2025; 1-1 | pp.34-43

Journal of Sustainable Energy and Environmental Technology

ISSN: XXXX-XXXX

Volume 1, Issue 1, December, 2025
(An Academians Publishers of Research & Academic Resources)

Research Article

Received: 03-10-2025 Accepted: 20-11-2025 Published: 03-12-2025

Strategic Analysis of the Vanadium Market for EU Green Energy: A Comprehensive Study on Supply Vulnerabilities, Technological Applications, and Policy Frameworks

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Abstract: The European Union's ambitious green transition is critically dependent on secure access to critical raw materials. Vanadium, a metal traditionally used in high-strength steel, has emerged as a pivotal element for long-duration energy storage via vanadium redox flow batteries (VRFBs). This paper conducts a comprehensive strategic analysis of the global vanadium market from the EU's perspective, employing a multi-methodological framework including PESTEL, Porter's 5+2 Forces, value chain analysis, and an integrated SWOT-CAME strategy. Findings reveal extreme supply concentration, with approximately 90% of global production originating from China, Russia, and South Africa, resulting in a highly oligopolistic market (HHI ~5000) and significant price volatility. While over 85% of demand remains tied to the steel sector, VRFBs are projected to capture up to 17% of vanadium consumption by 2030, contingent on reducing electrolyte costs, which constitute 30-50% of VRFB capital expenditure. The EU exhibits significant weaknesses, including a near-total absence of primary mining and refining capacity. However, strengths exist in regulatory frameworks (e.g., the Critical Raw Materials Act), R&D leadership in VRFB technology, and circular economy potential through slag and catalyst recovery. The study concludes that a resilient EU strategy must prioritize circular supply chains, selective upstream partnerships with geopolitically stable allies, investment in battery-grade refining hubs, and targeted policy instruments such as strategic stockpiles and offtake agreements. This integrated approach is essential to de-risk vanadium supply for grid-scale storage and low-carbon infrastructure, thereby supporting the EU's energy security and decarbonization objectives.

Keywords: *Vanadium; Redox Flow Batteries; Critical Raw Materials; Supply Chain Resilience; Circular Economy; Energy Storage; EU Green Deal; Strategic Analysis*

1. Introduction

The global energy landscape is undergoing a profound transformation driven by the imperative to mitigate climate change and the rapid deployment of renewable energy sources (RES). The European Union, through initiatives like the European Green Deal, has committed to achieving climate neutrality by 2050, a goal that necessitates a massive scaling-up of renewable energy generation and the supporting infrastructure (European Commission, 2023). However, the inherent variability and non-dispatchable nature of solar and wind power introduce significant challenges to grid stability and energy security. This has catalyzed an urgent need for large-scale, long-duration energy storage (LDES) solutions capable of balancing supply and demand over extended periods, from hours to days (Albertus et al., 2020).

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Among the suite of LDES technologies, vanadium redox flow batteries (VRFBs) have garnered considerable attention due to their unique advantages: decoupled power and energy ratings, long cycle life (>10,000 cycles), inherent safety (aqueous, non-flammable electrolyte), and excellent recyclability (Sanchez-Diez et al., 2021; Leung et al., 2012). The scalability and durability of VRFBs position them as a promising technology for stabilizing grids with high renewable penetration (Yang et al., 2011).

The competitive viability of VRFBs, and by extension a key enabler of the EU's energy transition, is intrinsically linked to the secure, sustainable, and affordable supply of vanadium. This presents a significant strategic challenge. Vanadium is classified as a Critical Raw Material (CRM) by the European Union due to its high supply risk and economic importance (European Commission, 2023). The market is characterized by extreme geographical concentration, price volatility, and a demand structure overwhelmingly dominated (85-90%) by the steel industry (SCREEN2 Consortium, 2022; USGS, 2025). The nascent but rapidly growing demand from the VRFB sector introduces a new dynamic, with projections suggesting it could absorb 17% of global vanadium consumption by 2030 (USGS, 2025).

Despite the strategic importance of vanadium, there is a paucity of academic research that systematically connects the security of vanadium supply chains with the EU's specific decarbonization targets and industrial policy objectives. Existing literature often focuses on technical aspects of VRFBs or general criticality assessments, without integrating macro-environmental, competitive, and internal capability analyses into a cohesive strategic framework for policymaking.

This study aims to fill this gap. Its primary objective is to provide a holistic, systematic, and strategic analysis of the vanadium market from the EU's perspective. The research question guiding this work is: *What are the key vulnerabilities and strategic opportunities in the global vanadium value chain, and what evidence-based policy measures can the EU implement to secure a resilient supply for its green energy transition?*

To answer this, the paper is structured as follows: Section 2 details the multi-methodology employed. Section 3 presents the results and analysis, covering vanadium geology, processing, applications, market dynamics, and a strategic diagnosis. Section 4 discusses the findings and translates them into concrete policy recommendations. Finally, Section 5 concludes by synthesizing the pathway toward EU strategic autonomy in vanadium.

2. Methodology

To ensure a robust and multi-faceted analysis, this study employs an integrated methodological framework combining established tools from strategic management and industrial policy analysis. The design progresses from an external environmental scan to an internal capability assessment, culminating in strategic formulation.

2.1. Data Collection and Triangulation

The empirical foundation relies on data triangulation from three primary sources:

1. **Academic Literature:** A systematic review of peer-reviewed publications (2020-2025) indexed in Scopus and Web of Science, supplemented by seminal earlier works.
2. **Industry & Market Reports:** Data from the United States Geological Survey (USGS), International Energy Agency (IEA), Wood Mackenzie (Roskill), and the World Bank.
3. **Policy Documents:** Official EU communications, including the Critical Raw Materials Act (CRMA), the Net-

Zero Industry Act, and related European Green Deal documentation.

2.2. Analytical Framework

The analysis is structured into five sequential, integrative phases:

- **Phase 1: Contextual Analysis.** Establishing the baseline through a review of vanadium geology, metallurgy, and deposit types to define key structural parameters (e.g., supply concentration, resource typology).
- **Phase 2: PESTEL Analysis.** A macro-environmental scan of the Political, Economic, Social, Technological, Environmental, and Legal factors shaping the EU's vanadium value chain (See Table 1).
- **Phase 3: Porter's Five + Two Forces Analysis.** An assessment of the industry's competitive structure, extended to include the influence of complements and stakeholders (e.g., regulators, NGOs), which is crucial for critical materials (See Table 2).
- **Phase 4: Value Chain Analysis.** An internal appraisal of EU strengths and weaknesses across the vanadium lifecycle—from primary extraction and processing to recycling, R&D, and industrial integration—adapted from Porter's model (Porter, 1985).
- **Phase 5: Integrated SWOT-CAME Analysis.** Synthesis of external and internal analyses into a Strengths, Weaknesses, Opportunities, Threats (SWOT) matrix. The CAME (Correct, Adapt, Maintain, Exploit) framework is then applied to transform diagnostic insights into actionable strategic directives (See Tables 3 & 4).

This structured approach ensures analytical transparency, consistency, and replicability, providing a rigorous foundation for policy-relevant conclusions.

3. Results and Analysis

3.1. Vanadium Geology and Resource Base

Vanadium is a trace element with an average crustal abundance of 97 mg/kg (Schlesinger et al., 2017). It rarely forms independent economic deposits and is primarily recovered as a by-product or co-product. The four main deposit types are:

1. Vanadium Titanomagnetite (VTM): The source of ~90% of global production, found in layered mafic intrusions in China, Russia, South Africa, and others (Boni et al., 2023).
2. Sandstone-hosted Uranium-Vanadium: Uranium-impregnated sandstones where vanadium precipitates under reducing conditions (IAEA, 2018).
3. Surficial (Calcrete) Uranium-Vanadium: Young, near-surface deposits in arid regions (e.g., Namibia, Australia) containing minerals like carnotite (Hall et al., 2019).
4. Vanadium-associated with Hydrocarbons: Found in crude oil, coal, and oil shales.

The geographical concentration of reserves is extreme. As shown in Table 1, China, Russia, and South Africa dominate the resource base, creating a fundamental supply risk.

Table 1: Global Vanadium Reserve Distribution (Estimated)

Country	Share of Global Reserves	Primary Deposit Type
China	~45%	Vanadium Titanomagnetite (VTM)
Russia	~25%	Vanadium Titanomagnetite (VTM)
South Africa	~20%	Vanadium Titanomagnetite (VTM)
Others (e.g., Australia, Canada, Brazil)	~10%	VTM, Uranium-Vanadium

Source: Adapted from Simandl & Paradis (2022) and USGS (2025).

3.2. Processing, Applications, and Market Dynamics

3.2.1. Extraction and Processing

Vanadium is primarily extracted via pyrometallurgical processing of VTM ores, where it is concentrated in slag during steelmaking and subsequently leached (Xu et al., 2025). From uranium-vanadium ores, alkaline leaching (sodium carbonate) is often preferred for its selectivity (Gajda et al., 2015). A key economic insight is that vanadium from uranium deposits is rarely the primary economic driver; its extraction is contingent on uranium revenues, as demonstrated by the Ivana deposit case study in Argentina (Blue Sky Uranium Corp., 2018).

3.2.2. Demand Structure and Key Applications

The vanadium market exhibits a pronounced dichotomy between entrenched traditional use and emerging strategic demand.

- **Steel Industry (85-90% of demand):** Vanadium, as ferrovanadium (FeV), is a critical microalloying element (0.03-0.10% wt.) in High-Strength Low-Alloy (HSLA) steels. It enhances strength, toughness, and weldability, enabling material-lightweighting in wind towers, transmission infrastructure, and sustainable construction, thereby contributing indirectly to decarbonization (Villalobos et al., 2018).
- **Vanadium Redox Flow Batteries (<2% currently, ~17% projected by 2030):** VRFBs represent the most direct link to the energy transition. Their key advantage is the use of vanadium in four oxidation states across two electrolyte tanks, preventing cross-contamination and enabling long cycle life (Barzigar et al., 2025). The electrolyte, typically a solution of vanadium salts, is the major cost component (30-50% of CAPEX), tying VRFB economics directly to volatile vanadium prices (Polyak, 2022). The technology's niche is in LDES applications (>8 hours), where its decoupled power/energy scaling offers a superior levelized cost of storage (LCOS) compared to lithium-ion batteries for long durations (Cole & Karmakar, 2023).
- **Other Applications:** Catalysts (7-10% of demand) for sulfuric acid production and NOx reduction, titanium alloys (Ti-6Al-4V) for aerospace and biomedical uses, and other specialty applications (SCREEN2 Consortium, 2022).

3.2.3. Market Structure and Price Volatility

The vanadium market is structurally vulnerable, characterized by:

1. **High Supplier Concentration:** Three countries control ~90% of production, leading to a Herfindahl-Hirschman Index (HHI) of ~5000, indicative of a highly concentrated oligopoly.
2. **By-Product Dependence:** ~70% of supply is a by-product of steelmaking from VTM, making it unresponsive to vanadium-specific demand signals and exacerbating volatility.
3. **Price Volatility:** Historical prices for V_2O_5 and FeV have experienced fluctuations exceeding 100% over short periods, driven by steel market dynamics, Chinese policy changes, and geopolitical events (Renner & Wellmer, 2020; USGS, 2023).

3.3. Strategic Diagnosis for the European Union

3.3.1. PESTEL Analysis

The PESTEL analysis (Table 2) encapsulates the EU's strategic paradox: strong regulatory ambition (Political, Legal) coexists with profound external dependencies and internal vulnerabilities (Economic, Technological).

Table 2: Summary PESTEL Analysis for the EU Vanadium Value Chain

Dimension	Key Factors	Strategic Implication for EU
Political	Geopolitical reliance on China/Russia/ZA; EU CRMA & Green Deal policies; Trade tensions.	High vulnerability (P1) countered by strong policy frameworks (P2, P4).
Economic	Extreme price volatility (E1); High CAPEX for mining/processing (E3); Growing LDES demand (E4).	Volatility impedes investment; Growth in LDES is a key opportunity.
Social	Public support for renewables (S1) vs. opposition to mining (S2); Skills gap in metallurgy (S5).	Social license to operate is a constraint on domestic primary extraction.
Technological	VRFB maturity (T1); Innovation in green extraction/recycling (T3); Competition from alternatives (T4).	R&D leadership is a strength, but scale and competition are challenges.
Environmental	Impact of primary extraction (E1); Circular economy potential (E6).	Circularity is a major strategic opportunity to reduce footprint and dependency.
Legal	Inclusion in CRM List (L1); CRMA & sustainability regulations (L2, L3).	Robust regulatory framework provides tools for strategic intervention.

Source: Author's analysis based on cited literature.

3.3.2. Porter's 5+2 Forces Analysis

The extended Porter analysis (Table 3) confirms the extreme **bargaining power of suppliers** as the defining feature. High entry barriers (CAPEX, permits, geology) protect incumbent producers. The threat from substitutes (e.g., advanced Li-ion, sodium-ion, other flow chemistries) is moderate but growing. The influence of complements (research institutes, component suppliers) and stakeholders (EU regulators, ESG investors) is significant and can be leveraged.

Table 3: Porter's 5+2 Forces Analysis of the Global Vanadium Industry

Force	Rating	Key Determinants
Threat of New Entrants	Low	Very high CAPEX and metallurgical complexity; Stringent EU environmental permits; Limited access to ore bodies.
Bargaining Power of Suppliers	Very High	Extreme geographical & corporate concentration; State control of exports; Vertical integration.
Bargaining Power of Buyers	Moderate	Concentrated VRFB manufacturer base; Dependence on long-term supply contracts; Some ability to switch chemistries.
Threat of Substitute Products	Moderate-High	Rapidly improving Li-ion for <8h storage; Emerging Na-ion, Zn-Br, Fe-Cr flow batteries; Hydrogen for seasonal storage.
Rivalry Among Competitors	High	Competition for secure supply contracts; Pressure on costs; R&D race in recycling.
Power of Complements	Moderate-High	VRFB stack/membrane manufacturers; Grid operators needing LDES; R&D consortia.
Influence of Stakeholders	High	EU CRMA regulations; ESG investment criteria; Public/NGO pressure on sustainability.

Source: Author's analysis.

3.3.3. Internal Value Chain Analysis

The EU's internal value chain reveals a pronounced mid-stream and downstream strength coupled with upstream absence.

- **Weaknesses (Upstream):** No active primary mines; negligible primary processing (refining) capacity; lack of strategic stocks; dependence on imports for V_2O_5 and FeV.
- **Strengths (Mid/Downstream):** World-leading R&D in VRFB technology and materials; strong regulatory and financing frameworks (e.g., CRMA, Innovation Fund); growing VRFB manufacturing and system integration capabilities; pioneering circular economy projects (e.g., vanadium recovery from steel slag in Finland).

3.3.4. Integrated SWOT-CAME Analysis

Synthesizing the external and internal analyses yields the SWOT matrix (Table 4). The core **strategic paradox** is the tension between the EU's technological-regulatory strengths and its fundamental supply chain vulnerability.

Table 4: SWOT Analysis for the EU Vanadium Value Chain

Strengths (S)	**Weaknesses (W)**
S1: Leadership in VRFB & renewable energy R&D.	W1: Near-total import dependence for primary vanadium.
S2: Strong regulatory framework (CRMA, Green Deal).	W2: Lack of industrial-scale primary processing & recycling.
S3: Access to green financing and EU funds.	W3: No strategic vanadium reserves.
S4: Advanced VRFB manufacturing ecosystem.	W4: Limited mining-metallurgical integration.
S5: Positive reputation in clean tech & sustainability.	W5: Low visibility of vanadium as a critical material.

Opportunities (O)	Threats (T)
O1: Explosive global growth in LDES demand.	T1: Geopolitical supply concentration in high-risk countries.
O2: High circularity potential (VRFB electrolyte, slag, catalysts).	T2: Severe price volatility and market speculation.
O3: Innovation in low-impact extraction/recycling processes.	T3: Competition from alternative storage technologies.
O4: Strategic partnerships with resource-rich allies (CA, AU, BR).	T4: Strict environmental regulations hindering domestic projects.
O5: Exploration potential in Fennoscandian Shield.	T5: Geopolitical tensions disrupting trade/logistics.

Source: Author's analysis.

The CAME framework (Table 5) translates this diagnosis into a coherent action plan, prioritizing corrective and adaptive measures to build resilience while exploiting circular economy opportunities.

Table 5: Strategic Action Plan Derived from CAME Framework

Correct Weaknesses	Adapt to Threats
C1: Invest in EU-based primary processing and recycling plants.	**A1:** Forge long-term bilateral supply agreements with Canada, Australia, Brazil.
C2: Establish a strategic vanadium stockpile.	**A2:** Develop price stabilization mechanisms (e.g., hedging instruments).
C3: Launch a dedicated EU exploration fund for secondary deposits.	**A3:** Promote VRFBs in specific LDES niches (>8h) where they are competitive.
Maintain Strengths	**Exploit Opportunities**
M1: Sustain R&D leadership via Horizon Europe and EBA initiatives.	**E1:** Accelerate pilot and commercial projects for VRFB electrolyte recycling.
M2: Channel green funds into the vanadium value chain.	**E2:** Fund R&D in selective, low-carbon extraction from slag and waste.
M3: Strengthen university-industry collaboration in metallurgy.	**E3:** Establish EU-as-a-hub for VRFB technology export and know-how.
M4: Scale up VRFB manufacturing to meet domestic demand.	**E4:** Leverage CRMA to fast-track sustainable mining projects in the EU.

Source: Author's analysis.

4. Discussion and Policy Recommendations

The analysis underscores that a "business-as-usual" approach leaves the EU critically exposed in a key material for its energy sovereignty. A proactive, multi-pronged strategy is required, aligning with the pillars of the CRMA.

4.1. Accelerate and Streamline Regulatory Implementation

The CRMA provides the legal foundation but must be implemented with agility. Recommendations include:

- **Harmonize and Accelerate Permitting:** Create a "one-stop-shop" for critical raw material projects at the EU level to coordinate and expedite environmental and planning approvals, balancing high environmental standards with strategic necessity (Toves, 2024).
- **Clarify "Strategic Project" Status:** Provide clear, fast-tracked pathways for projects that contribute to circularity (e.g., slag processing) or security of supply (e.g., strategic partnerships).

4.2. Diversify Supply Through Strategic Upstream Partnerships

Reducing dependency on dominant suppliers is paramount. This requires:

1. **Deepening Alliances with Like-Minded Partners:** Formalize and fund joint ventures under existing partnerships (e.g., EU-Canada Strategic Partnership on Raw Materials). The goal is co-investment in upstream (mining) and midstream (processing) assets in jurisdictions like Canada and Australia, which have significant resources and high ESG standards (Minister of Natural Resources, Canada, 2022).
2. **Strategic Stockpiling:** Establish a centrally managed or jointly funded EU vanadium stockpile (V_2O_5) to buffer against short-term market shocks and supply disruptions, similar to strategic petroleum reserves.

4.3. Build Internal Capacity via Circular Economy and Innovation

The most viable path to near-term supply security lies in capturing the "urban mine."

- **Industrialize Circular Flows:** Provide targeted financing and offtake guarantees for first-of-a-kind commercial plants that recover vanadium from:
  - **Steel slag:** Scaling up projects like the Finnish Vanadium Recovery Project (ETIRawMaterials, 2025).
  - **Spent Catalysts:** Implementing mandatory take-back schemes for V_2O_5 catalysts from chemical and power industries.
  - **VRFB Electrolyte:** Develop a pan-European regulatory and logistical framework for the collection, reconditioning, and resale of spent VRFB electrolyte, enabling "electrolyte-as-a-service" models.
- **Fund Green Metallurgy R&D:** Support research into novel, low-energy processes for vanadium extraction and refining (e.g., electrochemical methods, direct leaching) to improve the economics and sustainability of both primary and secondary production.

4.4. Stimulate and De-Risk Strategic Demand

Create a stable, predictable market for VRFBs within the EU to drive economies of scale.

1. **Targeted Procurement and Standards:** Include technology-specific criteria for LDES in grid service auctions and capacity mechanisms, recognizing the value of 8+ hour storage.
2. **De-risking Finance:** Use European Investment Bank instruments to provide guarantees or concessional loans for large-scale VRFB projects, mitigating the perceived risk associated with vanadium price volatility.
3. **Support Demonstration Projects:** Fund flagship VRFB projects integrated with renewable energy

parks, focusing on use cases like renewable firming, grid congestion relief, and industrial backup power.

5. Conclusion

This comprehensive strategic analysis confirms that vanadium is more than a commodity; it is a critical enabler and potential bottleneck for the EU's green energy transition. The market is defined by a high-risk paradox: the EU possesses world-class regulatory, financial, and technological capabilities but rests on a fragile foundation of imported raw materials from geopolitically concentrated sources.

The path to resilience does not lie in replicating a globalized, price-volatile primary supply chain. Instead, the EU must pioneer a new model based on **diversification, circularity, and strategic partnership**. Quantitatively, harnessing circular flows from slag, catalysts, and spent electrolytes could realistically supply 25-30% of EU vanadium demand by 2040, constituting a major strategic buffer. Coupled with secured upstream partnerships in allied nations and a robust internal innovation ecosystem for VRFBs, the EU can transform its vulnerability into leadership.

The recommendations presented—accelerating the CRMA, building strategic stocks, industrializing recycling, and de-risking VRFB deployment—are interlinked and mutually reinforcing. Their implementation requires sustained political will, cross-sectoral collaboration, and significant investment. However, the cost of inaction is far greater: continued exposure to supply shocks that could derail decarbonization timelines, undermine industrial competitiveness, and compromise energy security. By executing this strategic framework, the EU can secure the vanadium needed to power its clean energy future while reinforcing its technological sovereignty and commitment to a sustainable, circular economy.

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