28 VANADIUM

28.1 Overview

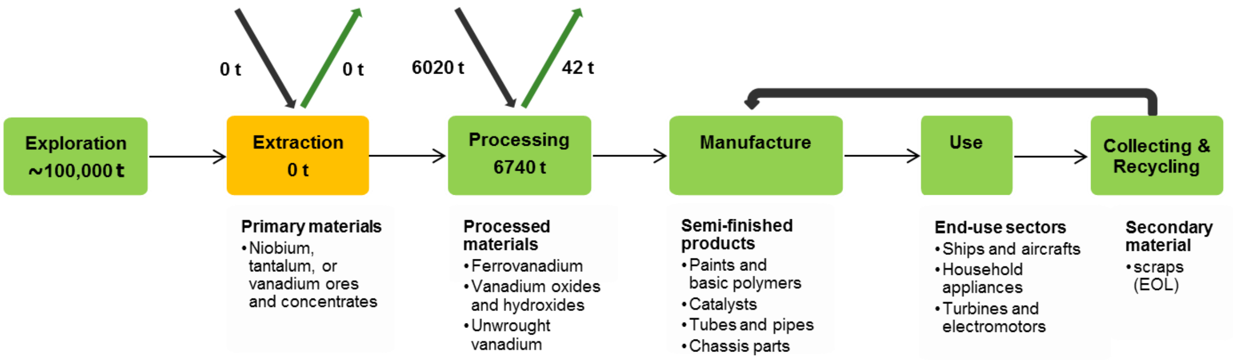

Figure 500: Simplified value chain for vanadium in the EU[287], 2012-2016

Vanadium (chemical symbol V) is a steel-grey, bluish, shimmering and ductile metallic element with the atomic number 23 and a density of 6.11 g/cm^3. Its melting point is 1,910 °C and its boiling point is 3,407 °C. Vanadium occurs in many minerals and is basically obtained as a by-product from the production of steel. Vanadium's earliest use was in 1903, when vanadium-alloyed steel was produced. Vanadium resists corrosion due to a protective film of oxide on the surface. Its main application is as an additive in steel and titanium alloys alloy steels to improve their strength and resistance to corrosion, as well as a catalyst for chemicals (BGS, 2015).

For the purpose of this assessment, vanadium is evaluated at both extraction and processing stage. At mine stage, vanadium is assessed as ore/concentrate (CN8 code 2615 90 90). At processing stage, vanadium compounds are assessed, namely the code "vanadium oxides and hydroxides" (CN8 code 2825 30 00), in the form of V_2O_5 (56% vanadium content). (Eurostat, 2019).

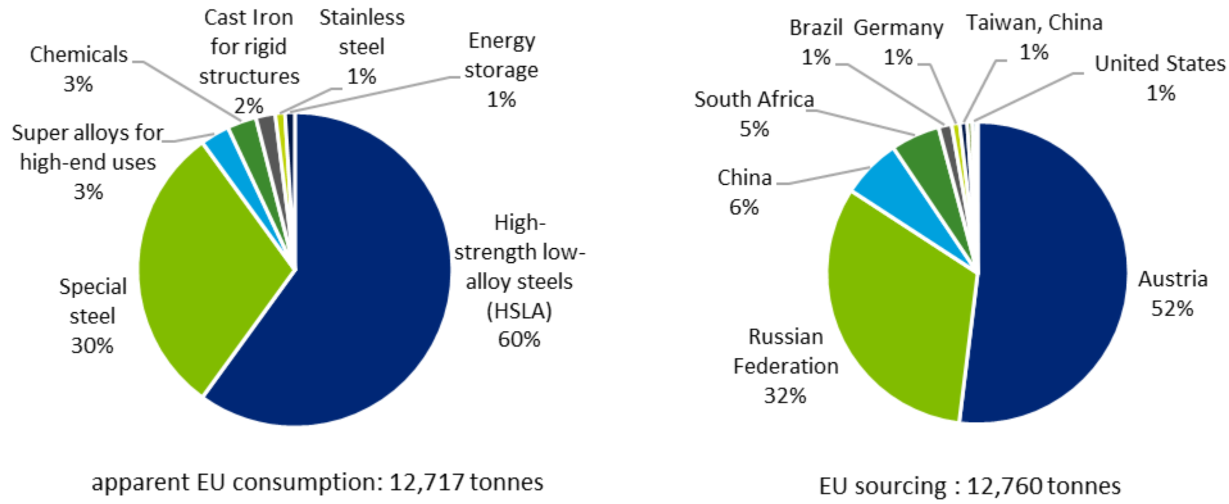

Figure 501: End uses (Atlantic, 2016) and EU sourcing of vanadium (processing stage), average 2012-2016 (Eurostat, 2019; TTP

[287] JRC elaboration on multiple sources (see next sections)

The global market is highly concentrated. Application of vanadium in the vanadium redox battery (close to 2,000 tonnes of vanadium world demand in 2016) is rapidly growing. Some analysts predicted demand for vanadium in this battery type for mass storage of energy (solar, wind) could increase to over 10,000 tonnes per year until circa 2021 (SWEREA, 2016). Demand for vanadium in the EU is projected to increase in all sectors (steel, titanium, chemicals and energy storage), especially driven by increased steel production, compounded by an increasing unit consumption of vanadium per ton of steel (SWEREA, 2016). The majority of ferrovanadium is traded at the open market.

The prices of vanadium are reported to be influenced by production process management costs, rather than by markets and trade developments. Over the last fifteen years, vanadium is one of the materials that have witnessed the greatest price volatility (European Commission, 2017), in spite of relative stable demand levels (55,000-65,000 tonnes per year) in this period. Also recently, in the period May 2018 to April 2019, vanadium showed the highest price volatility (60%) of all materials monitored by DERA, with an upward trend (DERA, 2019b).

The EU does not mine and not import significant amounts of vanadium in ores. At the processing stage, the EU is a net importer of vanadium (oxides), with an EU import reliance of 47%. The average apparent EU consumption of vanadium (vanadium ores) is around 12,700 tonnes per year between 2012 and 2016. The amount of vanadium imported in the shape of oxides[288] to the EU is 6,020 tonnes per year in average for this period, while re-exports are neglectible[289]. For the period 2012-2016, Russia is by far the most important supplier of vanadium oxides to the EU, taking on average 68%, or 4,112 tonnes per year, of the import share to the EU. China and South Africa follow with 815 tonnes per year (14%) and 670 tonnes per year (11%), respectively. The world's main producer of vanadium oxides, China, seems to direct its extractions primarily to other destination outside the EU or use the commodity themselves.

About 80% of the vanadium produced is used as ferrovanadium or as a HSLA[290] additive. Mixed with aluminium in titanium alloys, vanadium is used in jet engines and high speed air-frames, and in terms of tool steel alloys it is used in axles, crankshafts, gears and other critical components. Vanadium alloys are also used in nuclear reactors because vanadium has low neutron-adsorption abilities and it does not deform in creeping under high temperatures (Lenntech, 2016). Vanadium oxide (V_2O_5) is used as a catalyst in manufacturing sulfuric acid and maleic anhydride, and in making ceramics. It is added to glass to produce green or blue tint. Glass coated with vanadium dioxide (VO_2) can block infrared radiation at some specific temperature (Lenntech, 2016). V_2O_3 is used as feedstock for ferrovanadium production due to lower aluminium consumption.

The world resources of vanadium exceed 63,000,000 tonnes (USGS, 2019). Because vanadium is typically recovered as a by-product or co-product, demonstrated world resources of the element are not fully indicative of available supplies. For the EU, the European Minerals Yearbook provides vanadium resources data only for Sweden. Resources in Sweden are estimated to 24,600,000 tonnes (historic resource estimates, 0.43% vanadium), or 140,000,000 tonnes (JORC inferred resources, 0.2% vanadium), respectively (Minerals4EU, 2019). The world known reserves of vanadium are about 20,000,000 tonnes (USGS, 2019). Almost half of these reserves are located in China, and a quarter in Russia. Other important reserves are found in Australia

[288] Processed vanadium can have different forms, while the most important form are vanadium oxides. The most common way of reporting is V_2O_5.

[289] EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

[290] high-strength low-alloy steel

and South Africa. Minor vanadium reserves are reported in Norway, Finland, Sweden, and Ukraine.

During the years 2012-2016, the world annual production of vanadium in ores and concentrates was estimated at 61,400 tonnes in average, which is concentrated in only three countries: China, Russia, and South Africa, making up 96% of the global market (WMD, 2019). Further reported producers of vanadium ores and concentrates in this period were Brazil, Kazakhstan, the United States and Australia. Brazil is indeed a new player as it started extraction only in 2014 (WMD, 2019). Global production of vanadium oxides and hydroxides (vanadium compounds) amounted to 86,300 tonnes per year in average between 2012 and 2016 (TTP Squared, 2019).

The recycling of vanadium is generally very low. Two main kinds of secondary vanadium scrap can be discerned: steel scrap, which was recycled along with the vanadium content, and spent chemical process catalysts. Also certain vanadium-bearing tools can be recycled. The total share of world production of vanadium from secondary sources has increased in the period from 2004 to 2010 and was estimated in 2011 to around 44%. It is important to note that this includes vanadium supply from alloy recycling. Without the consideration of alloy recycling, secondary sources would cover about 15% of the required vanadium input (SWEREA, 2016). There is some economic activity in the EU specialized in vanadium recycling. The end-of-life recycling input rate (EoL-RIR) was determined by the Material Substance Analysis on vanadium to 2% (European Commission, 2019).

28.2 Market analysis, trade and prices

28.2.1 Global market analysis and outlook

Future supply from South Africa has been influenced by the recent closure of Evraz Highveld mine (Evraz Highveld, 2016). Future demand seems to be influenced by innovations in the manufacturing of battery products. Roskill’s vanadium report includes a focused chapter dedicated to the use cases, competing technologies, advantages, disadvantages and economics of vanadium redox batteries. To 2026, it is expected the market for stationary energy storage to increase (Roskill, 2016). Application of vanadium in the vanadium redox battery (close to 2,000 tonnes of vanadium world demand in 2016) is rapidly growing. Some analysts predict demand for vanadium in this battery for mass storage of energy (solar, wind) could increase to over 10,000 tonnes annually until 2025 (SWEREA, 2016).

Demand for vanadium in the EU is projected to increase in all sectors (steel, titanium, chemicals and energy storage), especially driven by increased steel production, compounded by an increasing unit consumption of vanadium per ton of steel (SWEREA, 2016).

Table 213: Qualitative forecast of supply and demand of vanadium

Materials	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Vanadium	x		+	+	+	+	+	+

Since 2016, there were plans that the Mustavaara Kaivos Clean Slag project, Finland, could significantly increase EU vanadium supply[291], and thus reduce the EU's dependence on vanadium imports (SWEREA, 2016). However, this project went into liquidation in early 2019 (GTK, 2019).

28.2.2EU trade

There are no EU imports and exports reported at the extraction stage. At the extraction stage, the code applicable is CN 2615 90 90 "Vanadium ores and concentrates", however there is no data available at Comext. Based on the consultation of the validation workshop, it is considered, that there are no imports[292] at mine stage to the EU, and exports from the EU, respectively.

At the processed stage, trade in vanadium was analysed for "vanadium oxides and hydroxides" (CN 2825 30 00)[293], in the form of vanadium oxide (V_2O_5). Russia is the most important supplier of vanadium oxides to the EU, taking 68% of the import share. China and South Africa follow with 14% and 11%, respectively. The world's main producer of vanadium oxides, China, seems to direct its production predominantly to other destination outside the EU, or use the commodity itself.

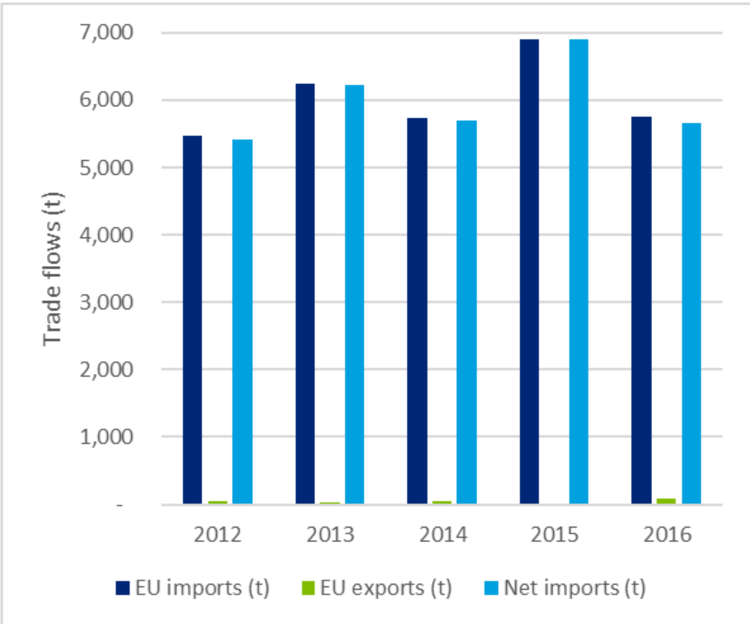

Figure 502: EU trade flows for vanadium oxides and hydroxides, 2012-2016 (Eurostat, 2019)

[291] The expected production amounted to around 5 ktonnes per year of FeV80.

[292] At UN Comtrade, there is no code specific to vanadium (but only mixed with niobium, tantalum, and zirconium) thus there is no way for confirmation with Comtrade data.

[293] EU trade is analysed using product group codes. It is possible that materials are part of product groups also containing other materials and/or being subject to re-export, the "Rotterdam-effect". This effect means that materials can originate from a country that is merely trading instead of producing the particular material.

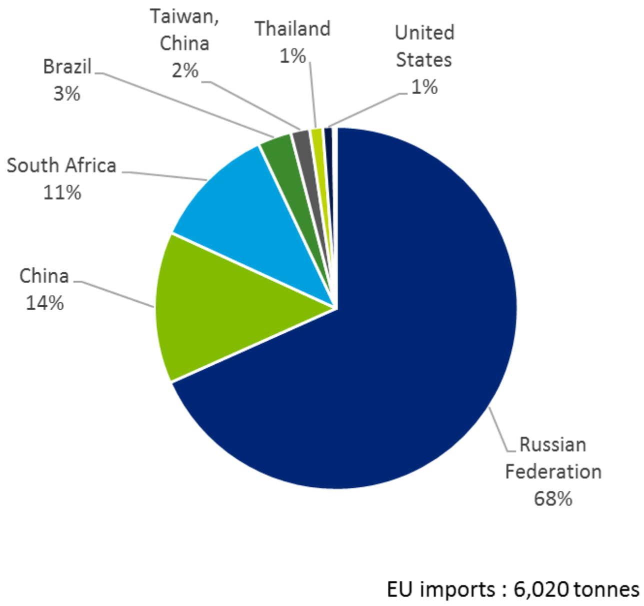

Figure 503: EU imports of vanadium oxides, average 2012-2016 (Eurostat, 2019; Brown *et al.*, 2018)

At extraction stage, export tax and other trade measures have been checked for code CN 2615 90 90, at processing stage for code CN 2825 30 00 (OECD, 2019). For vanadium ores and concentrates (essentially nickel, tantalum and vanadium), an export tax of 30% is reported for China, and one of 2-5% for Burundi (since 2015). For Brazil, a temporary export quota was in force in the amount of 250 tonnes (2012-2013) and 300 tonnes (2014-2015), respectively. Fiscal taxes on exports are reported for Rwanda (4%, since 2013), and for Burundi (FBU 15,000). However, the EU did not import vanadium ores and concentrates during the period 2012-2016. (OECD, 2019)

China, showing an import share of 14% (Eurostat, 2019), is the only country reported to tax vanadium oxides and hydroxides (processed stage), at an export tax rate of 5%. The export tax was already introduced in 2009 and still in force in 2017 (OECD, 2019).

28.2.3Prices and price volatility

Ferrovanadium is traded at the open market, e.g. the global B2B trade platform FerroAlloyNet[294]. Vanadium is associated with two main prices, usually traded in US dollars: one is for the ferroalloy ferrovanadium, and the other for vanadium pentoxide, of which much of the world's ferrovanadium is made of. Both ferrovanadium (70-80%) and vanadium pentoxide have been common forms for trading vanadium. Prices for vanadium ore and vanadium metal are not published.

Vanadium pentoxide has not been traded on the free market, but rather was a producer price, to that effect it showed a low volatility.

[294] http://www.ferroalloynet.com/

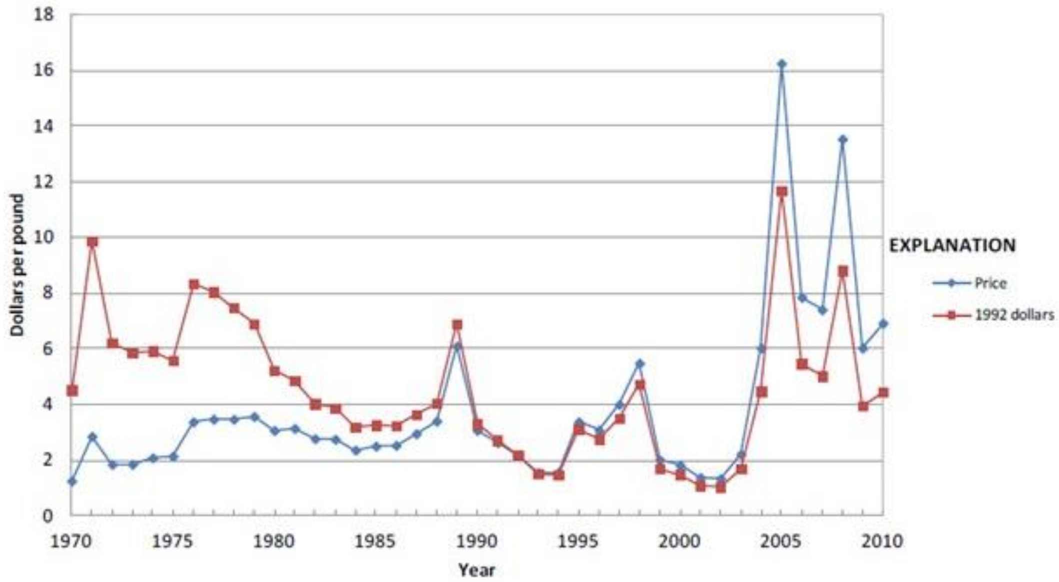

Figure 504: Price development of vanadium pentoxide, 1970-2010 (USGS, 2013)

The prices of vanadium are reported to be influenced by production process management costs, rather than by markets and trade developments. Since 2000 vanadium is one of the materials that have witnessed the greatest price volatility (European Commission, 2017), in spite of relative stable demand levels (55,000-65,000 tonnes per year) in this period. Also recently, in the period May 2018 to April 2019, the volatility of vanadium has the highest volatility (60%) of all materials monitored by DERA, with an upward trend (DERA, 2019b).

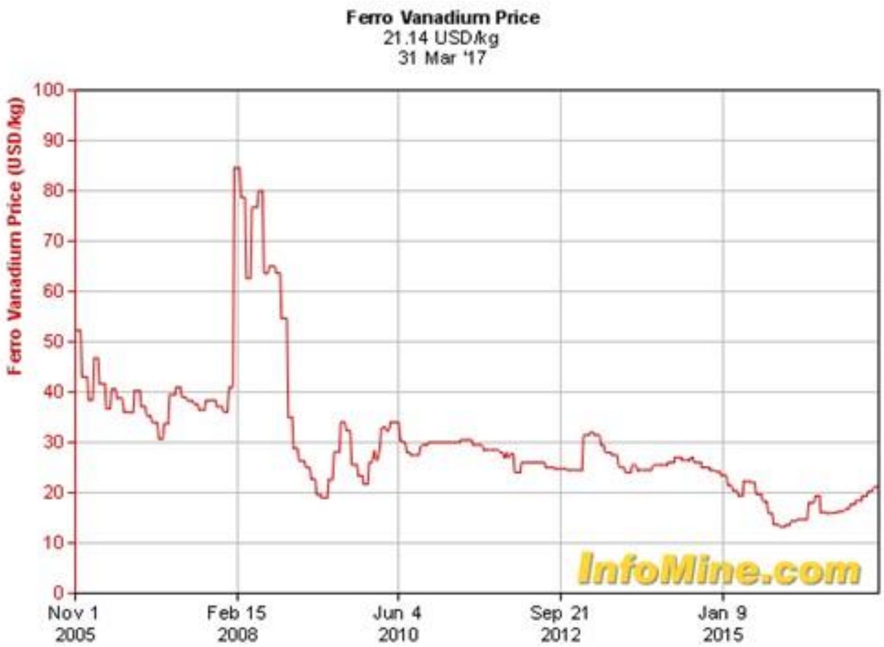

Figure 505: Price development of ferrovanadium,November 2005 to April 2017 (Infomine, 2017)

The average price of ferrovanadium[295] between 2011 and 2015 was US$25.11 per kilogram (DERA, 2016). For the period November 2018 to October 2019, average prices of US$56.0 per kilogram have been reported for ferrovanadium[296] (DERA, 2019a); the price development for October 2017 to October 2019 is shown in Figure 506.

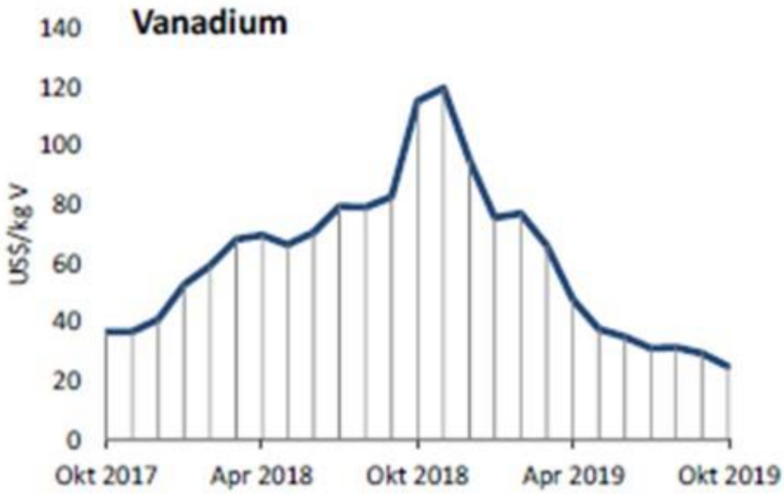

Figure 506: Price development of ferrovanadium, October 2017 to October 2019 (DERA, 2019a)

As vanadium is used to a large degree in the various steel sectors, steel demand has a strong influence on the vanadium supply and price. Given the close relationship between the vanadium and steel markets, the outlook for steel production has a large bearing on the outlook for the vanadium market.(USGS, 2013)

The long-term prices of vanadium oxide (V_2O_5) are shown in

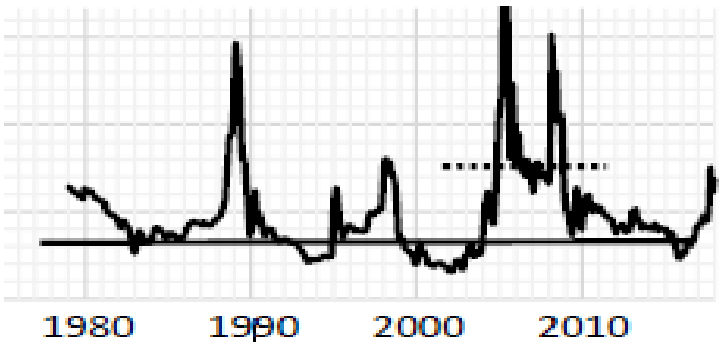

Figure 507. The price curve shows real prices.

[295] containing 78% of vanadium

[296] 70-80% vanadium, cif Europe

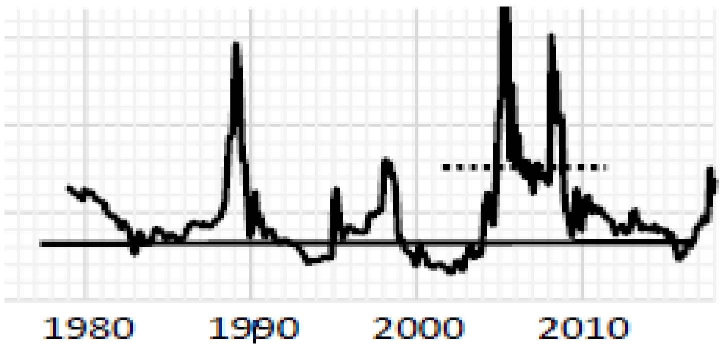

Figure 507: Vanadium oxide prices in US$ per tonne. Vertical dashed line indicate breaks in price specification.(Buchholz *et al.*, 2019)

28.3 EU demand

The world global market of vanadium in ores is about 62,000 tonnes in 2016 (WMD, 2019). Annual worldwide production of processed vanadium (vanadium oxides and hydroxides) is 77,000 tonnes in 2016. Vanadium is a strategic metal for Europe's industries, which used about 13% of worldwide production (11,000 tonnes in 2013) (BRGM, 2017).

28.3.1 EU demand and consumption

The apparent EU consumption[297] (production+imports-exports) of vanadium oxides is around 12,700 tonnes. The amount of vanadium being traded in the form of oxides through the EU as re-exports is around 43 tonnes.

28.3.2 Uses and end-uses of Vanadium in the EU

Vanadium is mainly used for the production of high-strength low-alloy (HSLA) steels, special steels, special alloys and catalysts. The global end-uses of vanadium are shown in Figure 508.

Vanadium is an important alloying element in HSLA steels, tool steels and certain types of other steels. The formation of vanadium-rich carbides and nitrides gives strength to steel, even when a few kilograms of vanadium per ton of steel is added. Furthermore, vanadium also inhibits corrosion and oxidation of the steels. In fact, most of the vanadium produced (about 80%) is used as ferrovanadium or as a HSLA additive.

Vanadium, when combined with titanium, produces a stronger and more stable alloy, and when combined with aluminium in titanium alloys, it produces a material suitable for jet engines and high-speed airframes, while tool steel alloys are used in axles, crankshafts, gears and other critical components. Vanadium alloys are also used in nuclear reactors because vanadium has low neutron-adsorption abilities and it does not deform in creeping under high temperatures (Lenntech, 2016).

[297] apparent EU consumption = domestic production + imports - exports

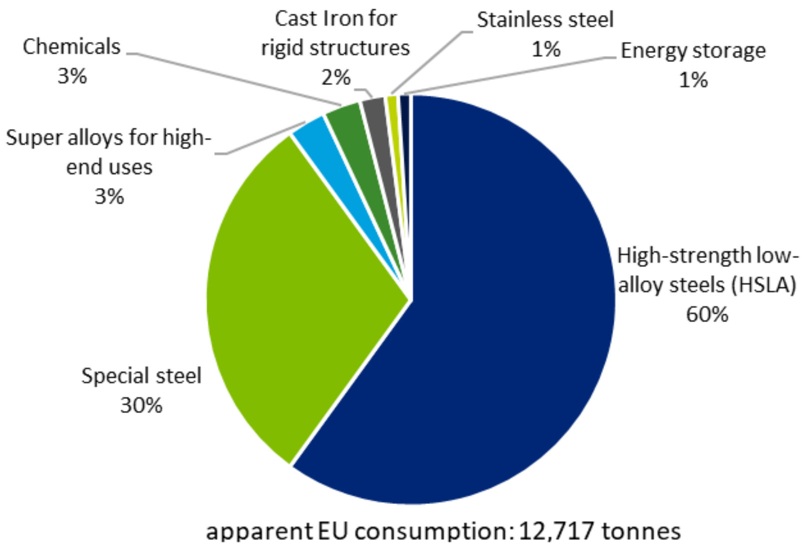

Figure 508: EU end uses of vanadium, average 2012-2016 (Atlantic, 2016)

Vanadium-bearing catalysts are used in hydrocarbon processing to remove nickel and vanadium from the process stream.

Vanadium compounds, in particular vanadium oxide (V_2O_5), is used as a catalyst in manufacturing sulfuric acid and maleic anhydride and in making ceramics. It is added to glass to produce green or blue tint. Glass coated with vanadium dioxide (VO_2) can block infrared radiation at some specific temperature (Lenntech, 2016). V_2O_3 is used as feedstock for ferrovanadium production due to lower aluminium consumption. Figure 508 presents the main uses of vanadium in the EU.

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2016c).

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 214). The value added data correspond to 2013 figures.

Table 214: Vanadium applications, 2-digit NACE sectors, associated 4-digit NACE sectors, and value added per sector (Eurostat, 2019)

Applications	2-digit NACE sector	4-digit NACE sector	Value added of sector (M€)
High-strength low-alloy steels	C24 - Manufacture of basic metals	24.45 Other non-ferrous metal production	55,426
Special steel	C25 - Manufacture of fabricated metal products, except machinery and equipment	25.29 Manufacture of other tanks, reservoirs and containers of metal	148,351
Super alloys for high-end uses	C29 - Manufacture of motor vehicles, trailers and semi-trailers	29.20 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers	160,603
Chemicals	C20 - Manufacture of chemicals and chemical products	20.12 Manufacture of dyes and pigments	105,514
Cast iron for rigid structures	C30 - Manufacture of other transport equipment	29.20 Manufacture of bodies (coachwork) for motor vehicles; manufacture of trailers	44,304
Stainless steel	C28 - Manufacture of machinery and equipment n.e.c.	28.11 Manufacture of engines and turbines	182,589
Energy storage	C27 - Manufacture of electrical equipment		80,745

- **Steel (HSLA – high-strength low-alloy):** The key demand driver at the current time is a move to lighter weight and higher strength steels. The addition of just 0.2% vanadium to steel increases steel strength by up to 100% and reduces weight in relevant applications by up to 30% (Infomine, 2016). Vanadium itself is soft in its pure form, but when it is alloyed with other metals such as iron, it hardens and strengthens them significantly. Consequently, vanadium is used extensively to make alloys (mostly steel alloys) for tools and construction purposes. Most of the vanadium consumed is used for these applications.

- **Steel (Carbon):** Vanadium is also alloyed with iron to make carbon steel, next to the HSLA mentioned above. These hard, strong ferro-vanadium alloys are used for military vehicles and other protective vehicles. It is also used to make car engine parts that must be very strong, such as piston rods and crank shafts.

- **Chemical applications:** Some vanadium is used in other industrial applications. For example, vanadium pentoxide (V_2O_5) is used production of glass and ceramics and as a chemical catalyst.

- **Batteries:** The vanadium redox battery (VRB)[298] is a type of rechargeable flow battery that employs vanadium ions in different oxidation states to store chemical potential energy (Knight, 2014). The use of vanadium in vanadium redox batteries started in the 1980s. Due to their relative bulkiness (amongst others), most vanadium batteries are currently used for grid energy storage, i.e., attached to power plants or electrical grids.

28.3.3Substitution

The substitution of vanadium in all types of steels is basically possible. However, the substitution is limited to only a few degrees by certain elements, such as columbium/niobium, due to poorer performance of common substitutes in the steels. Steels containing vanadium as an alloying component can be replaced by steels containing various combinations of other alloying elements (manganese, molybdenum, niobium, titanium, and tungsten to some extent) (USGS, 2019). However, niobium can only partially substitute vanadium in tool steels, as niobium can hardly contribute to the secondary hardness of tool steels during the heat treatment. A study done on niobium for vanadium substitution in steel making concluded that 46% of vanadium used in steel could potentially be substituted by niobium (Korchynsky, 2004). Replacement of vanadium with other elements requires significant technical adjustments of the steel production process to ensure the product specifications and at the same time to ensure that the quality of the steels is not compromised. Therefore, substitution for vanadium is normally not considered for short-term changes in market conditions because of the considerable effort involved in implementing the change (European Commission, 2017b; USGS, 2017b; USGS, 2017c; Wilmes & Zwick, 2002).

The above substitution options are available for all major uses of ferrovanadium, in tubes and pipes, turbines, automotive parts and building materials. Ferrovanadium used as noble alloy for special steel (FeV80, FeV50) can be substituted partially by ferroniobium. Key factors determining the degree of substitution are the relative price difference between the two FeV and FeNb, as well as the availability of niobium.

In special alloys, vanadium is irreplaceable. Currently, there is no acceptable substitute for vanadium in aerospace applications as vanadium-titanium alloys have the best strength-to-weight ratio of any engineered materials (USGS, 2017c; USGS, 2019).

In catalysts, vanadium can be replaced in some cases by other elements, such as nickel and platinum in several chemical processes (USGS, 2019).

In paints and varnishes, which is a specific part of the chemical applications of vanadium, titanium is a substitute for vanadium use.

Batteries using vanadium are serving a growing market, that has to be assumed can also be served by batteries containing more conventional materials from the alkaline group.

[298] also known as the vanadium flow battery (VFB) or vanadium redox flow battery (VRFB)

28.4 Supply

28.4.1 EU supply chain

There have been around ten major mine corporations engaged in vanadium extraction and refinery, located in the United States, Australia, China, Canada, South Africa, but also in Austria, Germany, and the Czech Republic (European Commission, 2017). Global extraction of vanadium is concentrated in China, Russia and South Africa, making up together 96% of global production. There is no extraction of vanadium in the EU, as well as no imports or exports of vanadium ores and concentrates.

In the EU, Austria (6,630 tonnes, 98%) and Germany (110 tonnes, 2%) produce vanadium oxides. The import reliance of the EU on vanadium oxides is calculated as 47%.

The base metal production in Europe is relatively less specialized in the use of vanadium. Annually, about 2,000 tonnes of ferrovanadium are produced in the Czech Republic (BGS, 2015). There is some economic activity in the EU specialized in vanadium recycling.

China is the only nation to tax vanadium oxides, at a tax rate of 5%. China also taxed vanadium ores and concentrates (essentially nickel, tantalum and vanadium), at a tax rate of 30% (in 2014, only), the Democratic Republic of Congo applies 10% tax, Rwanda shows a fiscal tax of 4% (OECD, 2016). Brazil applied an export quota of 300 tonnes per year. The Democratic Republic of Congo has a licensing requirement. There are a limited number of trade restrictions being applied to vanadium metal: Morocco, Vietnam and Argentina have a tax on vanadium, whereas China applies an export quota of 231 tonnes (OECD, 2016).

28.4.2 Supply from primary materials

28.4.2.1 Geology, resources and reserves of vanadium

Geological occurrence: The presence of vanadium in the earth's crust is moderate, with 97 ppm[299] upper crustal abundance (Rudnick & Gao, 2003); in seawater it is estimated to be about 0.0014 ppm. Among 65 minerals that contain vanadium, the most common vanadium minerals include magnetite (Fe_3O_4), patronite (VS_4), vanadinite [$Pb_5(VO_4)_3Cl$], and carnotite [$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$]. Vanadium is also present in phosphate, bauxite and iron ores. Moreover, it is present in fossil fuel deposits such as oil and coal. The main host mineral of oxidic vanadium ores is vanadium-bearing magnetite, commonly found in gabbro ore bodies. Typical vanadium grades are 0.7-1.5%.

Global resources and reserves[300]: Vanadium is found in certain iron ores, from which it can be extracted (BRGM, 2017). The world resources of vanadium exceed 63,000,000 tonnes (USGS, 2019). Because vanadium is typically recovered as a by-product or co-product, for example from

[299] parts per million

[300] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of vanadium in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template.[300], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

iron ores, demonstrated world resources of the element are not fully indicative of available supplies.

The world known reserves of vanadium (material content) are about 20,000,000 tonnes (USGS, 2019). Almost half of these reserves are located in China, and a quarter in Russia. Other important reserves are found in Australia and South Africa (Table 215).

Table 215: Estimated global reserves of vanadium in 2019 (USGS, 2019; GTK, 2012)

Country	Estimated Vanadium Reserves (tonnes)
China	9,500,000
Russia	5,000,000
South Africa	3,500,000
Australia**	2,100,000
Brazil	130,000
USA	45,000
Norway*	55,000
Finland*	25,000
Sweden*	15,000
Others	N/A
World total (rounded)	**20,000,000**

* Data from (USGS, 2015). ** For Australia, Joint Ore Reserves Committee-compliant reserves were about 1.3 million tons.

Compared to 2017, novel estimates for Brazil reserves were provided, and Chinese reserves increased by 500,000 tonnes based on government reports. Also the Australian reserves were increased by 300,000 tonnes. In summary, the reserves thus increased from by 1,000,000 tonnes in 2017 to 20,000,000 tonnes in 2019.

EU resources and reserves[301]: For the EU, the European Minerals Yearbook provides vanadium resources data only for Sweden (Table 216). Historic estimates amount to to 24,600,000 tonnes (0.43% vanadium), while inferred resources amount to 140,000,000 tonnes (JORC, 0.2% vanadium) . These cannot be summed as they do not use the same reporting code.

[301] For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for vanadium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for vanadium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for vanadium the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Table 216: Resource data for Europe compiled in the European Minerals Yearbook (Minerals4EU, 2019)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Finland	JORC	62.15	Mt	0.13 % V	
	JORC	6.55	Mt	0.12 % V	
Sweden	Historic code	24.6	Mt	0.43 % V	Historic resource estimates
	JORC	140	Mt	0.2 % V	inferred

In the SCRREEN project, further information is provided on vanadium resources in Finland, Bulgaria, Estonia, Greenland, Norway, Poland, Sweden and the United Kingdom (Lauri *et al.*, 2018).

In Europe, vanadium reserves are reported in Norway, Finland, Sweden, and Ukraine, but together they make up less than 1% of the global reserves (USGS, 2019; GTK, 2012; Minerals4EU, 2019). The European Mineral Yearbook does not report reserves for the EU member states, but provides reserves data only for Ukraine, with 15,500 tonnes of V_2O_5 contained in vanadium ores (Table 217).

Table 217: Reserve data for Europe compiled in the European Minerals Yearbook (Minerals4EU, 2019)

Country	Reporting code	Value	Unit	Grade	Code Reserve Type
Finland	JORC	99,000,000	t	unknown. ilmenomagnetite	
	JORC	62,150,000	t	0.13 % vanadium	
	JORC	6,550,000	t	0.12 % vanadium	
Ukraine	Russian Classification	-/-/3,493,000	t	n/a / n/a / n/a vanadium ore	A/B/C1
		-/-/15,500	t	n/a / n/a / n/a vanadium ore, V_2O_5 contained	A/B/C1

28.4.2.2 World mine production

Global mine production of vanadium from vanadium ores and concentrates between 2012 and 2016 amounted to about 61,400 tonnes per year in average. The main producers of vanadium ores are China, South Africa, Russia, Brazil, and Kazakhstan, United States, and Australia. Brazil is a new player on the vanadium market as it started the extraction only in 2014 (WMD, 2019).

Although Europe has some vanadium resources, these are mainly deposits of titanium-bearing iron ore containing about 1% of vanadium, or steel slag containing up to 3%. Mining these resources is not economically viable (BRGM, 2017). There is no production of vanadium ores and concentrates in the EU (Brown *et al.*, 2018).

The global mine production of vanadium is shown in Figure 509.

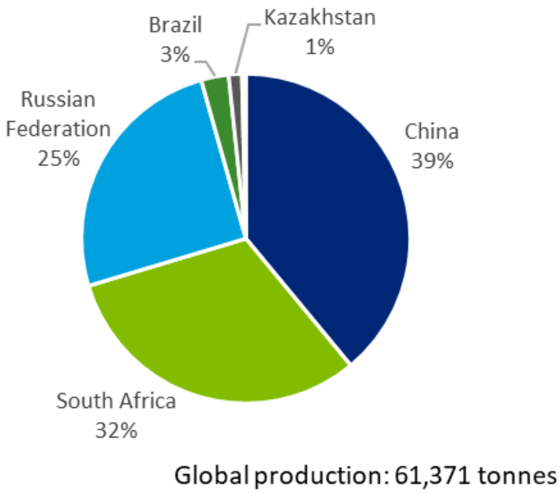

Figure 509: Global mine production of vanadium in tonnes, average 2012–2016 (WMD, 2019)

28.4.3Supply from secondary materials/recycling

The recycling of vanadium is generally very low. Two main kinds of secondary vanadium scrap can be discerned: steel scrap, which was recycled along with the vanadium content, and spent chemical process catalysts. Also certain vanadium-bearing tools can be recycled.

The total share of world production of vanadium from secondary sources has increased in the period 2004-2010 and is now believed to be still at around 44%. Important to note is that this includes vanadium supply from alloy recycling. Without the consideration of alloy recycling, secondary sources would cover 15% of the required vanadium input (SWEREA, 2016). There is some economic activity in the EU specialized in vanadium recycling.

28.4.3.1 Post-consumer recycling (old scrap)

End-of-life vanadium recycling takes place by the recycling of vanadium-containing steel scraps. The scrap is collected and segregated by material specification. Typical post-consumer recycling comprise spent catalysts, which are collected and then treated in induction furnace operations. The EoL-RIR of vanadium in the EU for the period 2012-2016 is 2% (Table 218) (European Commission, 2019).

USGS reports that the end-of-life recycling rate is 44% for the United States (Goonan, 2011).

Table 218: Material flows relevant to the EoL-RIR of Vanadium, average 2012-2016 (European Commission, 2019)

MSA Flow	Value (t)
B.1.1 Production of primary material as main product in EU sent to processing in EU	0
B.1.2 Production of primary material as by product in EU sent to processing in EU	640
C.1.3 Imports to EU of primary material	6,962
C.1.4 Imports to EU of secondary material	0
D.1.3 Imports to EU of processed material	9,236
E.1.6 Products at end of life in EU collected for treatment	7,425
F.1.1 Exports from EU of manufactured products at end-of-life	1,602
F.1.2 Imports to EU of manufactured products at end-of-life	16
G.1.1 Production of secondary material from post consumer functional recycling in EU sent to processing in EU	292
G.1.2 Production of secondary material from post consumer functional recycling in EU sent to manufacture in EU	0

28.4.3.2 Industrial recycling (new scrap)

The collection and handling of vanadium-containing metal scrap are fairly straightforward. Scrap is generated during semi-fabrication and manufacturing operations and consists of items such as clippings, stampings, and turnings. These are usually segregated by material specification and returned to controlled-atmosphere induction furnace operations, where the scrap is matched and melted into a product having the desired chemistry (Wernick & Themelis, 1998). Co-producers (via vanadium slag) and primary producers generally are the lowest cost producers. Those recovering vanadium from fly-ash, uranium and hard coal mining incur the highest cost. This is the reason that the share of secondary sources for vanadium production has dropped in the last years (Lindvall, 2015).

Entry barriers for new producers are high, with long development time required to master technology, large capital exposure and market risks.

Secondary vanadium can also be obtained from fossil fuel processing, including mineral oils. Vanadium is present in crude oil from the Caribbean basin, parts of the Middle East and Russia, as well as in tar sands in western Canada. Coal in parts of China and USA contains vanadium as well. During the refining or burning of these energy sources, a vanadium bearing ash, slag, spent catalyst or residue is generated which can be processed for vanadium recovery (Lindvall, 2015).

Such catalysts are as well required for the processing of uranium-vanadium ores, bauxite, phosphate rock and lead vanadates, that can contain vanadium. The material recovered (residue) is processed for the metal content, and the spent catalysts are recycled (Goonan, 2011). Vanadium recycled from spent chemical process catalysts is significant and may comprise as much as 40% of the total supply.

A new technology for the extraction of vanadium from vanadium-bearing iron ores in combination with secondary resources of vanadium is currently under development. The project EXTRAVAN[302] aims for improving the economic viability of the joint exploitation of primary and

[302] The project "Innovative extraction and management of vanadium from high vanadium iron concentrate and steel slags" (EXTRAVAN) developed innovative technologies for cost-efficient vanadium extraction limiting associated impacts on the environment; it is funded under the European ERA-MIN2 programme for sustainable production of raw materials in Europe (BRGM, 2017). The EXTRAVAN consortium consists of Swerea MEFOS (coordinator), the French Geological Survey (BRGM), the Geological Survey of Finland (GTK), KTH and Mustavaaran Kaivos Oy (SWEREA, 2014).

secondary resources, including the separation of materials undesired in this process like phosphorus.

28.4.4Processing of Vanadium

Vanadium, as primary material, is mainly produced as co-product from vanadium slag before the steel convertor. The processing of vanadium slag is a hot metal pre-treatment, resulting in vanadium products. For this reason, vanadium is assessed at the refining stage as vanadium oxides (V_2O_5 and V_2O_3). Figure 510 shows the sources and the most common production routes.

The vanadium slag process can be described as follows. Vanadium-titanomagnetite ores globally constitute the main source for production of vanadium containing commodities, most importantly vanadium pentoxide (V_2O_5) and ferrovanadium (FeV). FeV is produced from vanadium trioxide (V_2O_3) or vanadium pentoxide (V_2O_5). Extraction of vanadium as co-product to iron is usually done by concentrating the vanadium into a vanadium-slag. Production of vanadium-slag involves two main pyro-metallurgical steps. At first, the ore concentrate or DRI (Direct Reduced Iron) is reduced to a hot metal with a vanadium content of 0.4-1.3 wt%. In the second step, the vanadium in the hot metal is oxidized to the vanadium slag at around 1400 °C. The vanadium slag is an acid $FeO\text{-}SiO_2$ based slag with normally 9-15 wt% of vanadium. The vanadium slag is then converted to vanadium pentoxide (V_2O_5) by a salt roast and leach process. Vanadium slag is oxidized by oxygen and transformed into water soluble sodium vanadates in the presence of sodium salts (Na_2CO_3, NaCl, NaOH and/or Na_2SO_4). Thereafter, V_2O_3 or V_2O_5 is obtained from the leachate by precipitation and calcination (Lindvall *et al.*, 2016).

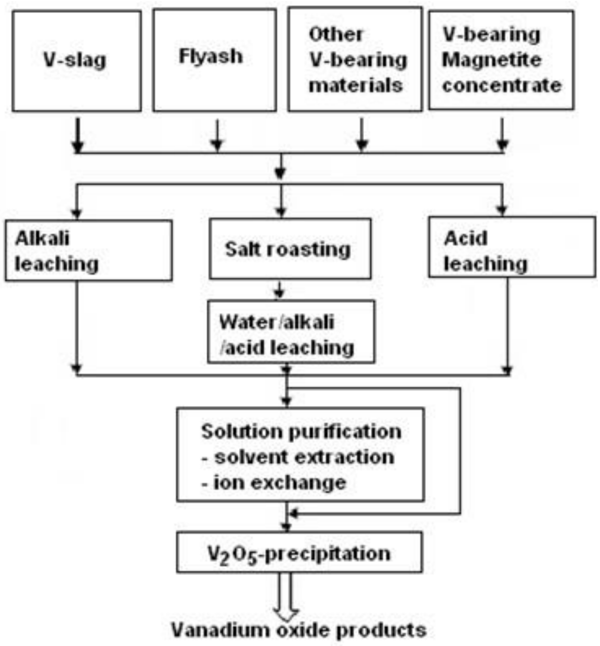

Figure 510: Production routes of vanadium

About 30% of the primary vanadium produced is from direct leaching of vanadium ores. Titanomagnetite is by far the most important mineral, a by-product mainly from vanadium slags, although other sources are available.(SWEREA, 2016)

Other sources of primary vanadium are mineral oils, uranium-vanadium ores, bauxite, phosphate rock and lead vanadates can contain vanadium, although vanadium from these sources is sometimes considered secondary material.

The average global production of vanadium oxides and hydroxides for the period 2012-2016 was about 86,300 tonnes (Vanitec, 2019). This production figure includes all vanadium oxides produced, vanadium in other chemical compounds as well as ferrovanadium that have not been produced via oxide routes. There is no vanadium pentoxide (V_2O_5) production in the EU, opposed to ferrovanadium (FeV).

28.5 Other considerations

28.5.1 Environmental and health and safety issues

It has been estimated that around 65,000 tonnes per year of vanadium enter the environment from natural sources (crustal weathering and volcanic emissions) and around 200,000 tonnes per year as a result of man's activities. The major anthropogenic point sources of atmospheric emission are metallurgical works (30 kilogram per tonne of vanadium produced), followed by the burning of crude or residual oil and coal (0.2-2 kilogram per 1,000 tonnes and 30-300 kilogram per 106 litres, respectively). Global vanadium emissions into the atmosphere from coal combustion in 1968 were estimated to 1,730-3,760 tonnes. The contribution of vanadium to the atmosphere from residual-fuel combustion was estimated at 12,400-19,000 tonnes in 1969 and 14,000-22,000 tonnes in 1970. In the production of ferrovanadium for alloy additions in steel-making, vanadium emission to the atmosphere was estimated at 144 tonnes in 1968. The burning of wood, other vegetable matter and solid wastes probably does not result in significant vanadium emission. In 1972, about 94% of all anthropogenic emissions of vanadium to the atmosphere in Canada (2,065 tonnes) resulted from the combustion of fuel oil and only 1.2% from metallurgical industries (WHO, 2000).

EU occupational safety and health (OSH) requirements exist to protect workers' health and safety. Employers need to identify which hazardous substances they use at the workplace, carry out a risk assessment and introduce appropriate, proportionate and effective risk management measures to eliminate or control exposure, to consult with the workers who should receive training and, as appropriate, health surveillance[303].

28.5.2 Socio-economic issues

No relevant socio-economic issues were reported.

28.6 Comparison with previous EU assessments

The results of this review and earlier assessments are shown in Table 219.

Table 219: Economic importance and supply risk results for vanadium in the assessments of 2011, 2014, 2017 and 2020 (European Commission, 2011; European Commission, 2014; European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
Vanadium	9.7	0.7		9.1	0.8		3.7	1.6		4.4	1.7

303 https://ec.europa.eu/social/main.jsp?catId=148

After the large drop of the Economic Importance in 2017[304], it rose again significantly from 3.7 to 4.4, mainly due to developments within the EU economy.

The Supply Risk increased steadily since the beginning. Until 2014 the Supply Risk was about 0.7 to 0.8, but then about doubled in both 2017[305] and 2020. Compared with the 2017 analysis, the 2020 analysis revised and corrected the interpretation of the underlying datasets. The assessment at the processing stage is based solely on trade data, due to missing information of vanadium oxide production. The source countries for the EU imports are strongly concentrated: Russia alone provides 68% of the imported vanadium oxides and hydroxides, and in sum 93% are provided by the top-three source countries (beside Russia also China and South Africa). In addition, the data availability implies the nonconsideration of EU production (in case existing).

28.7 Data sources

The quality of data sources of vanadium is mixed. Time series are available for trade in vanadium ores and oxides. Global production data is available for vanadium ores (WMD, 2019), while the USGS statistics on the production of vanadium oxides (USGS, 2016) is not continuously updated. Instead of the USGS Minerals Yearbook, data from the USGS Mineral Commodity Summaries could be used in future (which might differ).

For imports, the trade code applicable at the extraction stage is CN 2615 90 90 "vanadium ores and concentrates", but there is no data available. No adequate UN Comtrade trade code[306] is available to validate the Comext information; indeed, the shares of vanadium versus tantalum and niobium in the product group are not known (SWEREA, 2016). It is estimated and validated at the SCRREEN workshop that there are no imports at the extraction stage to the EU.

At the processing stage, no global production data is available[307]; data from the Material System Analysis (MSA) on Vanadium (in prep.) was not used here, as Vanitec, the source used at the MSA, does not provide data on country level. Trade in vanadium in processing stage was analysed for trade code CN 2825 30 00 "Vanadium oxides and hydroxides". Data was used from Eurostat Comext (2019) for the criticality assessment. Data from UN Comtrade (code 2825 30) were used for validation purposes.

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[304] The main difference from the previous two assessments is the lower score for vanadium in Economic Importance. This is, as in the case of some other alloying materials, probably due to the allocation to NACE-2 sectors rather than the "Megasectors". This approach had the base metal products and more advanced metal products assigned to megasectors with high Value Added totals such as machinery and transport equipment. The share of these end-use sectors at the end of value chains is now smaller.

[305] The SR result for 2017 is based on trade data for vanadium ore using both the global HHI and the EU HHI as prescribed in the revised criticality methodology. In the 2014 assessment, the major global producers were South Africa (37%), China (36%) and Russia (24%). The 2017 assessment also identifies these countries as the major global producers, however with slightly different shares: China (53%), which ranks as first producer, South Africa (25%) and Russia (20%). Contrary to the 2014 assessment, the 2017 assessment incorporates trade data on actual EU sourcing, which takes into account the EU supply to estimate the supply risk. The dependency of Russia and China for almost 85% of the EU imports explains the high supply risk result.

[306] At UN Comtrade, there does not exist a code specific to vanadium ores, but only mixed with niobium, tantalum and zirconium.

[307] The USGS Minerals Yearbook (USGS, 2016) does not cover processed vanadium, but extracted vanadium.

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