Endangered Element Vanadium: Can the Texas Oil and Gas Sector provide it a Sustainable Future?

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Abstract

Vanadium currently holds position two on the endangered element list. It is vital for emerging medium and large battery storage systems for wind and solar power sources (Chemical Innovation Knowledge Transfer Network, 2017; Ciotola, Maryegli, Colombo, & Poganietz, 2020). Vanadium is a crucial component in metallurgy, aerospace, rail, nuclear and chemical industries; efficient and environmentally friendly reprocessing of the metal is necessary (Zhang et al., 2017; Vanitec Ltd., 2018). Changes in the geopolitical landscape have already begun to affect many areas of the scientific community, namely access to markets as well as mineral commodities supplies required for advanced technology (Polyak, 2017; Moss, Tzimas, Kara, Willis, & Kooroshy, 2013; Ali et al., 2017; Henckens, van Ierland, Driessen, & E, 2016). So diversifying suppliers through more local recycling efforts can simultaneously alleviate uncertainty in supply and create new green jobs in Texas.

Keywords: Vanadium, endangered, elements, critical, minerals, metals, supply-chain, green

Introduction

Researchers have been concerned with the increasing demand for Vanadium (Ciotola, Maryegli, Colombo, & Poganietz, 2020). This issue highlights the uncertainties surrounding supply chain effects posed by possible vanadium shortages in numerous industries. Some identified risks include increased demand for new and more innovative uses for vanadium, supply uncertainties because of geographically concentrated production and geopolitical risks, and reliance on co-production (The American Chemical Society Green Chemistry Institute, 2014). Various industries depend on the availability of certain elements rapidly dwindling in availability due to centralized production from a few mines, countries, and suppliers (A.C.S. Green Chemistry Institute, 2018). The threat to Vanadium availability is significant because the metal has become an element of interest to the energy sector as a component in battery storage devices and carbon capture devices. Redox flow batteries can provide large-scale energy storage. However, one of the drawbacks to commercialization is the high costs of sourcing the electrolyte and manufacturing the battery stack (Kear, Shah, & Walsh, 2012; Ciotola, Maryegli, Colombo, & Poganietz, 2020). Thus, instances such as this have secondary implications for cost reduction by reusing and recycling vanadium materials. Global consumption of energy continues to increase as many emerging economies experience more growth fueled by increased demand for goods and services. Researchers have indicated that this demand is a function of population growth and living standards improvements (Siirola, 2014).

Background on Vanadium Sources and Chemistry

Vanadium is a trace metal that is ubiquitous in the environment. It is the 21st most abundant element in the Earth's crust, namely distributed in igneous and sedimentary rocks. The average crustal abundance is similar to that of Zinc and Nickel (Nriagu, 1998; Huang, Huang, Evans, & Glasauer, 2015). Vanadium is a transition metal found in soil, crude oil, water, and air. Vanadium is a steel-grey, corrosion-resistant metal, which exists in oxidation states ranging from -1 to +5. Metallic vanadium does not naturally occur, and the most common oxidation states are +3, +4, and +5 (Zwolak, 2014). Sources include vanadinite, carnotite, and phosphate rocks (Zwolak, 2014). The element is native to the following: vanadiferous titanomagnetite deposits, sandstone-hosted vanadium deposits, shale-hosted deposits, vanadate deposits, other Magmatic-Hydrothermal Vanadium deposits, and fossil fuels (Kelly, Scott, Polyak, & Kimball, 2017; Hukkanen & Walden, 1985). Other. The V(V) form (VO_3^{+2}) predominates in extracellular body fluids. In contrast, the V(IV) form (VO^{+2}) is the most common intracellular form (Barceloux, 1999). It also plays essential roles in biological systems, namely as a necessary element for many organisms. Many of its various compounds can be toxic and require careful handling. There is no evidence that it plays an essential part in human health. However, it can exhibit insulin-like effects in the vanadate form, which acts as a phosphate analog. However, after exposure to vanadium's inorganic form, adverse health effects are present in the literature.

These vanadium-induced effects are generally carcinogenic, immunotoxic, and neurotoxic (Pessoaa, Garribbab, Santosc, & Santos-Silvac, 2015; Moskalyk & Alfantazi, 2003; Zwolak, 2014; Liu et al., 2012).

Vanadium (V) is the most mobile form of vanadium in surface waters at their natural pH ranges. Vanadium oxide is very potent and can carry out pH-dependent aqueous reactions. These reactions generate multiple anionic species, including the vanadate ion. This species also mimics the phosphate ion. Vanadium (III) and (IV) can accumulate in reducing environments of biological systems (Nriagu, 1998). One such example is the natural product Amavadine, found in the A*manita mascaria* mushroom has been isolated and found to contain the vanadyl ion (VO^{2+}). There is a strong possibility that this compound plays an electron-transfer catalyst role in the mushroom (Asri Nawi & Riechel, 1987; Bayer & Kniefel, 1972; Berry et al., 1999).

Vanadium takes a very high polish, has a high melting point, and good corrosion resistance at low temperatures. It is also an essential byproduct of crude oil and coal processing and a component in metallurgic slags (Moskalyk & Alfantazi, 2003). Vanadium is associated with most crude oil samples obtained from offshore platforms and oil wells associated with marine sources (Dickson & Udoessien, 2012). Vanadium and Nickel form stable organometallic complexes in high molecular weight fractions of crude oil (Nriagu, 1998). It is used in steel alloys, both ferrous and non-ferrous primarily, because of its high tensile strength, hardness, and resistance (Kelly, Scott, Polyak, & Kimball, 2017; Moskalyk & Alfantazi, 2003). There are a limited number of ores from vanadium that can be extracted economically as a single product. So, as mentioned earlier, the mineral appears as a byproduct and coproduct during the extraction of other metals like uranium, iron, and phosphorus (Nriagu, 1998). Vanadium also displays very intricate redox chemistry in the Earth's magma, rocks, sediments, and specific organisms. Some researchers propose that vanadium played a significant role in biological electron transfer systems in the Earth's early history (Huang, Huang, Evans, & Glasauer, 2015).

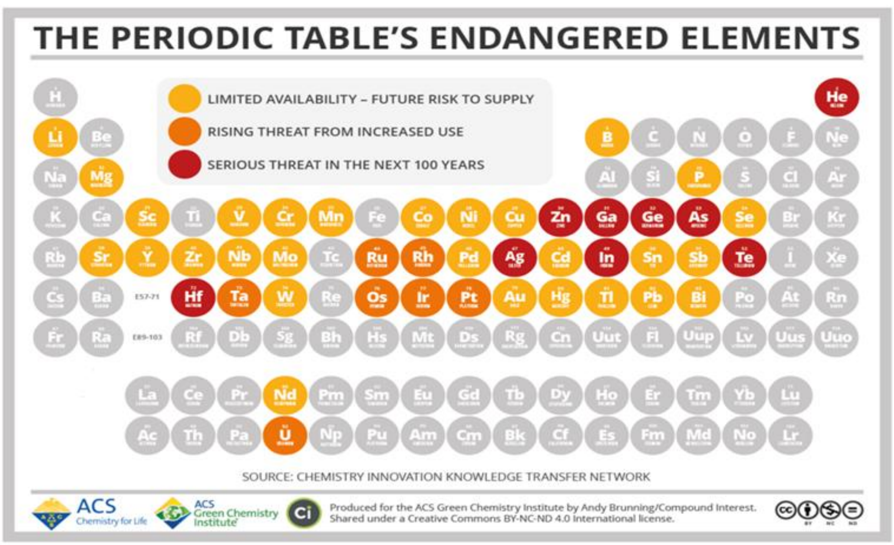

Figure 1 American Chemical Society Endangered Elements (Chemical Innovation Knowledge Transfer Network, 2017)

Industrial Applications of Vanadium

Innovations in Green technologies and sustainable energy systems require minerals that are already on the endangered elements list (Chemical Innovation Knowledge Transfer Network 2017). Metals supply chain security is of great importance due to the high risk of security associated with them and the advantage of recycling end-of-life products (Løvika, Hagelükenb, & Wägera, 2018). The availability of some elemental components might impact further advancements in battery storage and carbon capture devices, catalysts, optically active ceramics, and bioactive glass (Deliormanli, Vatansever, Yesil, & Ozdal-Kurt, 2016; Choi et al., 2017). Researchers have also been working on technologies involving vanadium oxide materials and structures as Lithium-ion battery positive electrodes. The cathode usually limits lithium-ion batteries' capacity, so improving its performance also enhances battery performance. Vanadium oxide (V_2O_5) acts as an intercalation compound because of its layered structure. It has empty lattice spaces of suitable size while conserving its formal lattice structure. Vanadium pentoxide improves performance in organic light-emitting diodes. These diodes are of interest in developing low-cost, lightweight, and flexible displays for organic electronics (McNulty, Buckley, & O'Dwyer, 2014; Saikia & Sarma, 2017).

The production of special vanadium-iron steels, iron and Steel refining, and tempering, in the production of hard metals and temperature resistant alloys, as catalysts, in inks, paints and pigment formulation, in ceramics and welding electrodes all require Vanadium (Nriagu, 1998; Reese, 2000; Zhao, Wei, Man, Li, & Chang, 2016; Fernández-Osorio, Jiménez-Segura, Vásquez-Olmos, & Sato-Berru, 2011; Masui, Honda, Wendusu, & Imanaka, 2013).

The three-layer steel/vanadium alloy/steel composite material is essential as a structural material is super heavy service environments. In the application of severe mechanical loads, the strength and toughness of quenched and tempered steel forms should be used (Rogachev, Sundeev, V, & Khatkevich, 2016; Chen, Zhang, Yang, & Zheng, 2015). Hence, this element's versatility ensures the further development of many new and more innovative technologies. The global push towards "Green Engineering and Technology" requires this fundamental pursuit (Zhang et al., 2017; Rydh, 1999).

In the aerospace division, vanadium guarantees high strength, low density, and the capacity to sustain material strength at high operating temperatures, critical for making components used in applications such as aero-engine gas turbines and aircraft undercarriage manufacturing. These same properties put vanadium in a position vital to the manufacturing of Tools and Dies because it reduces wear at extreme temperatures (Vanitec Ltd., 2018; Viafara, Castro, Velez, & Toro, 2005).

Clean Energy Demands and other Factors Affecting Global Vanadium Supplies

The demand for cleaner forms of energy to mitigate climate change effects is inevitable. It relies upon energy production with new and more efficient technology. Simultaneously, continued population growth has increased global energy consumption as wealth increases globally. So, citizens demand "greener" systems and can better afford them as wealth increases (Siirola, 2014). Therefore, researchers have already begun to utilize the intricate redox patterns demonstrated by vanadium in various renewable energy technologies. An upsurge in demand for vanadium is likely to occur in the future because of the wide range. The construction materials industry and the renewable energy sector are commerce areas where these increases are expected (Huang, Huang, Evans, & Glasauer, 2015).

More and more countries worldwide realize that some critical raw materials sustained availability is coming under increasing pressure. Many nations are dependent upon imports of these raw materials, namely metals and minerals, from sometimes hostile sources. Many advances in technology are dependent upon raw material imports from around the world. Consequently, raw materials security increases concern as we push towards more sustainable commercial goods and supplies. Some experts predict moderate risks to this metal's supply-chain in vanadium's cases to increased demand (Moss, Tzimas, Kara, Willis, & Kooroshy, 2013; E. U. Ad Hoc Working Group on Defining Critical Raw Materials, 2014). Some of the key global supply giants mentioned earlier are China, Russia, and South Africa. There are several upcoming suppliers like Australia and the United States (Moskalyk & Alfantazi, 2003). Therefore, soon increased demand for Steel increases the need for vanadium-related products (Reese, 2000). Since the last election cycle, many political issues have exposed some deep rifts in global political alignments that can potentially disrupt the supply chain.

Recent announcements of Trade tariffs on Steel have already seen U. S. A. Steel prices increase several percentage points since February 2018. The presence of taxes (Tariffs), coupled with supply-chain concerns, adds more uncertainty around particular commodities (D.B.S Group, 2018; Wells Fargo Securities, 2018; Department of Commerce, 2018; Saefong, 2018). Hence, the sometimes-toxic mix of economics and politics can bring undue burdens upon emerging economies, for example, due to shortages in much-needed raw materials like Vanadium (Shahrokhi et al., 2017).

Policymakers have been taking necessary steps to minimize negative impacts on strategic metals supplies through various policy moves. One proposed method is by providing incentives for businesses to find solutions, which can augment any anticipated deficiencies. Materials Essential to American Leadership and Security Act or the METALS Act (H. R. 1407) was introduced on March 17, 2017, by Representative Duncan D. Hunter. The act was to establish the Strategic Materials Investment Fund was under consideration by the United States House of Representatives. The Bill was since referred to House Energy and Commerce Subcommittee on Commerce, Manufacturing, and Trade on 03/17/2017 (United States Congress, 2017). This strategy aims to provide equipment manufacturers with funds to develop the national strategic and critical industrial base. The plan also includes making interest-free, five-year loans to domestic producers of such materials and compensating them for the extra costs of purchasing products made domestically in the United States (United States Congress, 2017).

Additionally, the Secretary of Defense established the Strategic Materials Protection Board to perform specific duties, some of which include but are not limited to the following:

1) Assess the need for a long-term secure source of these materials deemed critical to national security to meet national defense needs.
2) Conduct risk analysis should those materials become unavailable.
3) Recommend means to restore supplies to the Secretary of Defense.
4) Recommend other suitable solutions to the Secretary considered by the Board to strengthen the industrial base as it pertains to materials critical to national security (U.S. Government Publishing Office, 2015)
5) Publish recommendations for critical materials including a list of specialty metals in the Federal Registry at least every two years.

Vanadium Recycling Texas

Recycling is one measure that the E. U., several non-E.U. Nations and the A.C.S. have indicated protecting the environment and presenting gaps in supplies (A.C.S. Green Chemistry Institute, 2018; European Commission DG Environment News Alert Service, 2018; E. U. Ad Hoc Working Group on Defining Critical Raw Materials, 2014). However, in the United States, not much effort is being placed into recycling Vanadium. In 2004 Vanadium consumption in the United States was about 4,052 metric tons encompassing steel manufacturing and manufacturing superalloys, catalyst, cast iron, and other chemicals. Records show that producers recovered more than 2,700 tons of Vanadium-containing spent catalysts. More significant recovery efforts are necessary to stockpile vanadium supplies for future domestic use. Furthermore, recycling the metal in North America as more hydrocarbon resources containing vanadium is anticipated (Goonan, 2011; U.S. Government Publishing Office, 2015).

Additionally, we must also carefully consider the source of the metal for recycling purposes. "A Perspective on Mineral supply for Sustainable development" by Ali et al. (2017) highlighted that the number of time metals for recycling spends in both consumer products and industrial infrastructure affects recycling efforts. Consequently, the increased durability of some products results in a reduction in the material available for recycling. Bearing this in mind, Texas's State might consider the beneficiation of crude oil refinery waste as a vanadium recycling source. Carbon black waste, an oil refinery waste, contains a high concentration of vanadium (V) leftover from crude oil processing (Zhan, Ng, Lin, Koh, & Wang, 2018).

Crude oil is a complex mixture containing sulfur and heavy metals like Nickel and Vanadium. (Gutiérrez Sama, Barrère-Mangote, Bouyssière, Giusti, & Lobinski, 2018). Texas has an economy centered on crude oil and is subject to fluctuations and vulnerabilities in global financial markets, consumption rates, production capacity, and geopolitical instability (Difiglio, 2014; Priest, 2012). On the other hand, this puts Texas in a unique position to lead a more stable economy circular economy based on its oil refining capability. The U. S. Energy Information Administration (E.I.A.) also projects more growth from Texas and New Mexico's Permian region in 2019 and 2020. For that reason, the State of Texas has the potential to be the epicenter for recycling programs from refinery waste. As of October 2020, Texas field production of crude oil is about 143,640 thousand barrels, according to a data release from the E. I. A. on December 31, 2020. Below, Table 1 provides a snapshot of the capacity Texas has in terms of the number of online refineries that can generate enough supplies of wastewater to initiate a severe recycling effort (The U. S. Energy Information Administration, 2020).

Texas Number and Capacity of Petroleum Refineries			
Description	**# Of Series**	**Frequency**	**Latest Data for**
Number of Operable Refineries	3	Annual	2019
Atmospheric Crude Oil Distillation Capacity	6	Annual	2019
Downstream Charge Capacity (Barrels per Stream Day)	28	Annual	2019
Downstream Charge Capacity (Barrels per Calendar Day)	4	Annual	2019

Table 1. Number and Capacity of Petroleum Refineries in the State of Texas in 2019 (The U. S. Energy Information Administration, 2020)

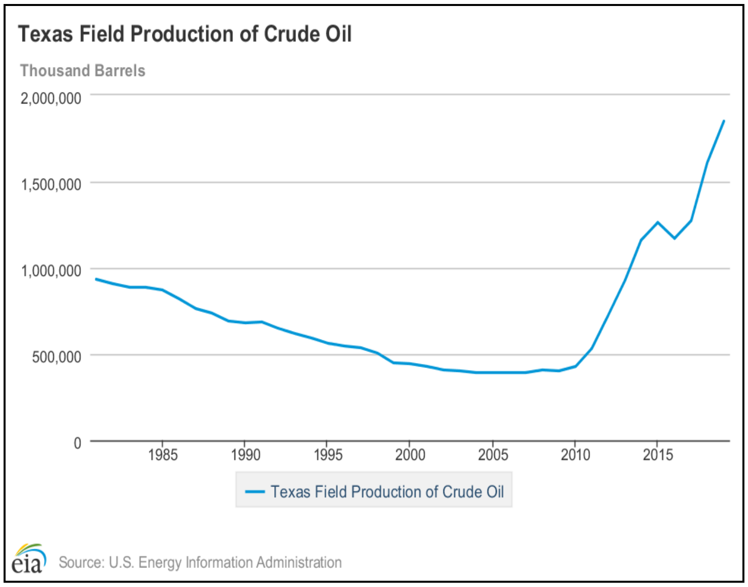

Figure 2 Annual Texas Oil Field Production 2019

Conclusion

Many nations must prepare for the eventuality demands for vanadium is on the rise. They are acknowledging that production concentration in a few countries can soon result in supply-chain risks. The increased need arose from the public and markets' demands to provide greener energy sources and high-quality Steel, indicating supply-chain risks. So significant research is on track to identify effective scientific methods for salvaging residual vanadium from steel-industry waste or steel slag.

European nations have already decided to put measures in place to avoid bottlenecks in the vanadium supply chain. The European Union (E. U.) is also assessing risks to the vanadium supply chain. Members are also compiling some suggestions to stave off a potential crisis. Strategies include reuse and recycling, European production of metal-reducing waste, and finding more sustainable alternatives (E. U. Ad Hoc Working Group on Defining Critical Raw Materials, 2014; Ciotola, Maryegli, Colombo, & Poganietz, 2020).

However, in Texas, we can consider industrial oil refinery waste as a viable resource for vanadium's recovery. Spent vanadium-based catalysts and some vanadium-aluminum alloys from petroleum residues have already begun (Reese, 2000). Researchers have already reported significant recovery amounts of vanadium from converter vanadium slags with about 94.6% recovery rate; this provides a future detailed recycling program (Zhang et al., 2017).

The push towards a more sustainable future has many companies and other entities such as the American Iron and Steel Institute support recycling efforts. The A.I.S.I. has demonstrated its commitment to sustainability by using steel scrap to make new Steel, thus conserving energy, emissions, raw materials, and natural resources. This recycled product still maintains the quality or strength because of Steel's very nature. More than 90 percent of the coproducts from the steel-making process are reused or recycled. Recycled products include slag, water, gasses, dust, and energy (American Iron and Steel Institute, 2018). This example proves that corporate recycling goals are attainable and can generate end products of comparable quality to those made using virgin resources. The vanadium supply chain in Texas can become more secure with assistance from Texas's petroleum industry. Developing and implementing collaborative, sustainable research and waste management initiatives to recycle any post-production vanadium waste is vital. This effort can become even more secure with the benefit of government incentives making future safe supplies of Vanadium to American industries accessible.

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