover, Invinity opened a **manufacturing facility in Vancouver** in June 2023, thus reinforcing its Baojia production plant in Suzhou, China. This plant has the capacity to produce 200 MWh of VRFB per year.[12] The BC Centre for Innovation and Clean Energy (CICE) also announced $0.5 M funding to support Invinity's next-generation VRFB product, coined Mistral.[13] The company employs over 150 people and is based in the UK and Canada. It has 82 projects across 15 countries.[14]

Vanitec accounts for 33 vanadium projects that are under development or operational in Canada. This includes 24 mining projects, 4 chemical or metallurgical facilities, and 5 energy storage stations.[15]

1.2 Scenario Outline

Canada should leverage its assets by prioritizing vanadium recovery, processing and VRFB production in the Alberta Industrial Heartland to take advantage of the proximity to petroleum vanadium sources. Already existing assets, such as Invinity's Vancouver facility or VRB Energy's know-how, should be leveraged and expanded. Primary sources of vanadium can come online in the long term as co-products of mining operations.

- **In the Short Term:**
  - Build a Vanadium processing and recovery plant and VRFB production facility in the Alberta Industrial Heartland or Fort McMurray. Leverage the proximity to the oil sands industry to have steady access to bitumen and petroleum vanadium sources.
  - Encourage sending secondary sources of vanadium to this plant by boosting recovery from fly ashes from coal and oil power plants (AB, SK, Maritimes)
- **In the Long Term:**
  - Develop vanadium co-production by collaborating with iron, uranium, and aluminum mines.

1.3 Signature Projects

- Vanadium processing facility and VRFB manufacturing plant in Alberta.
- Uranium, iron, and aluminum mines co-producing vanadium (BC, SK, QC, NL)

1.4 Strategic Priorities

- **Build a Vanadium Processing and VRFB Production Hub in Alberta:**
  - **Develop a vanadium recovery and processing facility in the Alberta Industrial Heartland**, integrated with a vanadium redox flow battery (VRFB) production plant.
  - **Leverage the proximity to the oil sands industry:** This location benefits from proximity to the oil sands industry in Edmonton, offering access to petroleum-based vanadium resources, which can streamline extraction and processing. The region's well-established industrial infrastructure makes it an ideal location for such a facility. Fort McMurray's availability of vanadium-bearing petroleum products can also be leveraged.
  - **Secure a consistent supply of key chemicals and reagents**, such as sulfuric acid, limestone, solvents, and alkali, to support efficient vanadium processing and electrolyte and redox flow battery production. The availability of these materials in the region will help reduce costs and operational delays.
  - **Draw inspiration from successful models** like Township in Queensland, Australia, where companies such as Idemitsu, Vecco, and Sumitomo Electric have created a similar vanadium processing and VRFB hub. This collaboration offers valuable insights into how partnerships and location synergies can drive success.
- **Access Primary Vanadium Resources by Developing Synergies with Other Mining Industries:**
  - **Work with iron mining companies in Quebec and Labrador to recover vanadium from titanomagnetite ores,** using the established process of pyrometallurgy, alkali roasting, and leaching. Collaborating with iron mining companies in Quebec and Labrador, such as ArcelorMittal, Rio Tinto, Champion Iron, and Tacora, provides an opportunity to tap into these resources and co-produce vanadium as a byproduct of iron mining operations.
  - **Revisit the historical vanadium production pathway from uranium ores,** previously utilized in Colorado, to establish synergies with uranium miners in Saskatchewan, such as Cameco and Orano. This would allow for the recovery of vanadium from uranium mining activities, providing another primary source of vanadium.
  - **Explore the potential to recover vanadium from byproducts of bauxite processing**, an underutilized resource. Partnering with aluminum mining companies like Rio Tinto in Kitimat could create opportunities to extract vanadium from these byproducts, contributing to the diversification of vanadium supply in Canada.

- **Secure Secondary Vanadium Resources from Waste Generators:**
    - **Focus on identifying secondary waste generators,** including oil and coal-fired power plants in Alberta, Saskatchewan, and the Maritimes, as potential sources for vanadium recovery. These facilities produce fly ash and oil residues, both of which can contain valuable amounts of vanadium.
    - **Collaborate with these power plants** to develop vanadium recovery systems that can be integrated into existing processes, allowing for the efficient extraction of vanadium from waste byproducts. This approach supports sustainability goals and diversifies the sources of vanadium production while reducing waste and promoting a circular economy.
- **Research & Development:**
    - **Invest in research to develop new methods for extracting vanadium from mining tailings,** turning what is often seen as waste into a valuable resource.
    - **Encourage collaboration between academic institutions and industrial partners** to develop more efficient, lower-emission vanadium extraction processes. Special attention should be paid to optimizing pyrometallurgical steps to reduce greenhouse gas emissions and coupling them with carbon capture, utilization, and storage (CCUS) technologies to further minimize environmental impacts.
    - **Focus on exploring shorter, more sustainable pathways from vanadium extraction to battery production.** This can include developing innovative techniques that reduce energy consumption and waste, ensuring that Canada's vanadium industry is both competitive and environmentally responsible.
- **Draw Smart Regulations for a Vanadium Industry:**
    - **Advocate for regulatory frameworks encouraging oil and coal plants to facilitate vanadium recovery** from waste byproducts, ensuring these valuable resources are captured and not sent abroad. This will help keep vanadium processing and its economic benefits within Canada.
    - **Support the creation of new mining ventures focused on vanadium co-production**, drawing on successful examples from countries like Australia that have implemented modular mining projects. By streamlining the permitting process and providing regulatory clarity, Canada can accelerate the development of vanadium projects.
    - **Promote collaboration between government, industry, and academia** to create a more efficient vanadium supply chain, ensuring all stakeholders are aligned on the importance of vanadium as a critical mineral. This includes providing funding opportunities for new ventures and supporting the entire value chain from mining to battery production.

- **Government Incentives and Protection from Price Volatility:**
    - **Unlock specific government funding and support mechanisms tailored to vanadium projects**, especially for exploration, discovery, and processing. Countries like the U.S. and China have already implemented similar strategies for critical minerals, and Canada can follow suit by providing financial incentives to develop its vanadium resources.
    - **Implement market-stabilizing measures,** such as government procurement contracts, contracts for differences, and government-guaranteed future purchases of locally sourced vanadium. These mechanisms can protect vanadium producers from price volatility, ensuring stability without significantly increasing the cost of vanadium-based products.

2 Vanadium: A Polyvalent Metal for Specialty Alloys, Catalysts, and Flow Batteries

2.1 General Properties

2.1.1 Physical Properties and Applications

Vanadium is a steel-grey/bluish ductile metal with a very high melting point (1910°C). It is mainly used as an additive in steel and titanium alloys, improving strength and resistance to heat and corrosion. As such, high-strength alloys and special steels have applications in tools, construction, jet engines, motors, axles, crankshafts, and automotive frames. Pure vanadium and vanadium alloys also hold several advantages over stainless steel: a higher thermal conductivity, better strength, and a lower density and thermal expansion, which is why it was considered for fuel cladding in nuclear reactors.[16] Vanadium is also a ceramic additive. Added to glass, it can give the material a blue or green tint, and VO_2-coated glass can block infrared wavelengths.[17] Finally, using vanadium electrolytes in flow batteries for energy storage is considered an essential development of the vanadium industry.

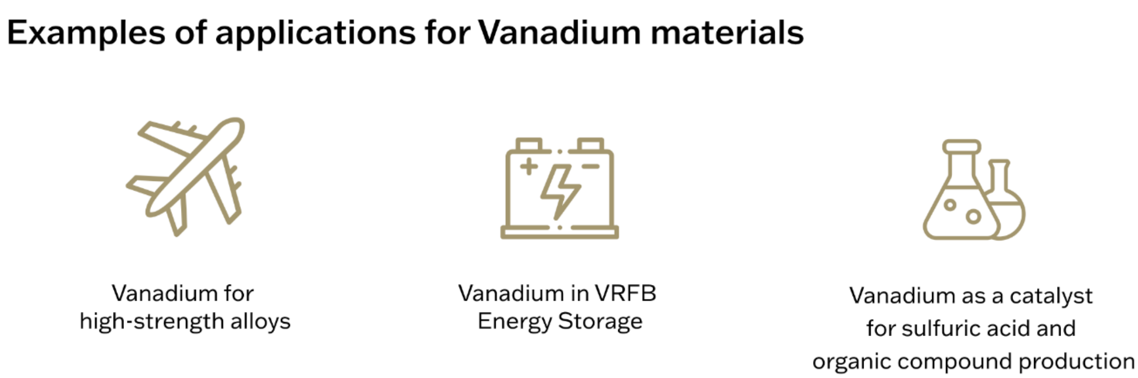

Figure 1 Examples of applications for vanadium materials

With applications in specialty alloys, catalysis and energy storage, numerous countries and international organizations such as Australia, the U.S., the EU, the IEA, Indonesia, the UK, Brazil, South Africa and Canada consider vanadium a critical material.

2.1.2 A Brief History of Vanadium and Its Industry

Andrés Manuel del Rio discovered vanadium in 1801 in the form of vanadinite $Pb_5(VO_4)_3Cl$ from a brown lead sample from central Mexico, coining the new metal erythronium. This newly discovered element had such similarities with chromium that the scientific community confused both materials in the early 1800s, up until Nils Gabriel Sefström rediscovered it in 1830 after treating iron from Sweden with acid. Subsequent investigations and proof by Friedrich Wöhler in 1831 confirmed that it was another metal different from chromium but similar to Del Rio's erythronium.[18] It was Sefström who gave it its accepted name of vanadium, after Vanadís, another name of the Norse goddess of beauty Freyja, because of the beautiful aspect of many vanadium minerals. The isolation of vanadium metal took several decades as using carbon as a reductant from vanadium oxides only yielded vanadium carbide. Sir Henry Enfield Roscoe managed to reduce vanadium chloride VCl_2 with hydrogen in 1867, thus obtaining vanadium metal for the first time.

The production of vanadium-alloyed steel started at scale in England in 1903, and Henry Ford began to support its use for the automotive industry in 1908 when it was incorporated into the Ford Model T car chassis.[16] At the time, vanadium originated from **vanadinite** $Pb_5(VO_4)_3Cl$ deposits in Extremadura in Spain and large deposits of **patrónite** VS_4 from Minas Ragra in Peru. The latter was developed by and fed the Vanadium Corporation of America, a company established by Joseph and James Flannery in Pennsylvania in 1906. This company started to smelt the Peruvian ore. It produced ferrovanadium in Bridgeville by the following year, soon to sell its products to railway companies, to the U.S. government for the construction of the Panama Canal or to armament companies.[19] By 1914, Minas Ragra produced 75% of the global vanadium output.[20]

Due to price collapse and decreases in ore grades through the first half of the 20th century, deposits in southern Africa, Namibia, and Zambia replaced the vanadium produced by Peruvian mines. Then, the co-production of vanadium from uranium ores in Placerville, Colorado, as well as from phosphate deposits in Idaho, became important after World War II.[16] Since the 1950s, vanadium-bearing titanomagnetites, found in Russia, South Africa, Finland, the U.S., and Australia, have become the primary source of producing V-products.

2.1.3 The Importance of Vanadium Pentoxide for Alloys and Catalysts

Vanadium pentoxide V_2O_5, also known as vanadium oxide or vanadia, is the most important vanadium compound, as it is both the precursor to vanadium alloys and an essential catalyst. Heating vanadium pentoxide with scrap iron and either ferrosilicon or aluminum (or previously carbon) as a reductant will produce ferrovanadium with a V-content of 35–85 wt.%. Added to steel or other alloys, it produces finer grains and hardens and toughens the material. It is suitable for ferrous alloy pieces needed for high-temperature resistance, wear resistance, weldability, and corrosion resistance to alkaline media or sulfuric and hydrochloric acids.[16,21] After fully reducing V_2O_5 to pure metal form, vanadium can also be used as an alloy for titanium to enhance its strength properties and creep resistance.

Other than alloying, vanadium pentoxide is also a primordial **catalyst** for various essential industrial chemicals. BASF patented the use of V_2O_5 in 1913 to catalyze the conversion of sulfur dioxide SO_2 gas to sulfur trioxide gas SO_3, which then forms sulfuric acid H_2SO_4 in contact with water. Vanadium catalysts were cheaper and more robust in the 1930s, replacing the previously used platinum catalysts.[22] Adopting this inexpensive process led to developing the modern contact process for sulfuric acid production, where vanadium catalysts are now used almost exclusively. This links vanadium to the sulfur recycling processes necessary in many pyrometallurgical processes of other critical minerals such as copper or nickel sulfides. Vanadium pentoxide is also a valuable catalyst to produce maleic anhydride, an essential reagent for polyester resins and curing agent for epoxy resins, and for the synthesis of phthalic anhydride, a precursor to plasticizers. V_2O_5 is also used as a corrosion inhibitor to help capture CO_2 by potassium carbonate K_2CO_3 during the Benfield Process in petroleum refining.

2.1.4 The Biological Role of Vanadium and its Toxicity

Vanadium is essential for certain species, and its high concentration in sea life or mushrooms has been reported, but its biological role or benefits are still unknown. However, the structural analogy and similarities between the vanadate and phosphate ions might explain why vanadate sometimes easily substitutes phosphate in certain enzymes.[23] Some bacteria use vanadium for various biological functions, such as respiration, nitrogen fixation and reduction.[24] Certain species of algae, lichens, fungi and bacteria also use vanadium-dependent enzymes to produce halomethanes naturally, a category of gases that deplete the ozone layer.

Despite its role in certain life forms and innocuity in trace amounts, vanadium and its parent compounds (V_2O_5, $NaVO_3$, Na_3VO_4, $VOSO_4$, NH_4VO_3) are toxic in more significant amounts to both humans and animals.[16,17] The International Agency for Research on Cancer (IARC) categorizes vanadium pentoxide as possibly carcinogenic to humans, as it showed cancer-inducing effects in mice by inhalation but lacked sufficient and adequate evidence for humans.[25] However, V_2O_5, in the form of dust, has acute toxicity and can cause respiratory issues such as asthma and bronchitis and lead to eye irritation. CAREX Canada estimated that around 7,600 Canadians are exposed to V_2O_5 at work, especially in the fabricated metal product, boiler, tank and shipping container production industry.[26] Boilermakers, welders, specialized cleaners, processing industry workers, industrial mechanics, petroleum refiners, and ceramicists are among the exposed occupations.

2.2 Role in Energy Storage

2.2.1 Flow Batteries, an Alternative to Regular Rechargeable Batteries

Vanadium redox flow batteries (VRFB, VRB, or VFB) are a promising technology for safe and long-life span energy storage. Traditional flow batteries are defined as batteries in which two chemicals dissolved in liquid electrolytes are pumped to flow in their respective separated circuits. They undergo a redox reaction where the two circuits meet in two half cells along an ion-transfer membrane, producing an electrical current. Contrary to conventional batteries, the active material and, thus, the chemical energy is not stored in the electrodes but in the liquid electrolytes: in brief, the electrodes do not participate in chemical reactions and are just electron acceptors or donors. Therefore, the actual capacity of flow batteries depends on the amount of electrolyte stored in both tanks.[27] The electrochemical cells can be stacked in parallel or series. Some flow batteries contain solid electroactive components and are thus classified as hybrid flow batteries (HFB). Several flow battery technologies exist, such as chlorine-zinc, bromine-zinc, aqueous or non-aqueous organic electrolyte, *etc.* However, VRFB is the most mature and commercially successful type of flow battery cell.

Bromine-zinc redox flow batteries were the earliest to be discovered and patented by John Doyle in 1879. By the late 19th century, early flow batteries powered airships and cars for demonstration.[28] It was only by the 1970s–80s that flow batteries gained increased interest and that more patents were filed. The Lewis Research Centre in Cleveland, funded by NASA in 1973, notably pursued the advancement of redox flow battery systems using iron and chromium.[29,30]

2.2.2 The development of VRFB

Several studies by Oei and Kummer investigated the use of vanadium electrolytes in half-cells in the early 1980s in partnership with the Ford Motor Company,[31] but it was Australian scientist Maria Skyllas-Kazacos, along with Sum and Rychcik who developed and patented the first all-vanadium battery 1986.[32] The Australian Department of Resources and Energy provided the original funding, and the first patents were filed in Australia and the U.S., with the University of New South Wales and Unisearch Limited as applicants. After subsequent research funded by the Australian government and various commercial entities, Unisearch later granted licenses to Thai Gypsum for residential PV applications in Thailand and Mitsubishi and Kashima-Kita for load levelling and PV development in Japan. After acquiring the license from Unisearch in 1998, Pinnacle VRB also granted licenses to Sumitomo Electric Industries in Japan and VRB Power Systems in Canada. The latter was then acquired by a U.S. and China-based company, Prudent Energy, in 2009.[33]

In the U.S., UniEnergy previously held its own VRFB design: In 2012, researchers in Washington began developing a promising vanadium redox flow battery with U.S. Department of Energy (DOE) funding. Despite early success, the company struggled to find U.S. investors, leading to a partnership with a Chinese firm, Dalian Rongke Power. By 2017, manufacturing had shifted to China under a sublicense, which violated DOE rules requiring U.S. production. Since then, Dalian Rongke Power has become a top global manufacturer of VRFB. In 2021, UniEnergy transferred the license to Vanadis Power, a European company planning to manufacture in China and Germany. The DOE approved the transfer without adequate oversight. The situation resulted in the U.S. losing control of taxpayer-funded technology to foreign entities, allowing China to dominate production and deploy large-scale vanadium battery farms.[34]

2.2.3 VRFB: Working Principles & Characteristics

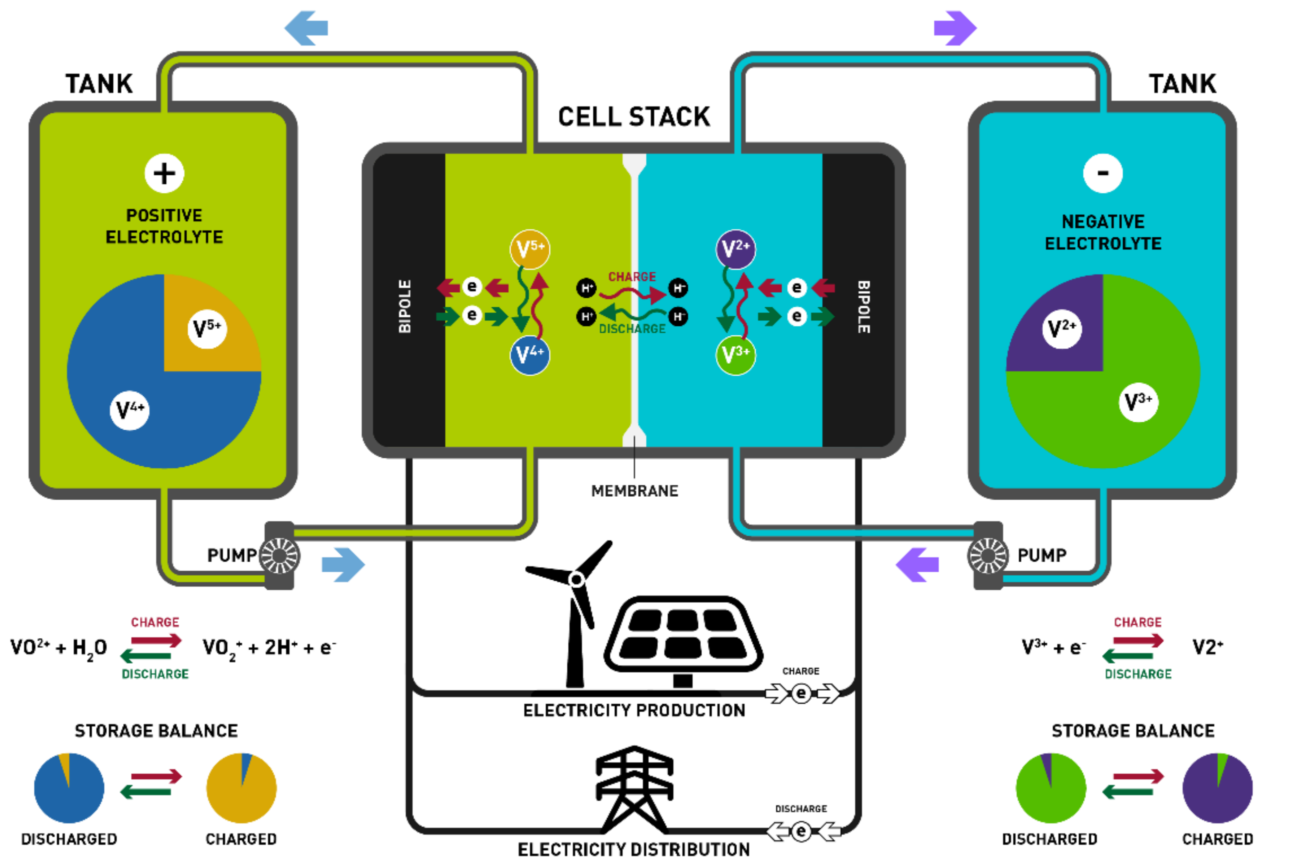

Figure 2 Description of a VRFB system, source: VRB Energy[35]

As its ions are stable in various oxidation states, vanadium electrolytes can be used in both flow battery half-cells and tanks. Accordingly, the two redox couples used in VRFB are V^{3+}/V^{2+} and VO_2^+/VO^{2+} (pervanadyl and vanadyl ions) for the negative and positive electrode circuits, respectively. During charge, V^{2+} would be oxidized to V^{3+}, and VO_2^+ would get reduced to VO^{2+}, while the opposite reactions would happen during discharge. Pumps help the electrolytes circulate in their half-cell circuits from the tank to the membrane and then back to the tank. In practice, the original VRFB electrolyte solutions were a mixture of vanadium sulfate and sulfuric acid.[27] Chloride or bromide anions have also been proposed, but all electrolytes are mostly aqueous-based, which allows for safety and low cost.[36] The inert electrodes are carbon-based, such as carbon or graphite felt. The ion exchange membrane separator used is often made of Nafion, a fluorinated and sulfonated polymer that can effectively transfer protons H^+ between the two half-cell circuits, thus achieving electrical neutrality. At 25°C, the voltage of a VRFB is 1.4 V per cell.

VRFB are suitable for applications such as electric grid storage or EV charging stations: their performances do not decrease for at least 25 years of operation,[37] and could undergo virtually unlimited charge/discharge cycles (over 10,000 cycles vs. 3,000 on average for Li-ion). Lithium-ion and sodium-ion batteries are only suitable for energy storage durations of 4–8h, thus overlapping with VRFB technology, which has an even longer storage duration, up to 12h.[38] These increased cycling and storage duration performances allow VRFB to be amenable to different types of energy storage beyond the peak replacement use that lithium-ion offers, such as arbitrage, wind smoothing, or overnight availability of renewables. In addition to those characteristics, vanadium is not a conflict mineral, VRFB can operate at 100% depth of discharge without performance loss, and there is a limited fire hazard due to the non-flammability of materials compared to NMC batteries.

As for the drawbacks, VRFB have very low energy densities (25–35 Wh/L)[36] making them too heavy and bulky for electric vehicles and mobility in general. Although fire hazards are limited compared to lithium-ion batteries, due to the use of aqueous electrolytes over flammable organic ones, the toxicity of vanadium compounds can still be relatively problematic. The vanadium electrolytes and VRFB production capacity is still limited, which could be a bottleneck for the supply chain. Another inconvenience is the unwanted migration of vanadium ions from the positive electrode to the negative electrode circuit throughout the membrane, a phenomenon which can lead to a difference in concentration.[27] Finally, VRFB's round-trip efficiency is still lower than that of lithium-ion batteries (75–80% for VRFB compared to 85–95% for LFP and NMC), meaning that VRFB are more prone to energy loss when comparing the charged input and discharged output.[39]

2.2.4 The VRFB Industry and Its Deployment Around the World

As indicated, VRFB is a relatively mature technology, but scaling up its rapid adoption could be problematic due to the current low mining level, limited manufacturing production, and high vanadium prices. Despite those issues, a non-exhaustive list of large VRFB deployments is described below.

Mitsubishi Electric Industries and Kashima-Kita Electric Power Corporation installed the first VRFB implementation in Japan for load-levelling usage in 1995.[32] Sumitomo Electric also trailblazed larger-scale VRFB installations by building a 4 MW/6 MWh facility paired with the Tomamae wind farm in Hokkaido, Japan, in 2005.[40] Since then, they opened the massive 15 MW/60 MWh Minami Hayakita Substation VRFB installation in 2015 as a large-scale flow battery demonstration for grid control. This demonstration project was completed by a 17 MW/51 MWh commercial facility coupled with wind turbines in 2022. The Japanese company also has several smaller operations in the U.S., Morroco, Belgium and Taiwan.[41]

In Dalian, China, a vanadium flow battery demonstration plant is operated for energy storage to reduce peak loads and increase the grid stability of the Dalian peninsula. The 100 MW/400 MWh facility was connected to the grid in late 2022 and is projected to be expanded by operator Dalian Rongke Power.[42] Canadian-based company VRB Energy previously signed an agreement in 2021 to build a 100 MW/500 MWh power station in Xiangyang, in the province of Hubei in China.[9] Invinity Systems also built a 2MW/5MWh VRFB plant paired with a lithium-ion storage system in the UK and a 2MW/8 MWh system collocated with a solar PV plant in South Australia.[43] Additionally, Invinity has built several VRFB storage facilities in the U.S., Canada, Europe, South Africa, China, South Korea, Taiwan and Thailand.[44] Other major VRFB manufacturers include Schmid, Delectrik, Cellcube, and UniEnergy Technologies Battery.

It is worth noting that several of these actors are **vertically integrated from mining to electrolyte or battery production**, such as South African mining company Bushveld Minerals buying most shares from Cellcube, Largo Resources venturing into battery making with their subsidiary Largo Clean Resources, Ivanhoe Electric owning the majority of VRB Energy, Australian Vanadium Limited forming VSUN Energy, or VanadiumCorp Resources developing a mine and an electrolyte production plant.[45]

Vanitec, a vanadium-specialized international technical committee and industry association, lists **over 300 VRFB energy storage projects globally** which are either operational, under construction, contracted or announced.[46] Over a third of those projects are located in China.

2.2.5 Vanadium as an additive to lithium-ion batteries

Finally, Li-ion batteries, sometimes dubbed lithium vanadium phosphate batteries (LVP), using vanadium as $Li_3V_2(PO_4)_3$ cathode material, or even $LiVPO_4F$, have been proposed.[47–50] Moreover, the addition of vanadium as a doping agent onto regular LFP cathode materials also has performance-enhancing effects.[51]

2.3 Substitutes

Vanadium used as an alloy for high-strength low-alloy steels or special steel can be substituted by manganese, molybdenum, titanium, niobium, tungsten, chromium or tantalum. In particular, molybdenum and tungsten alloys can achieve similar performances but at a higher cost.[17] There is no substitute for titanium-vanadium alloys for aerospace.[52]

Regarding energy storage, VRFB can be substituted by LFP or sodium-ion batteries, although those solutions are less suitable for more extended storage durations or as many cycles. Iron-air batteries could also be a substitute for VRFB, but they are more suitable for longer storage durations, up to weeks. Other redox flow batteries based on different electrolytes, such as iron-chromium, halogen, or zinc were developed, but none outperformed vanadium-based redox flow batteries, which also have the advantage of having the most mature value chain.[36]

2.4 Supply & Demand

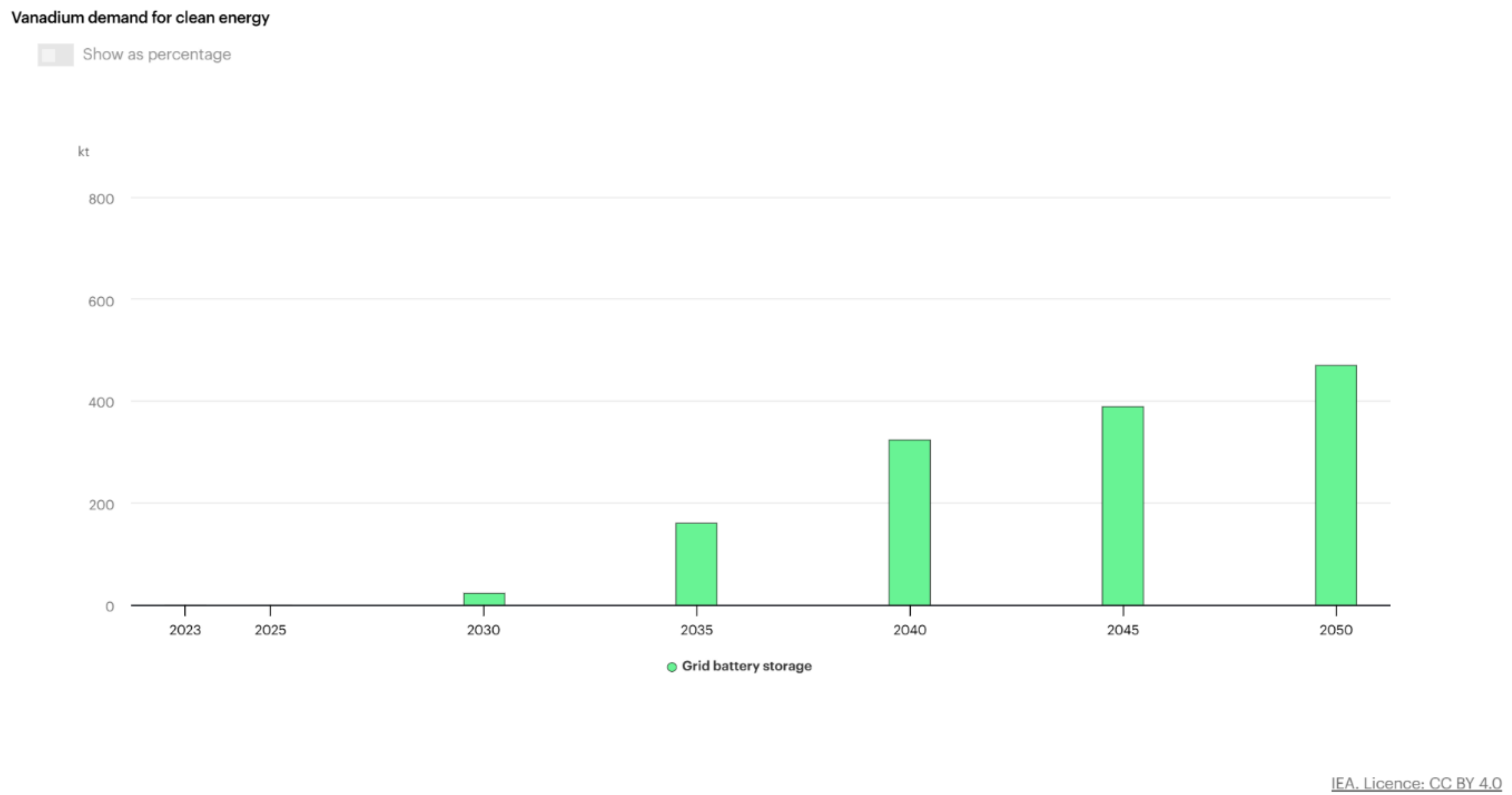

Figure 3 Vanadium demand for clean energy demand, according to the IEA Stated Policy Scenario. IEA 2024, Critical Minerals Data Explorer, License: CC BY 4.0[53]

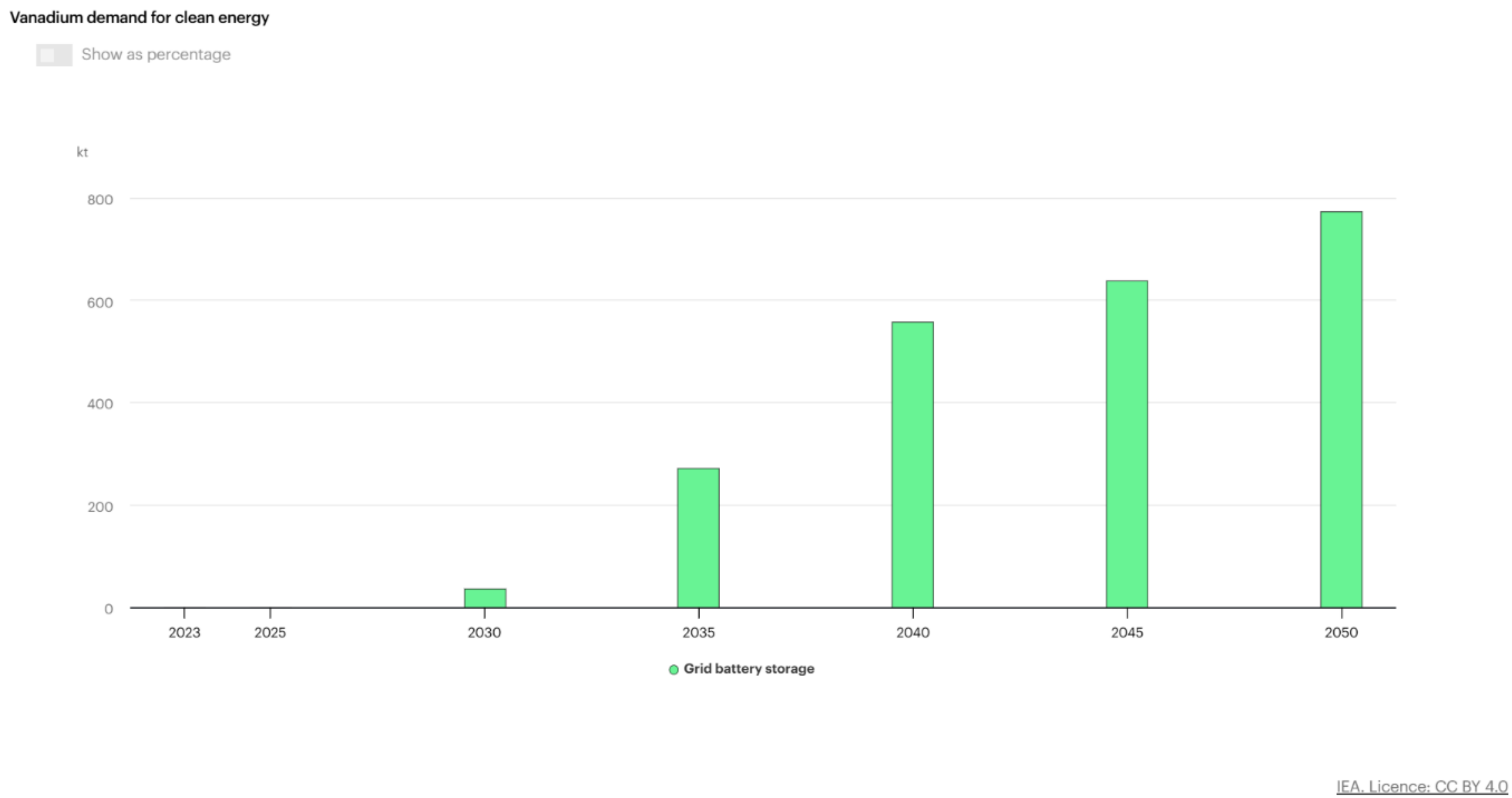

Figure 4 Vanadium demand for clean energy demand, according to the IEA Net Zero Emissions by 2050 Scenario. IEA 2024, Critical Minerals Data Explorer, License: CC BY 4.0[53]

As vanadium's primary use is as a ferroalloy, its pricing and demand usually depend on the steel industry, particularly the Chinese steel industry.[54,55] The variation of V_2O_5 prices has been volatile due to several events affecting the major producing countries, such as the introduction of vanadium steel standards or the revision of product standards in China and the rationing of electricity in South Africa.[56] The closure of South African and Russian mines seemed to have impacted pricing as well.

According to the different scenarios investigated by the IEA, the projected global demand for vanadium for clean technologies, mainly driven by grid battery storage, would be between 22–35 kt in 2030 and 469–773 kt in 2050.[53] Their boldest NZE scenario estimates an average yearly demand of around 300 kt of vanadium for 2031–2040.[37] Additionally, a variation considering the early adoption of VRFB in the NZE scenario showed that the demand for lithium for energy storage could potentially decrease by 6%.[57]

A more conservative estimation by a work commissioned by the World Bank in 2020 projected that the annual demand for vanadium in 2050 would rise to 138 kt, still representing 189% of the global output in 2018.[58]

Finally, a more recent and bullish forecast by Guidehouse Insights indicated that energy storage alone might consume around 140 kt of vanadium annually by 2031.[46] In their white paper, they estimate that the global annual installed VRFB revenues would grow from under USD $1,000 M in 2022 to almost $ 8,000 M in 2031, following the worldwide VRFB energy capacity increase from around 1,000 MWh in 2022 to almost 34,000 MWh.[59]

All these predictions, with as much variation as they may show, are all based on the fundamental assumption that vanadium flow batteries have a significant potential to capture shares of the energy storage market from Li-ion batteries. The actual extent and timeline of the adoption of this technology and its deployment remain the underlying questions.

3 The Vanadium Flowsheet: From Iron Ores, Uranium Ores and Oil Residues to Vanadium Pentoxide and Beyond

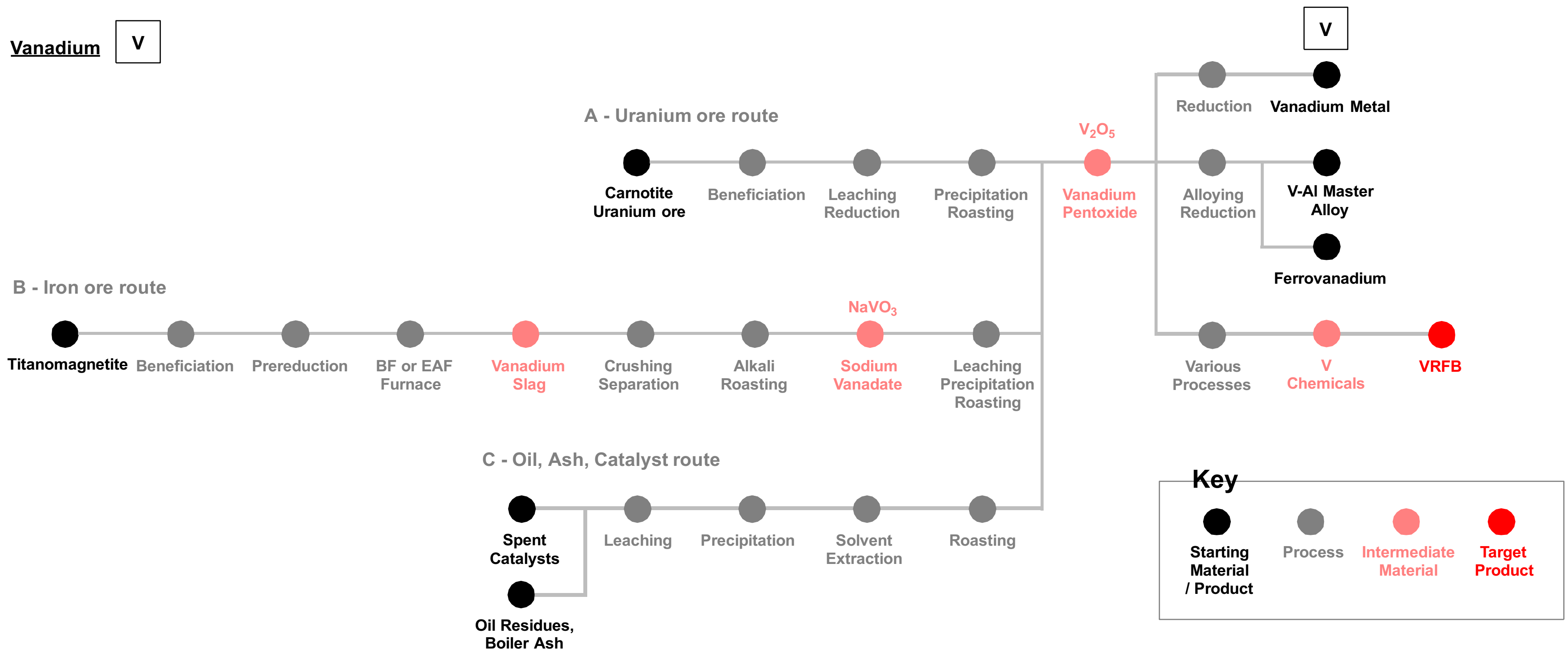

Figure 5 Simplified flowsheet of vanadium

3.1 The Different Types of Vanadium Ores

Vanadium is available under the form of **roscoelite** $K(V^{3+},Al,Mg)_2AlSiO_{10}(OH)_2$ or **carnotite** $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$. Roscoelite is a vanadium-rich mica mineral typically found in low-temperature hydrothermal deposits. It is a secondary mineral associated with uranium ores. Carnotite is a uranium-vanadium ore occurring in sandstone-hosted deposits. Significant carnotite deposits are found in the Colorado Plateau in Utah and Colorado, where it was actively mined along with roscoelite for vanadium and uranium during the Cold War. Although these mines are largely inactive today, carnotite and roscoelite remain potential sources of vanadium if economic conditions favour its extraction.

Patronite VS_4 is a rare vanadium sulfide mineral historically mined in Peru, specifically at the Minas Ragra deposit. It was a primary vanadium ore during the early 20th century, but the deposit is now exhausted, and no active mining of patronite occurs today. See the section on the history of vanadium and its industry above for more details. **Vanadinite** $Pb_5(VO_4)Cl$ is a lead vanadate mineral found in the oxidation zones of lead ore deposits. It has been mined as a secondary vanadium source in Morocco, Namibia, and parts of Mexico. However, vanadinite is not a primary vanadium ore due to its lower vanadium content and association with lead.

Finally, **vanadiferous titanomagnetite** $Fe^{2+}(V^{3+},Ti^{3+})O_4$is a vanadium-bearing iron ore formed in igneous deposits. The trivalent ferric iron is sometimes replaced with either trivalent vanadium V^{3+}, or titanium Ti^{3+}. It is currently the main source of vanadium. It occurs in layered mafic intrusions and vanadiferous magnetite deposits. Prominent examples include the Bushveld Complex in South Africa, the Kachkanar Deposit in Russia, and the Largo Resources Maracás Menchen Mine in Brazil.

3.2 International Vanadium Production & Reserves

Table 2 Estimated reserves & production of vanadium by country in tonnes

Country	**Vanadium Mining Production in 2022**[a] (in tonnes)	**Country**	**Vanadium Reserves in 2024**[a] (tonnes x 10^3)
United States	/	United States	45
Australia	/	Brazil	120
Brazil	5,840	South Africa	750
South Africa	8,870	China	4,400
Russia	20,000	Russia	5,000
China	66,900	Australia	8,500
World Total	**102,000**	**World Total**	**19,000**

[a]Data from the 2024 U.S. Geological Survey.[54]

Vanadium is the 20th most abundant element on Earth's crust, averaging at 120 ppm (g/tonne).[18,60] This makes Vanadium relatively available, as, in comparison, it is twice as abundant as copper and six times as abundant as lithium. By this measure, it is one of the most abundant battery metals in the Earth's crust.[61] Considering the estimations and forecasted demand, vanadium availability will not be an issue, even in the most aggressive VRFB adoption scenario. Known global reserves are estimated at 22–24 Mt of vanadium, which could certainly accommodate the VRFB-driven IEA NZE scenario, where the average annual demand reaches 300 kt of vanadium during 2031–2040.[37,56] More globally, the total world resources are estimated to be over 63 Mt of vanadium.[54]As such, the expected bottlenecks are more likely to occur in the vanadium processing and electrolyte production segments of the value chain.

China is the world's top vanadium producer (66% of world V production in 2022), ahead of Russia (20%), South Africa (9%), and Brazil (6%), with a global output of 102 kt, according to the U.S. Geological Survey.[54] A different accounting for the same year by Vanitec estimated that almost 118 kt of vanadium was produced and that 116 kt was consumed.[62]

In 2023, 6.8% of the global vanadium consumption was for VRFB, and China accounted for 92% of this amount.[413]

However, alloying remains the main application for vanadium: the steel sector represented 92% of the total vanadium demand in 2021, with steel slag co-production being the major production pathway (73%), followed by extraction from primary resources (17%) and secondary sources (10%).[37]

3.3 Processing

3.3.1 From Uranium

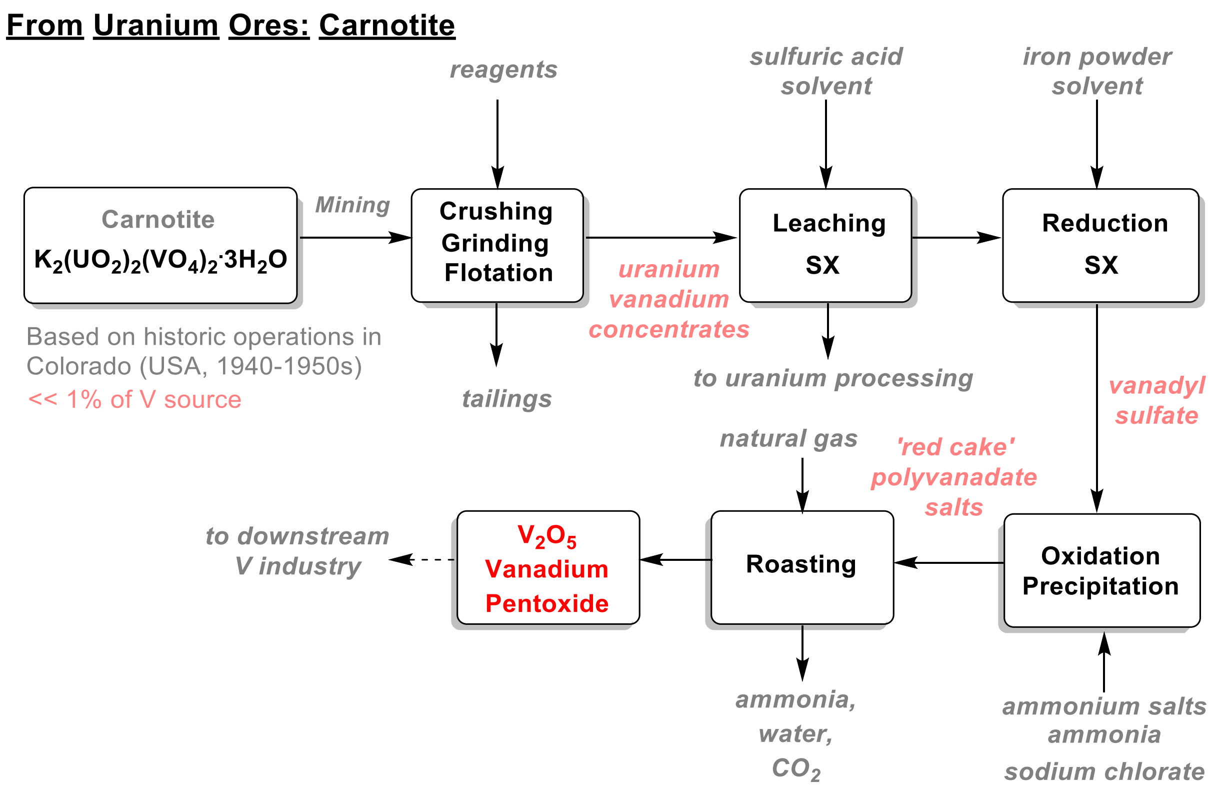

Figure 6 Flowsheet from uranium-vanadium resources to vanadium pentoxide

Vanadium extraction from uranium ores typically involves two main processes: sodium salt roasting or leaching and pressurized acid leaching.[63]

The **Sodium Salt Roasting-Leaching Process** method involves roasting uranium-vanadium minerals (*e.g.*, carnotite) with sodium salts (commonly sodium carbonate or sodium chloride) at high temperatures (typically 800–850°C). The roasting converts vanadium and uranium into water-soluble **sodium vanadate** $NaVO_3$ and sodium uranyl carbonate. The roasted material is leached with water or an alkaline solution to dissolve the vanadium and uranium compounds. These elements are separated in the liquid phase using selective precipitation or solvent extraction. Vanadium recovery is 70–80%, and uranium recovery is 90–95%. While effective for uranium, the process leaves a portion of vanadium unrecovered in the residue due to incomplete reaction or structural inaccessibility. The later stages of this pathway follow the same route as the titanomagnetite pathway, starting from the leaching and filtration of sodium vanadate. See the appropriate section below for more details.

In the **Pressurized Acid Leaching Process**, in this method, finely ground uranium-vanadium ores are directly leached with sulfuric acid (H_2SO_4) at elevated temperatures (150–160°C) under oxygen pressure in an autoclave. Sulfuric acid is the primary leaching agent, and oxygen is supplied continuously to maintain oxidative conditions that favor the dissolution of uranium and vanadium. After leaching, vanadium and uranium are separated in the liquid phase using solvent extraction or ion exchange techniques. Uranium recovery reaches 90–94%, but vanadium leaching rates are typically lower at 65–72%, as the mineral structure resists complete dissolution. A **vanadyl sulfate** solution is the product. The high temperature and pressure enhance reaction kinetics, making it suitable for processing low-grade ores. This was also the main method used by industry.

In both processes, vanadium recovery is less effective than uranium, leaving untapped potential in the residues. The need to separate vanadium and uranium in the liquid phase adds operational challenges. Researchers have then focused on tailing to recover additional vanadium; in one instance, metallurgy used microbial processes to extract vanadium from tailings, achieving recovery rates of around 45%.

After the acid-leaching process, the vanadyl sulfate solution can be oxidized by using sodium chlorate at high temperatures. Then a subsequent addition of ammonia or ammonium salt precipitates the vanadium as '**red cake**', a mixture of **ammonium polyvanadate** (APV) and **sodium polyvanadate**. After roasting, ammonia is eliminated, and only alkali-containing **vanadium pentoxide** remains V_2O_5.[16]

3.3.2 From Titanomagnetite

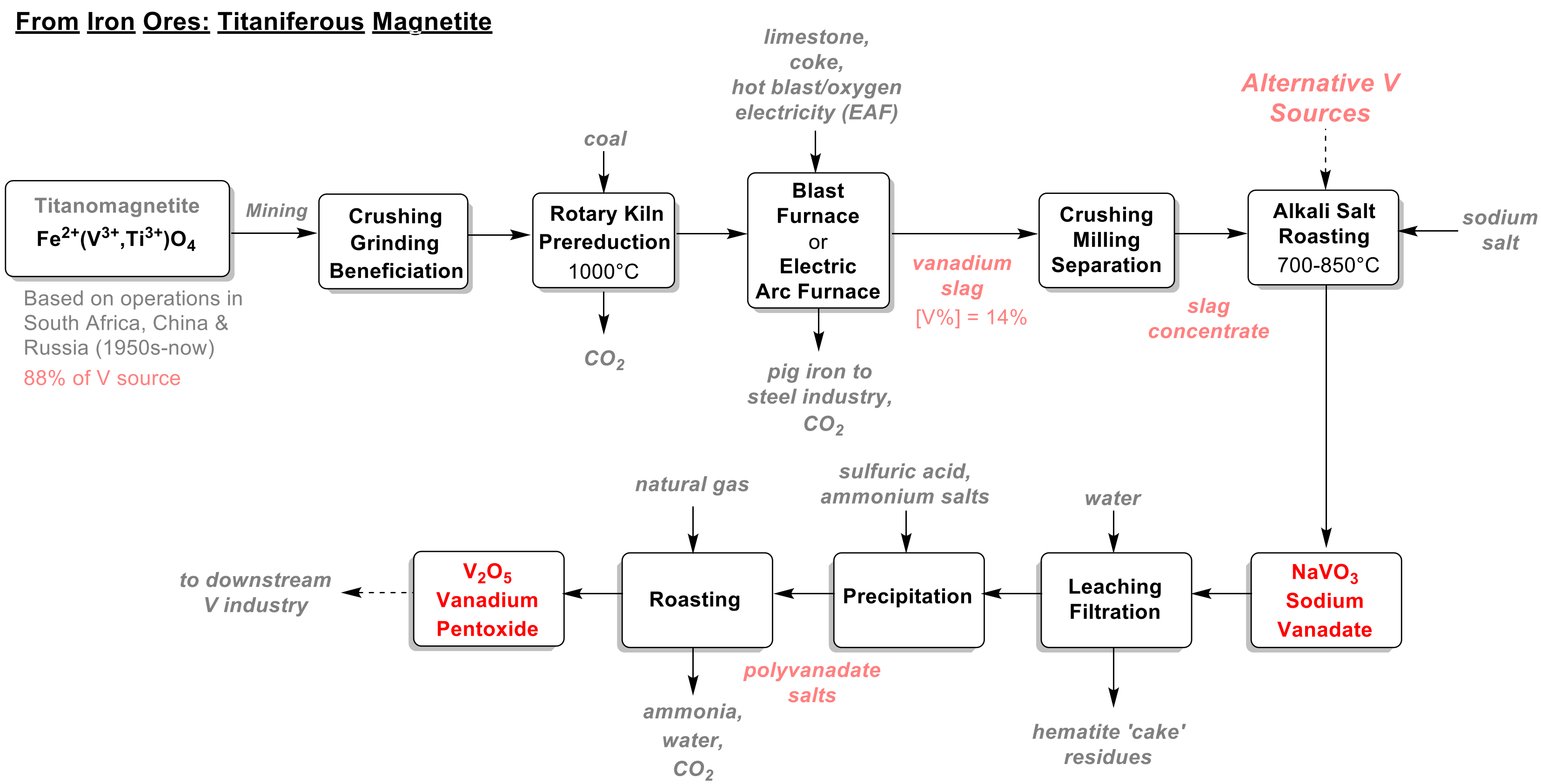

Figure 7 Flowsheet from titanomagnetite resources to vanadium pentoxide

Vanadium extraction from titanomagnetite ores (VTM) and vanadium slag involve a multi-step process to recover vanadium in vanadium pentoxide (V_2O_5), and it is often a by-product of iron and steelmaking plants. High-grade vanadium concentrates can be directly processed through direct extraction or direct reduction.

After beneficiation, titanomagnetite ore, typically containing 1.5–1.7% V_2O_5, is partially reduced with coal at approximately 1000°C in rotary kilns. The reduced ore is further processed in an electric arc furnace, producing pig iron with 1.4% V_2O_5 and vanadium-rich slag containing up to 25% V_2O_5 in South Africa (or 14% V) or 14–22% in China or Russia. Vanadium from pig iron can be transferred to the slag using a shaking ladle and oxygen lances. The slag also contains titanium dioxide.[16] The rotary kiln/EAF pathway is mainly used in South Africa, while a blast furnace is used in China and Russia

The slag is finely ground (<100 µm) and roasted with sodium salts (*e.g.*, Na_2CO_3 or NaCl) at 700–850°C in rotary kilns or multiple-hearth furnaces. This oxidizes vanadium into water-soluble **sodium vanadate** ($NaVO_3$). The roasted material is leached with water, dissolving sodium vanadate and leaving impurities behind. This produces a vanadium-rich solution. Calcium, magnesium and aluminum impurities form other vanadate salts that are insoluble in water, thus reducing the yield.

Ammonium salts (*e.g.*, NH_4Cl or $(NH_4)_2SO_4$) are added to the leachate to precipitate **ammonium metavanadate** (AMV) or **ammonium polyvanadate** (APV) at elevated temperatures and with sulfuric or hydrochloric acid. The AMV is calcined/roasted at 700°C to produce high-purity **vanadium pentoxide** V_2O_5, which is then melted and cooled into flake form for commercial use.

If the titanomagnetite ores have a vanadium content > 1%, they are eligible for alkali roasting directly after beneficiation, bypassing the pre-reduction or slag steps. The product obtained is also vanadium pentoxide and the process is similar to the one mentioned above. Companies in South Africa and Brazil can follow this method in an economically viable manner.[63]

In general, the sodium salt roasting process generates high-salinity wastewater and acidic gases. Improving environmental compliance includes replacing sodium salts with lime (calcification roasting), reducing harmful emissions, and recycling process water.

A newer Direct Alkaline Leaching method bypasses high-temperature roasting using highly concentrated alkaline solutions (40–60% NaOH) at 150–200°C under oxygen pressure, achieving over 90% vanadium recovery. However, it requires specialized corrosion-resistant equipment and is mainly suitable for high-grade vanadium slag. Other alternative routes include Microwave-Assisted Roasting; this innovation improves reaction kinetics, increasing vanadium extraction efficiency during leaching.

Vanadium slag is the world's primary raw material for vanadium production, with major producers in South Africa, China, and Russia. The slag pathway has a few advantages, with a small processing load for extraction, a high vanadium content in the slag, or iron as a by-product which can be used for steelmaking. However, global recovery rates from titanomagnetite remain low (~50%) due to inefficiencies at various stages.63 The process must balance economic viability, resource conservation, and environmental sustainability with ongoing research into cleaner and more efficient extraction method

3.3.3 From Oil Residues and Spent Catalysts

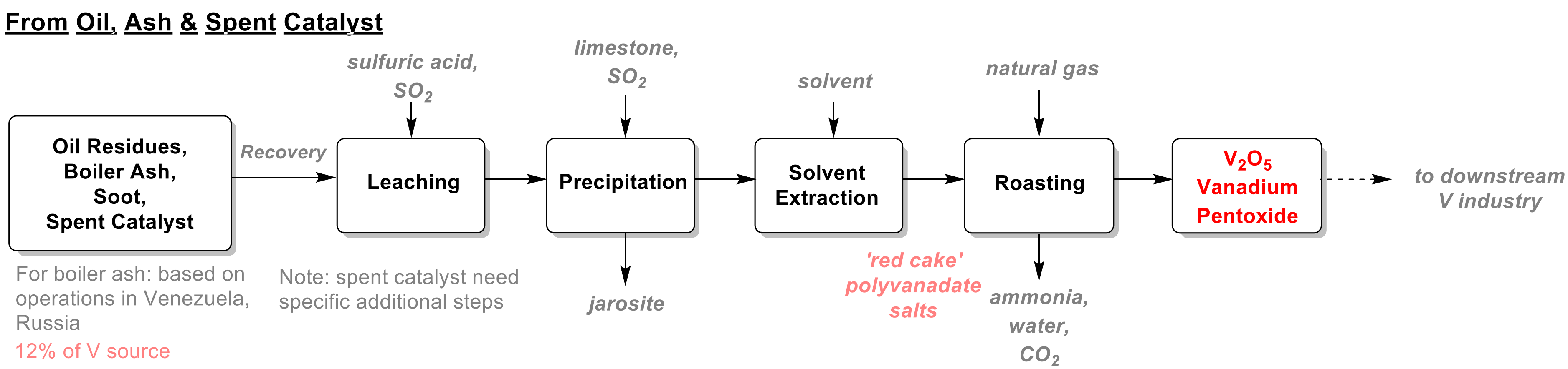

Figure 8 Flowsheet from petroleum-based vanadium and spent catalyst resources to vanadium pentoxide

Secondary vanadium can be extracted as a secondary raw material from oil and coal combustion residues, such as soot and ash from oil-fired boilers and oil refinery residues. These by-products, often containing significant vanadium content (sometimes exceeding 50% V_2O_5),[16] can be a source of vanadium, but it can come at a higher processing cost.[17] Coal ash has a lower vanadium content than petroleum fly ash. Ash is typically recovered in a collection system such as an electronic precipitator or a cyclone and has a high carbon content and includes a minor amount of non-ferrous metals.[64]

Heavy crude oils, such as those from the Orinoco Basin in Venezuela, Russian oil fields, parts of the Middle East and the tar sands of western Canada, can contain vanadium. In Venezuela, heavy asphalt-like oil deposits are emulsified with water and magnesium nitrate to create a fuel used in power stations, generating boiler ash rich in vanadium.

The process for extracting vanadium from these secondary sources typically involves a combination of roasting, leaching, and precipitation, similar to the methods used for vanadium titanomagnetite ores. The objective is also to produce **vanadium pentoxide** V_2O_5. However, additional steps, such as filtering, solvent extraction, and ion exchange, are required to handle complex waste streams.

Another important secondary source of vanadium is spent catalysts: spent hydrodesulfurization (HDS) catalysts for oil refining and selective catalytic reduction (SCR) catalysts for NO_x conversion (in incinerators, vehicles or power plants). Metals such as molybdenum, nickel, cobalt, and aluminum are also present and can be recovered during processing. A complete description of the different processes for secondary sources of vanadium can be found in the literature.[64]

3.3.3.1 From Vanadium Pentoxide to Different Vanadium Products

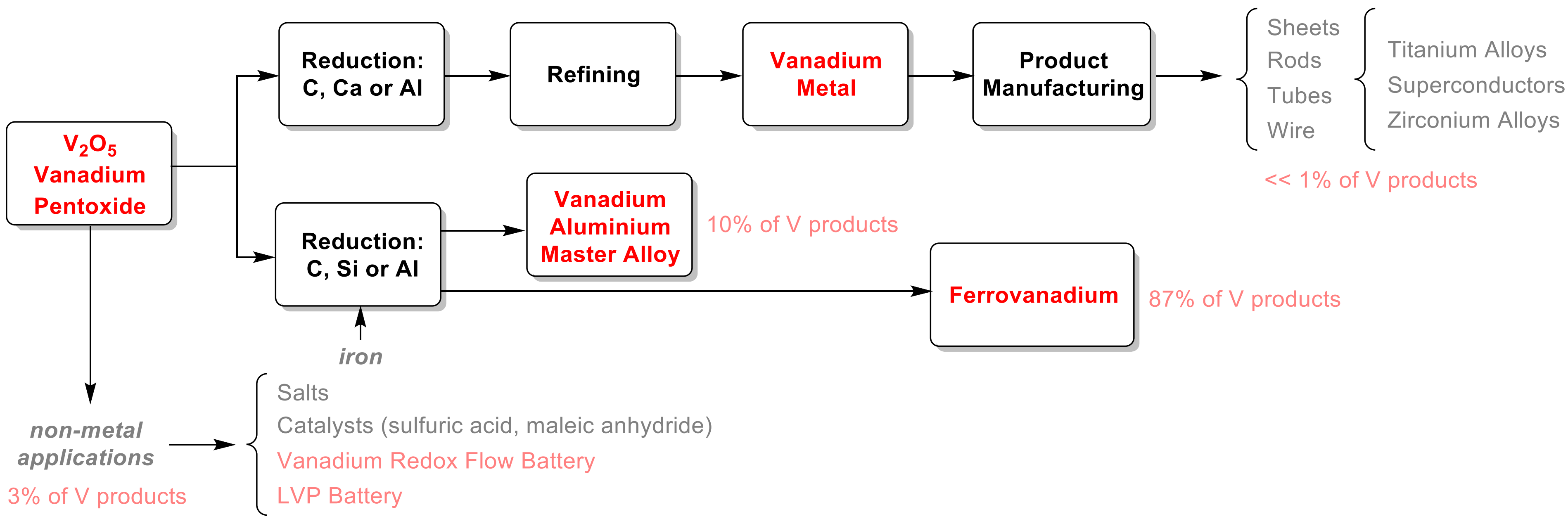

Figure 9 Flowsheet from vanadium pentoxide to finished vanadium products

Whether from titanomagnetite, carnotite, fly ash, or other secondary vanadium sources, the main chemical intermediate produced is **vanadium pentoxide** V_2O_5. Different processing routes link vanadium pentoxide to diverse vanadium products.

As the steel industry still accounts for most of the vanadium demand, products such as ferrovanadium make up most of the vanadium products. Ferrovanadium's most common grade is FeV80 (80% vanadium), but content can range from 35 to 85%. Ferrovanadium is mainly obtained from aluminum reduction, also known as **aluminothermic reduction**, a very exothermic reaction.[65] Vanadium oxide is mixed with aluminum, iron scrap, an initiating mixture and flux (such as lime) in an electric arc furnace. After initiation with the electric arc, the reaction is self-sustaining. The reaction is quick and only requires a few minutes while cooling the furnace can take several days. FeV60, 80, and even FeV90 can be produced this way.[16] Instead of aluminum, silicon or carbon can also be used for this reduction reaction, but the silicothermic reduction suffers from low yield and low profitability, while the carbothermic reaction will also form vanadium carbide, and has been supplanted by the other two methods. Other vanadium alloys can be obtained *via* similar processes.

Vanadium metal can also be obtained through a similar reduction of V_2O_5 in the absence of iron. Carbon, calcium or aluminum can be used as a reductant, although the carbothermic reaction is rarely used, while the aluminothermic method in inert a also seems to be preferred by the industry.[66] After the reduction, refining through either electron-beam melting or after crushing and heating in a vacuum can be performed to obtain high-purity vanadium ingots. Further refining methods include iodide refining (Arkel process), molten salt electrolysis or electro-transport. The Arkel process can notably yield 99.95% pure vanadium.

The vanadium electrolyte used for VRFB is usually a sulfuric acid solution containing vanadyl sulfate salts $VOSO_4$ and $V_2(SO_4)_3$. The original method to synthesize electrolytes developed by the Skyllas-Kazacos team was to dissolve the **vanadyl sulfate** $VOSO_4$ blue solid in sulfuric acid. However, $VOSO_4$ is expensive, and has to be prepared by reducing V_2O_5 with sulfur dioxide in aqueous sulfuric acid. Since then, methods using more inexpensive V_2O_5 directly (or vanadium trioxide V_2O_3) to prepare electrolytes were developed, amongst which: the dissolution of V_2O_5 in sulfuric acid and its subsequent reduction (using oxalic acid, ascorbic acid, *etc.*) to yield V(IV) electrolyte; or the electrolytic reduction of V_2O_5 in an electrolytic cell with sulfuric acid under direct current, producing V(IV) and V(III) electrolytes. Other methods completely bypassing the use of V_2O_5 have been proposed, such as the solvent extraction of vanadium-containing wastewater or leaching solution to produce $VOSO_4$ or even the leaching and solvent extraction of vanadium slag. More detailed descriptions of those processes can be found in the literature.[67–69]

3.3.3.2 Vanadium Circularity and Recyclability

The data on vanadium recycling is uncertain but generally appears low. In 2011, the UNEP estimated Vanadium's general End-of-Life recycling rate to be lower than 1%.[70] Similarly, the EU accounted for an end-of-life recycling input rate of 1% for the EU in 2022.[71] These old scrap analyses focus on recycled vanadium after usage, which is mainly spent catalysts and chemicals collected and treated to manufacture new catalysts. The U.S. Geological Survey's annual mineral commodity summaries stated that from the 2010s until 2022, the quantity of vanadium recycled from spent catalysts could account for as much as 40% of the total vanadium catalysts in the U.S. More recent summaries from the same institution disclose that the uncertainty for this figure was significant.[54]

Vanadium from alloys can be recycled by re-melting it into a similar alloy, especially in the case of tool steel scrap,[65] but as the V concentration in those alloys is low, it is not specifically collected, and the addition of different steel scrap feed will ultimately dilute vanadium.[50]

Vanadium in VRFB is easy to recycle; in 2021, U.S. Vanadium showed a 97% recovery rate when recycling electrolytes from decommissioned vanadium flow batteries. [72]

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