Resources, Environment and Sustainability 13 (2023) 100121

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.elsevier.com/locate/resenv

Research article

Modelling the dynamics of the industrial vanadium cycle using the WORLD7 Integrated Assessment Model

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ARTICLE INFO

Keywords:
System dynamics
Vanadium
Supply
Sustainability
WORLD7
Redox-flow batteries

ABSTRACT

The industrial dynamics of vanadium was simulated using the integrated assessment model WORLD7. The vanadium market may see strongly increased demand in the near future, and a pertinent question is if the new demands can be met. The WORLD7 model was used to assess the risk for future supply shortages. The global presence of vanadium in geological deposits was found to be about 710 million ton of vanadium. The extractable part was estimated to be about 60–70 million ton of vanadium, the rest being technically or economically inaccessible. Vanadium extraction is dominated by secondary extraction from primary metal production. The simulations suggests that there will be physical scarcity under business-as-usual for vanadium in after 2040. The vanadium price increases after 2030 according to the simulations, as a response to the scarcity. The introduction of a large-scale use of vanadium in battery technologies in the near future would aggravate future scarcity, even with more efficient recycling. Large scale use of vanadium for batteries, may keep vanadium prices high and require enhanced recycling to counter the threat of physical shortage after 2030.

1. Introduction

Vanadium is being considered for a number of new uses, in addition to an expanding steel market. Most vanadium was used in steelmaking, but it is increasingly more used in new technologies. Vanadium is a metal with mainly secondary extraction to other metals, and an important question is if the supply of vanadium can be increased and keep pace with the new demands. Earlier studies used very simple assessment methods and generally lacked all systemic aspects, ignoring effects of market and price dynamics and the fact that demand is also a variable with many feedbacks. Vanadium supply is dominated by secondary extraction, and strongly affected by the dynamics of the primary resources. The only way to do this in a sustainability assessment is to use dynamic assessment models for the whole metal supply system. We have not found any earlier system dynamics model applied to the industrial ecology and supply chains for vanadium. A systemic modelling of the vanadium system, linked with the metal systems and energy supply is needed. This requires research into the feedback system of the vanadium system, linking geological occurrence, extractability, market dynamics, dependencies and demand dynamics. A vanadium module was developed and included in the WORLD7 Model.

Global sufficiency of metals has been assessed in different ways in a number of studies: The pioneering work in Limits to Growth by Meadows et al. (1972, 1974), and more recently by Heinberg (2001, 2011), Bardi (2013) and Sverdrup and Ragnarsdottir (2014). These studies presented different types of metal supply assessments and expressed worries about a potential scarcity or future peak in metal production. Further assessments are found in reports by the International Resource Panel (Reuter et al., 2013a,b; van der Voet et al., 2013). The earlier sustainability assessment studies (Meadows et al., 1972, 1974; Bardi, 2013) have used different types of simplified methods, this was discussed by Sverdrup and Ragnarsdottir (2014). The WORLD7 model was developed for this type of assessment tasks.

The use of vanadium in batteries are about 0.8 kg/kWh battery capacity when vanadium substitutes for cobalt in lithium batteries. The trend is less material per kWh, but larger batteries use more vanadium in total. For vanadium flow batteries, it is about 4 kg/kWh (Conca, 2019; Dvorak, 2013). The total use for electric vehicles and intermittent storage of electricity in flow batteries could drive demand into volumes from 100,000 ton/year towards 700,000 ton/year (Hykawy, 2009; Petranikova et al., 2020). The importance of redox flow batteries based on vanadium is that they have good capacity and stability. They may in be recharged millions of times with no decline in performance. In a battery system, there will be three types: lithium batteries covering both long and short response times and production capacities up to single megawatts, conventional lead-sulphuric acid batteries with short response times, typically less than one hour, and across any capacities, and vanadium redox flow batteries that have large capacities, but

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https://doi.org/10.1016/j.resenv.2023.100121
Received 31 December 2022; Received in revised form 3 April 2023; Accepted 3 April 2023
Available online 7 April 2023

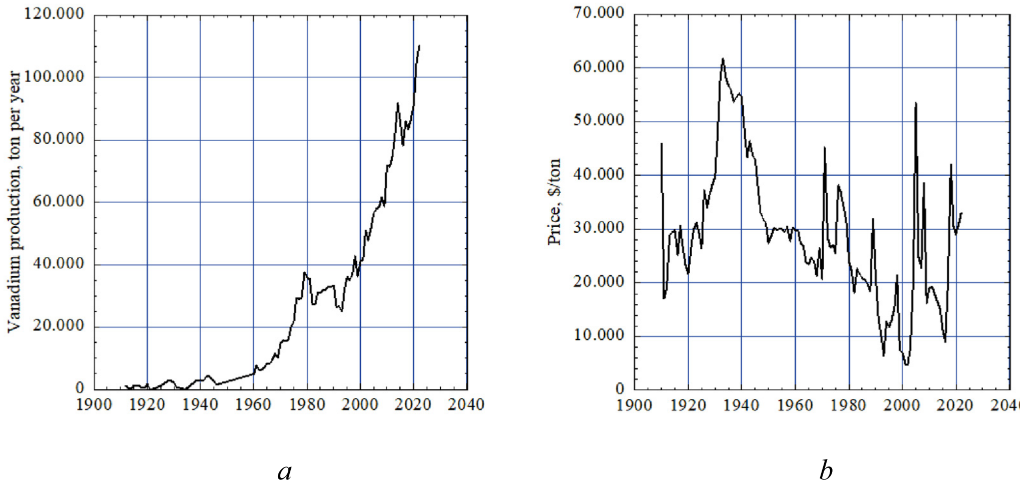


Fig. 1. (a) The recorded vanadium production as vanadium contained and (b) the inflation adjusted price according to data extracted from the USGS and Statista websites during the time 2010–2021.

longer response times of several hours. Lithium ion batteries can be made very compact and are light, lead batteries are less dense and very heavy, vanadium redox flow batteries are large and bulky, but can be recharged endlessly.

About 90% of the vanadium used goes into steel alloys, of this, one quarter of that to different types of speciality tools steel alloys (chromium–vanadium–molybdenum alloys), and stainless steels (Hykawy, 2009; Petranikova et al., 2020). Vanadium is a component in titanium steel alloys. Vanadium is a minor component in superalloys, used for high performance turbines and jet engines (Sverdrup et al., 2019a,b). Vanadium is used as a chemical catalyst in sulphuric acid production. The spent catalyst can easily be recycled.

Vanadium has been incorporated in two types of new rechargeable batteries, as a substitute for cobalt in lithium batteries. Cobalt or vanadium is the key for making the batteries rechargeable (Uhrig et al., 2016; Petranikova et al., 2020; Hykawy, 2009). It is the main metal in vanadium redox-flow batteries, and this may cause a significant demand increase in the future (Joerissen et al., 2004; Rychcik and Skyllas-Kazacos, 1988; Hykawy, 2009; Petranikova et al., 2020). The other use is in industrial redox-flow cell batteries which have fast responsiveness and near limitless number of recharging cycles. Such new technologies may increase vanadium demands significantly, if they are successful. Nrigau (1998), Nriagu and Pirrone (1998) and Hope (1997, 2008) addressed the dispersal of vanadium as a pollutant to the environment.

Fig. 1a shows the recorded vanadium production as vanadium contained. Since 1990, the production has been steadily increasing to the present date. Fig. 1b shows the inflation adjusted price according to the USGS (2022). Much of the vanadium production occur as a part of steel production, and pure elemental vanadium is not always produced when the final target is metal alloy with titanium or iron alloys. The price in the markets is normally listed for vanadium pentoxide V_2O_5. 1 kg of pentoxide has 0.53 kg vanadium by weight. The diagram and simulations are in per ton vanadium element content (USGS, 2022). Recently in 2020, the vanadium price has spiked up again to 75,000 $/ton (Petranikova et al., 2020), it later came down to around 20,000 $/ton.

Hope (1994, 1997, 2008) published a modelling of the biogeochemical cycle of vanadium with emphasis was on modelling the large scale global cycles, and vanadium transport to the environment as a result of human activity, rather than the industrial dynamics itself. Their model was based on flow charts for the system and solved using the STELLA Architect system dynamics simulation software. The model of Hope (1994, 1997, 2008) focused on the large terrestrial and global flows in the biosphere and geosphere and the big picture over 3000 years. The anthropogenic inputs to the model are specified as input files, and not as the result of an industrial dynamics process. They concluded that in the future, vanadium losses from human activities will be the main source of vanadium pollution in ecosystems. The simulations estimated a vanadium pollution peak between 2000 and 2050 (Hope, 1994, 1997, 2008). Approximately 110,000 ton of vanadium per year is lost to the environment with smoke and ash pollution from coal and oil combustion (Hope, 1997, 2008). Their study is valuable for parameterizing certain parts of our submodule in WORLD7. Petranikova et al. (2020) makes a review of vanadium resources and reserves and how vanadium is technically produced from these. Our study follows the methodology described in our earlier studies sustainability assessments for individual metals using WORLD7 (Olafsdottir and Sverdrup, 2020; Sverdrup and Olafsdottir, 2019a,b; Sverdrup and Ragnarsdottir, 2014, 2017; Sverdrup et al., 2018, 2019a,b, 2021). This study follows those earlier assessment approaches. Schlesinger et al. (2017) describes the biogeochemical cycle of vanadium. The study is useful for parameterization of some aspects, but no simulation model is involved in their study and no estimate of any extractable resources.

2. Objectives and scope

The objective of this study is to develop a module for vanadium extraction, use and recycling in the WORLD7 model. After inclusion of the vanadium module, the WORLD7 integrated system dynamics model will be used to provide vanadium supply and vanadium market price for the industrial dynamics section and to assess the long-term sustainability of the supply. The effect of recycling is studied within what is possible and feasible. Model responses to demand changes associated with new battery technologies was done.

3. Methods

The methodology used is systems analysis as the standard tool for conceptualization, as the preparation for building a simulation model using the STELLA software. The main standard methods of systems analysis and system dynamics modelling are used (Haraldsson, 2004; Meadows et al., 1972; Senge, 1990; Haraldsson and Sverdrup, 2005; Sverdrup et al., 2022). The system is analysed using stock-and-flow charts and causal loop diagrams. The learning loop is the adaptive learning procedure followed in our studies (Senge, 1990). The mass balance expressed differential equations resulting from the flow charts and the causal loop diagrams were numerically solved using the WORLD7 in the STELLA® modelling environment (Haraldsson and Sverdrup, 2005; Sverdrup et al., 2022). Constants and settings have been based on observed system parameters, in order to eliminate the need for calibration. The model is not driven by feed-in time-series. System state data was used for testing the performance of the WORLD7 model (Sverdrup and Olafsdottir, 2019a,b). An overview of the WORLD7 model is shown in Figure S1 the supplementary materials. The vanadium module is shown in Figure S3 in the supplementary material. The method has several steps: (1) Establish how much metal is geologically present, (2) Sort up the total geological resource in quality classes, based on extraction costs and process yields, (3) Establish the fraction of the present metal that will be ultimately recovered, based on ore grade cut-off limit and extraction yield estimates. The recoverable resources are estimated following the methodology applied in Krautkraemer (1988), Johnson et al. (2011), Sverdrup and Ragnarsdottir (2014) and Olafsdottir and Sverdrup (2020). Extraction cut-off is dependent on technology and degree of repetitiveness of the extraction method. It is composed of different elements: The access yield is the part of the resource that can be accessed for extraction Y_A. The prospecting yield is the fraction of the hidden resource that will be discovered and will get an extraction classification with an associated extraction cost; Y_P. The mining yield is the fraction of the accessible ore that will be recovered when mining is done Y_M. Extraction yield: the fraction of the excavated rock that will become substrate for refining, involving the cut-off grade Y_E. Extraction yield is a known mining engineering design parameter. Refining yield is the fraction of the metal recovered from the refining substrate (Y_R). The total yield will be the multiplication of them all:

$$Y = Y_A * Y_P * Y_E * Y_M * Y_R \tag{1}$$

The extraction yield is defined as:

$$Y_E = \frac{(\text{Ore grade} - \text{extraction cutoff ore grade})}{\text{Ore grade}} \tag{2}$$

Beneficiation only works down to a certain limit. That is the point when the extraction will sometimes change method and goes to heap leaching. Then there will be a leaching process yield and a subsequent refining yield. The recoverable resource (R) is estimated as (Krautkraemer, 1988; Johnson et al., 2011):

$$R = R_M * x_V * Y \tag{3}$$

Where R_M is the total amount mother metal. x_V is the content of vanadium in the mother metal. is the total yield for taking the vanadium out of the mother substance. There are no primary vanadium mines, it is a secondary product, dependent on the rate of extraction of source metals. Vanadium extraction is dependent on the resource size, but equally much on how well it can be accessed and in which metals company it will be mined.

4. Theory and model description

Soft scarcity is when the initial demand is reduced by high price. Hard scarcity is when the demand cannot be delivered because of physical unavailability. Two metrics for indicating scarcity are used: (1) vanadium supply in kg per person per year and (2) vanadium stocks-in-use as kg per person. Supply as kg per person per year is what is available to support growth, maintenance and renewal. Vanadium as stocks-in-use as kg per person is the vanadium that is being used producing utility. Decline in stocks-in-use implies decline in utility.

The WORLD7 model addresses many metals and materials used in society, and they are all in some way all linked in their extraction or production. The module for vanadium follows the logic of earlier published metal modules (Sverdrup et al., 2018, 2019a,b; Olafsdottir and Sverdrup, 2020, Sverdrup and Olafsdottir, 2021). The WORLD7 energy module supplies energy from fossil fuels, renewables, and nuclear power, with a market price generated by supply and demand in the model (Sverdrup and Olafsdottir, 2019a,b; Sverdrup et al., 2022). The simulations start in 1850 and run to 2200. The WORLD7 model includes dynamic changes in supply, demand, price, production rates, population, recycling, use efficiency, and all these are linked. Supply is composed of both primary production, secondary extraction as a by-product of the production of other metals and recycling of used material. From mass the balance concept, it is established that the supply is equal to the production plus recycling and losses. The flow chart for the industrial vanadium cycle is shown in Fig. 2, this is reflected inside the vanadium module inside the WORLD7 model system. Significant amounts of recycling is done internally to the industry and does not really pass over the market. Special attention was paid to this in the vanadium module in the WORLD7 model. Recycling expands the total flux going through the system, without demanding new primary material to be added. Recycling rates could be considerably increased for many metals based on governmental policies, but those policies need to be set in place (Sverdrup and Ragnarsdottir, 2014; Sverdrup et al., 2017). To increase vanadium production, the unused potentials in the secondary production must be realized through investment in additional extraction technologies. The WORLD7 model is operated as one concerted whole, where everything runs simultaneously.

The mining rate is driven by profit from operations. The price is determined by how much metal is available in the market (Sverdrup and Ragnarsdottir, 2014; Sverdrup and Olafsdottir, 2019a). A high metal price will increase profits and promote larger supply to the market, and limit demand (Perles, 2012; Olafsdottir and Sverdrup, 2020). More supply to the market will increase the amount available and lower the price. This is shown in Fig. 3a. The mining cost is modified with oil price and ore grade. If demand is higher than production, the price goes up; in the opposite case the price is moved down. This is a self-adjusting mechanism that balances the trade by adjusting the prices until the demand to buy an amount at a price match the offers to sell an amount at a price. The system causality effect in profits go to income from supply when the amount is supplied and paid, at once into the metal exchange warehouse. The same applies with a forward sale, when the metal is paid upfront but physically delivered later. If not, all or part may be paid when the supplied amount has been cleared out from the physical warehouse (Perles, 2012; Olafsdottir and Sverdrup, 2020).

The scrapping process for stock-in-use in society is not strongly driven by price. After the metal become scrap, the metal price will have a promotion effect in causing somebody to recover it. When the price will go below the cost of actual production and extraction, profit will be negative, and the production will be stopped (Dahmus and Gutowski, 2007). The price curve describes the price dependence on the market amount, the curve for vanadium is reported in Sverdrup and Olafsdottir (2019a). With this curve, it is possible to estimate the metal price from the market flows and dynamics. Fig. 6b shows the increase in recycling that occur when the price increase. Recycling is for many metals dependent on price (Sverdrup and Ragnarsdottir, 2014; Sverdrup and Olafsdottir, 2019a). This principle is applicable for vanadium when an item is mainly made of vanadium. This is normally not the case, as vanadium is mostly used as a small part of something else. Most vanadium recycling is indirect with the metals it is alloyed with, and the vanadium price has very little impact on the recycling of vanadium specifically. Therefore we have distinguished direct recycling and indirect recycling, when vanadium is recycled with another metal. Recycling is on a low level for vanadium, whereas re-use of vanadium-bearing alloys may possibly be enhanced. Spent vanadium catalyst is sometimes put in landfills and lost. Flow battery vanadium is recycled to a very limited degree at present, but the vanadium used should be easy to recycle. Vanadium-alloyed steel is normally thrown in with unspecified scrap iron and disappears into the global scrap iron pool. Titanium alloys are recycled because of the high titanium price and good awareness in that sector for the necessity of recycling. This implies that the actual degree of global recycling of vanadium is in principle unknown and largely unavailable for planning production.

In the vanadium model, vanadium demand is distributed according to equal demand share of the vanadium supply. Each sector has their defined vanadium demand, and when there is a shortfall, then each

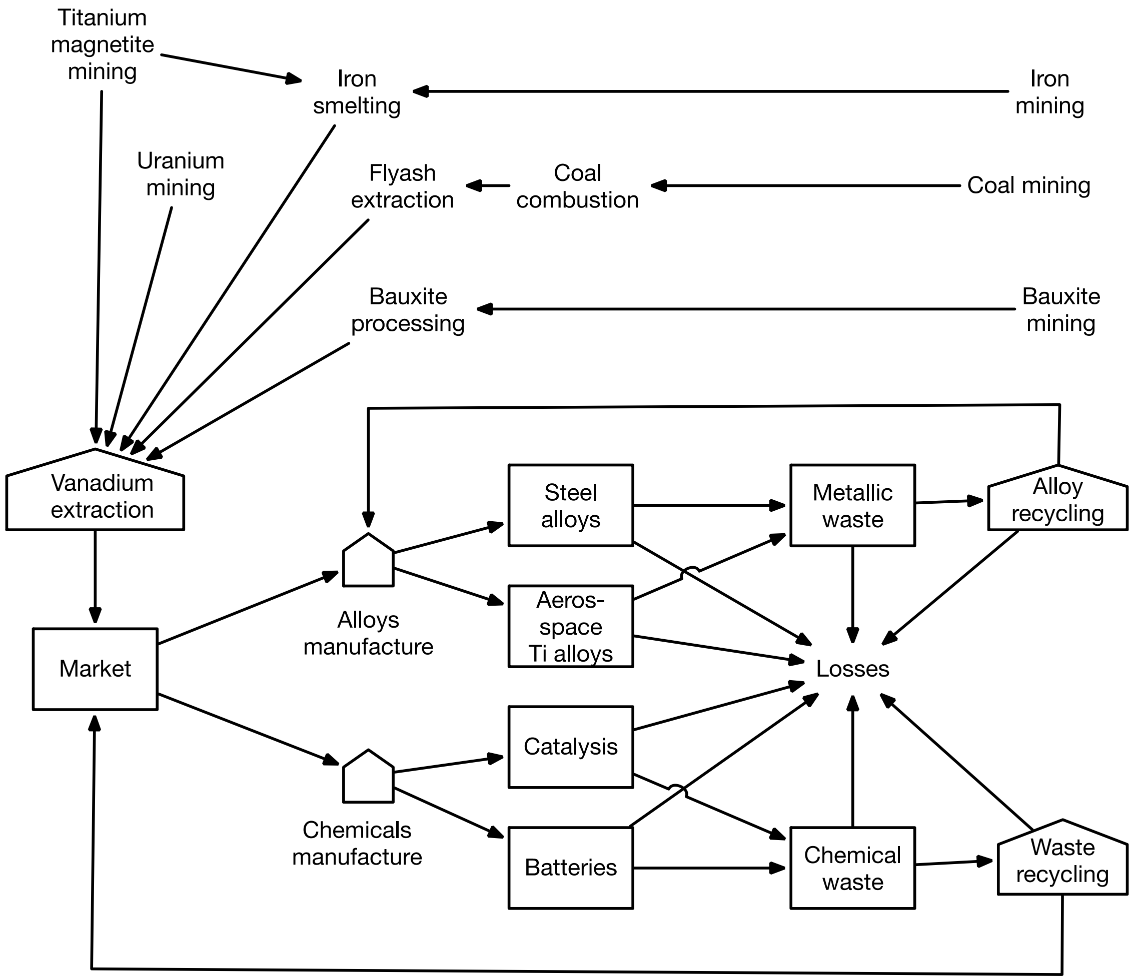


Fig. 2. Flow chart for the industrial vanadium cycle. Significant amounts of recycling is done internally to the industry and does not really pass over the market. Attention was paid to this in the vanadium module in the WORLD7 model.

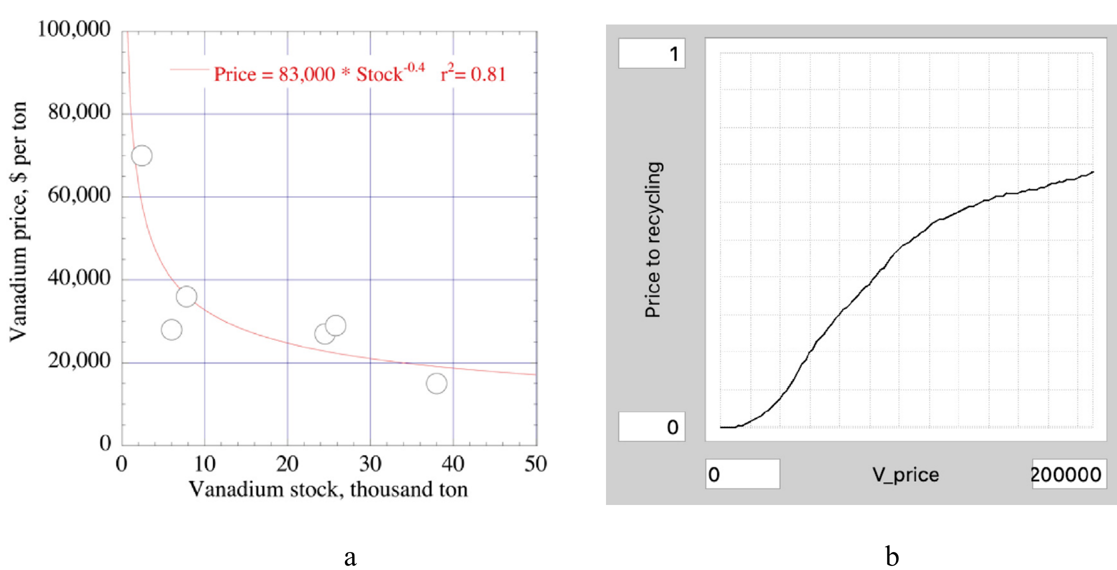


Fig. 3. The relationship between the immediately tradable amount of vanadium oxide in the market (a) and the vanadium oxide market price. (b) shows the increase in recycling that occur when the price increase.
Source: Adapted from the database developed by Sverdrup and Olafsdottir (2019a).

sector will get the share of the vanadium supply corresponding to their share of the vanadium demand. This is equivalent to assuming a free market with equal strength agents operating, without any political intervention. The procedure in most vanadium production is as follows: Mining of mother metal > vanadium residuals > extraction > vanadium alloys or metal. The rate of vanadium extraction is modelled as a function of the rate of mining of iron, titanium, uranium, bauxite for aluminium and flue gas production:

$$\begin{aligned} r_V = {} & r_{Fe} * x_{Fe(V)} * f(Fe) * g(Fe) + r_{Bx} * x_{Bx(V)} * f(Bx) * g(Bx) \\ & + r_U * x_{U(V)} * f(U) * g(Fe) + r_{Ti} * x_{Ti(V)} * f(Ti) * g(Ti) \\ & + r_{FG} * x_{FG(V)} * f(FG) * g(FG) \end{aligned} \tag{4}$$

where f(Fe) is the fraction of iron slag used for vanadium extraction, f(BX) is the fraction of bauxite used for vanadium extraction, f(Ti) is the fraction of the Titanium magnetite ore used for extracting vanadium, and f(FG) the fraction of available fly ash for vanadium extraction. xi(V) is the fraction vanadium in the mother ore and r_i is the rate of extraction of the mother metal i. g(i) are the functions turning on the specific extraction at the right point in time, corresponding to when it took place (Fig. 3). The rate of mining of these metals and for flue gas are all derived in the WORLD7 modules for these metals. The flue gas amounts originate in the fossil fuels module in WORLD7 (see Fig. 4).

5. Input data and model parameterization

Important input data are the reserves and resources, after consideration of availability for mining, extraction yields in every step and efficacy of recycling. The market price model is that of Sverdrup and Olafsdottir (2019a,b). The profit function feedback was set as in earlier simulations (Molybdenum and rhenium; Sverdrup et al., 2018, Niobium and tantalum; Sverdrup and Olafsdottir 2017, Stainless steel: Sverdrup and Olafsdottir, 2019a,b, Nickel; Olafsdottir and Sverdrup, 2020). Some data was also extracted from the work of Hope (2008). They used Nriagu and Pacyna (1998) as a source for anthropogenic inputs, and derived input curves from that. WORLD7 is an industrial dynamics model and generates this endogenously in the WORLD7 vanadium submodule (Sverdrup, 2020). Demand in the model is driven by population, GDP and vanadium use per person, and is adjusted down with increasing price. The recycling rate in 2012 and in 2100 as the fraction of the total market supply being from recycled waste from society based on a number of reports and assessments (UNEP 2013) was used as check points. One way of keeping a large flux of metal in society but based on a small net input of primary metal is to have efficient systemic recycling.

Vanadium is found in a number of deposit types (Petranikova et al., 2020; USGS, 2022), and there are three pathways for obtaining vanadium:

1. Primary vanadium ore deposits (17%)
2. Secondary extraction (78%)
   a. iron ores with vanadium content, vanadium captured in the slag
   b. titanium–iron magnetite ores with vanadium content
   c. Slags and ashes from combustion of fossil fuels that have trace amounts of vanadium
   d. Mining rock waste landfills.
3. Indirect mining (5%)
   a. Vanadium capture in steel or iron alloy during the steel making process.

Titaniferous magnetite is the most important source for vanadium presently accounting about 85% of the current world V_2O_5 production. This iron ore typically contains 1–1.5% V_2O_5 (Hykawy, 2009; Petranikova et al., 2020). Titaniferous magnetite ore is mined in South Africa, Russia and China and processed for vanadium extraction. Vanadium is present in crude oil in 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 the USA contains small amounts of vanadium. During the refining or burning of these energy sources a vanadium bearing ash, slag or solid waste is produced. From chemical industry spent catalyst or residue is generated which can be processed for vanadium recovery. It is present in the pyrolysis slag produced in Venezuela for the upgrading of heavy crude oils. Vanadium bearing oil based fuels are burnt in the boilers of electric power generating plant and vanadium is left in the fly ash and boiler slags.

Titaniferous magnetite iron–titanium mines account for about 26% of global vanadium production (Petranikova et al., 2020). Coproduct steelmaking slag resulting from the processing of titaniferous magnetite ore supports about 59% of global vanadium.

Table 1 shows an overview of annual production in 2018, known reserves, hidden resources and the ultimately recoverable resources available. The resources available were estimated according to recent publications (Petranikova et al., 2020), USGS ds140 series 2022, (Polyak, 2019; Reese, 2002; Magyar, 2009, Geoscience Australia 2020). The indirect extraction estimates are very uncertain and represent our own guesswork. The vanadium resources are significant, but not always easily extractable. Table 2 shows the resource qualities and types available. Resource quality is important in the model as only the quality with an extraction cost below market price will be extracted in the model. Table 3 shows an overview of annual production in 2018, and the known reserves, hidden resources and total extractable amount of vanadium. hidden resources and the ultimately recoverable resources available. In 2023, 17% of the vanadium was from primary production (USGS, 2022, 2018). Primary production is dominated by South Africa. The Swedish vanadium production is generally underestimated, the amount given is the amount that follows from the ore extracted in Sweden into the final steel, not really appearing as a vanadium product in the market. Thus, it does not appear in the production statistics of the EU. About 27,000 ton vanadium is extracted annually with iron ores, but most end up in the slag that contains 3–5% vanadium. Indirect production as part of the Swedish steel production, another 22,000 ton of vanadium goes to slag landfills annually, 5,000 ton/year is in the steel from the iron ore. Vanadium cumulatively produced to 2019 is 1.7 million ton vanadium (Petranikova et al., 2020; Kelly and Matos, 2011; Rogich and Matos, 2008).

Table 2 shows an overview of the ultimately recoverable resources available, considering mining cut-off limits is shown. Other deposits with 3% are different types of steel slags, found in landfills near steel works. The content in these can be substantial and sufficient for primary mining operations. The extraction potentials and minimum cost limits in 2018 have been estimated in Table 4. Costs were taken from the literature cited earlier in the text. Table 3 shows an overview of extraction potentials and the 2020 cost limit for extraction (Data in part come from Groen and Craig, 1994; Huang et al., 2015). Table 4 shows an assessment of present recycling and potential for the future. The present recycling at maximum 8% is very low. Most of the low content addition to carbon steels are not effectively recyclable other than as whole alloy. The largest part of used vanadium is lost into the iron pool as a minor component of scrap iron. There are significant cost and energy challenges to recycling vanadium from the iron pool, and when vanadium has entered the general scrap iron pool, it can be considered as lost. Other minor contributors to vanadium production include roscoelite, used in alumina production in India which yields a vanadium-bearing sludge. Carnotite, a uranium mineral containing vanadium is mined in the USA, and iron sands with vanadium used in steelmaking in New Zealand (Hykawy, 2009; Petranikova et al., 2020; Jorgenson and Kirk, 2003). Titaniferous magnetite mines account for about 26% of global vanadium production, making both iron and vanadium, and at times titanium from the ore. Coproduct steelmaking slag using titaniferous magnetite ore accounts for about 59% of the

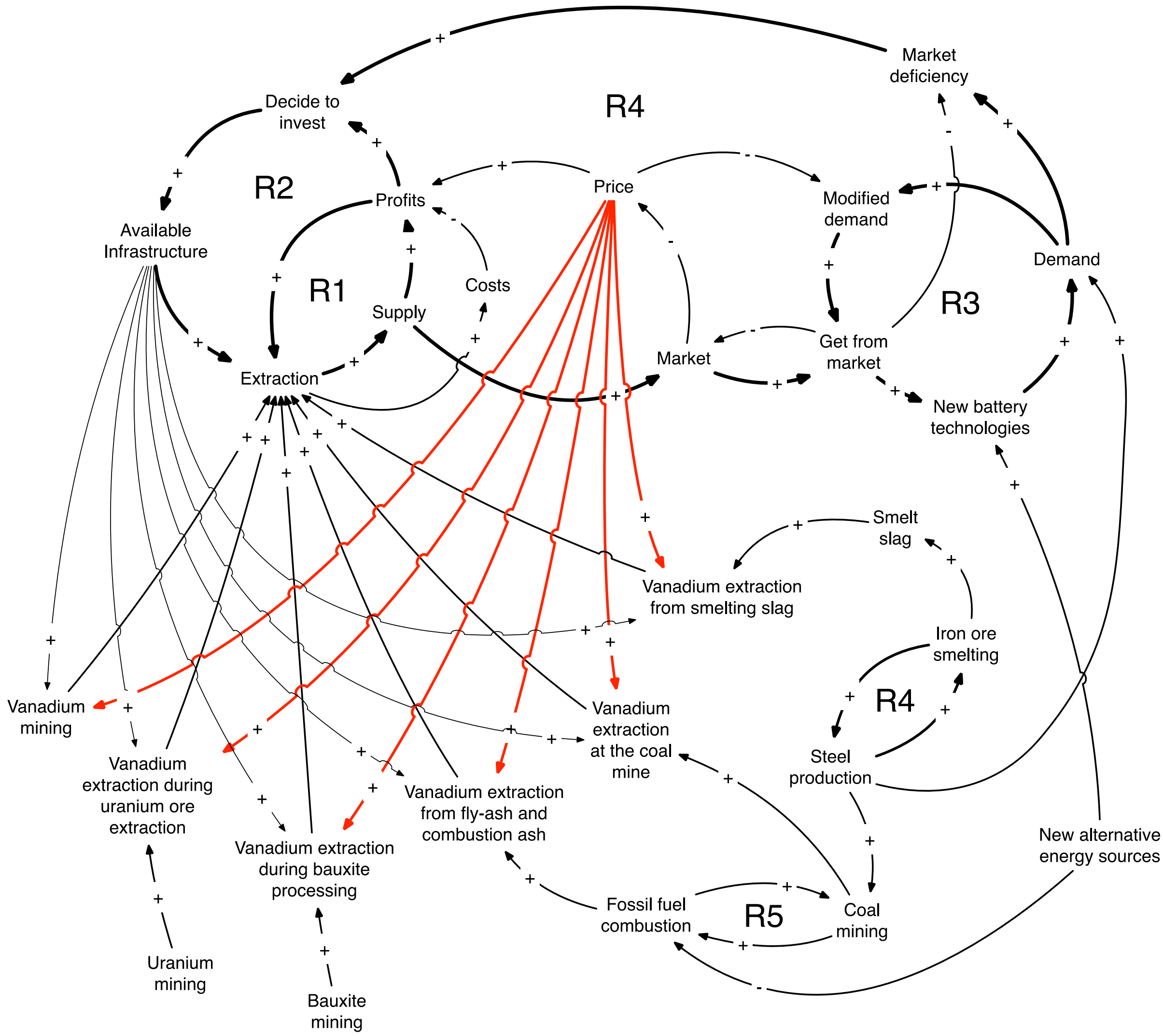


Fig. 4. Causal loop diagram for the vanadium system interactions as modelled by us in the vanadium module in the WORLD7 model. The three main reinforcing loops have been indicated by thicker arrows and R1, R2 and R3. The red arrows show how price push the different possible sources as a source of vanadium extraction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Overview of annual vanadium production, known reserves, hidden resources and the ultimately recoverable resources for 2018. There are no major changes from 2018 to 2022. The numbers change from year to year and there are significant differences between the sources such as Statista or USGS (2022). This is a reflection of the uncertainty in such estimates. Thus, every number is in reality very approximate.

Nation	2018 Production, ton per year	2022 Production, ton per year	Reserves million ton	Resources million ton	Total million ton
South Africa	13,000	8,584–9,100	3.8	21	24.8
China	43,000	69,960–73,000	9.0	15	24.0
Russia	16,000	19,533	5.0	19	24.0
Sweden	5,000	5,000–5,500	4.3	16	20.3
Australia	300	500	2.1	8	10.1
Brazil	8,400	6,900–7,582	1.5	7	8.5
Ukraine	3,000	2,000	1.5	3	4.5
United States	500	20	0.1	4	4.1
Others	5,000	?	1.0	9	10.0
Indirect	8,000	9,000	5.0	10	15.0
All counted	86,216	110,000	33.3	114	147.3

global vanadium production. Secondary sources supply about 15% of today's vanadium production (Hykawy, 2009; USGS, 2022; Petranikova et al., 2020). The steel smelting slags from South Africa contains up to 25% V_2O_5, whereas the slag from China and Russia contains 14%–22% vanadium (Hykawy, 2009; Petranikova et al., 2020). Vanadium metal is 68% of the weight in the V_2O_3. Vanadium from Colorado carnotite ore is extracted as a co-product during uranium production.

Vanadium oxides are used for the production of ferro–vanadium and vanadium–aluminium alloys required for the addition of vanadium to

Table 2
Overview of annual production in 2018, known reserves. hidden resources and the ultimately recoverable resources available, considering mining cut-off limits.

Ore	Source ore	Part of all ore deposits	V content	Mining cut-off	Available for extraction %	Extraction and refining yield	URR Extractable vanadium
	Mill ton	%	Mill ton	%	Mill ton	%	Mill ton
Titanium-magnetite, 2% V	2,000	0.6	40	0.5	30	85	25.5
Iron ores, 1% V	2,000	0.6	20	0.5	10	85	6.0
Iron ores, 0.3% V	10,000	3	30	0.3	0	–	–
Iron ores, <0.5% V	324,000	90	486	0.2	0	–	––
Uranium ore, 3% V	10	50	0.3	0.3	0.25	85	0.2
Oil and coal, 0.5% V	14,000	100	70	0.2	35	80	28.0
Other deposits, 3% V	165		5	0.5	4	85	3.5
Primary low grade 2%	–	100	30	0.5	23	85	19.6
Primary ultralow grade, 0.5%	–	100	40	0.2	24	85	20.4
Sum of all deposits	–	100	711	–	126.3	–	103.5

Table 3
Overview of extraction potentials and the 2020 cost limit for extraction.

Ore	Extraction method and substrate	Cost limit, $/kg
Titanium-magnetite ores with 2% vanadium	Extract from smelter slag	15
Iron ores, 1% vanadium	Extract from smelter slag	10
Iron ores, 0.3% vanadium	Extract from smelter slag	12
Iron ores, <0.5% vanadium	Extract from smelter slag	15
Uranium ore, 3% vanadium	Secondary extraction process	30
Oil and coal, 0.5% vanadium	Extract from fly-ash	25
Coal with 0.2-0.8% vanadium	Secondary extraction process	50
Primary deposits , 3% vanadium	Mining	20
Bauxite deposits , 1%–3% vanadium	Secondary extraction process	35

Table 4
Assessment of present recycling and potential for the future by the authors.

Nation	Fraction of use	Recycling at present	%-point effect on the whole	Potential % recycling	%-point effect on the whole
Speciality steels	24%	25%	6	80	19.2
Carbon steels	69%	0%	0	10	7.0
Chemical catalyst	3%	65%	2	90	2.7
Other use	4%	0%	0	65	2.6
System recycling			8%		31.5%

steel and titanium respectively. Vanadium is added to steel as a ferroalloy. Ferro–vanadium is available in alloys containing 40%, 60% or 80% vanadium (Hykawy, 2009; Bushveld, 2020; Vanitec, 2020). Vanadium additions to titanium and steel alloys are made with aluminium–vanadium master alloys. The industrial production capacity is about 100,000 ton per year of contained vanadium (Hykawy, 2009). A significant part of the vanadium production has vanadium pentoxide (V_2O_5) as the final product (Hykawy, 2009; Petranikova et al., 2020), as well as the master alloys mentioned above. The vanadium metal production is less than 1% of the whole volume. Vanadium is expressed as amounts of pure vanadium in the model regardless of alloy or material, but it should be remembered that it generally occurs as a chemical or as a component in an alloy.

Future vanadium uses are in Redox Flow batteries, and as a substitute for cobalt in lithium batteries. Potentially, the vanadium demand for this type of use may be as large as 300,000 ton/year (Uhrig et al., 2016; Petranikova et al., 2020), and maybe even larger. For a full transition of the global energy system, a huge capacity for batteries as intermittent storage capacity will be needed. Increased use in speciality steel for tools could increase demand further.

The different estimates for vanadium reserves and resources are uncertain, and all the different reports do not always agree on the estimates of what is available. This is usual in resource estimates for metals (Sverdrup and Ragnarsdottir, 2014), and necessary to adapt to. The numbers presented in the Tables 1 to 4 are not fully internally consistent, and this represents the available data. The vanadium content in iron-titanium ore, aluminium ore, uranium ore and ash from fossil fuel combustion has a potential of about 3.5 million ton vanadium per year at an extraction rate of 3.3%/year, if can be made technically feasible. Vanadium is not a scarce metal, resource access and industrial ability are the limiting factors. The total resource of vanadium was found to be in the range of 103–165 million ton of vanadium contained, more than earlier reported. The extractable part of this global resource was estimated to be about 60–72 million ton of vanadium. The cost of vanadium production is about 13,000 $ per ton of vanadium for extraction from iron smelting slag based on magnetite ores, 17,000 $ per ton of vanadium from primary mining of vanadium ore and 28,000 $ per ton vanadium for secondary extraction from other metals and fossil fuels combustion ashes in 2020 (Hykawy, 2009; Bushveld, 2020; Conca, 2019; Singer, 1993, 2007; Singer and Menzie, 2010). The model have a number of switches:

1. Switch on titanium magnetite iron ore smelting slags extraction at a vanadium price of 10,000 $/ton to have full effect at 20,000 $/ton
2. Switch on primary mining and low grade smelting slags at 15,000 $/ton and have full effect at 25,000 $/ton fly-ash.
3. Switch on extraction from fly-ash and combustion slags at 20,000 $/ton and have full effect at 30,000 $/ton
4. Switch on other extraction from bauxite extraction, uranium deposits from coal deposits at 30,000 $/ton and have full effect at 40,000 $/ton
5. Switch on other extraction from coal deposits at 40,000 $/ton and have full effect at 60,000 $/ton.

These switches are expressed as curves, scaled from 0–1 depending on the price of vanadium and the availability of substrate, such as suitable bauxite, suitable coal with vanadium content, availability of combustion ash and smelter slag with vanadium.

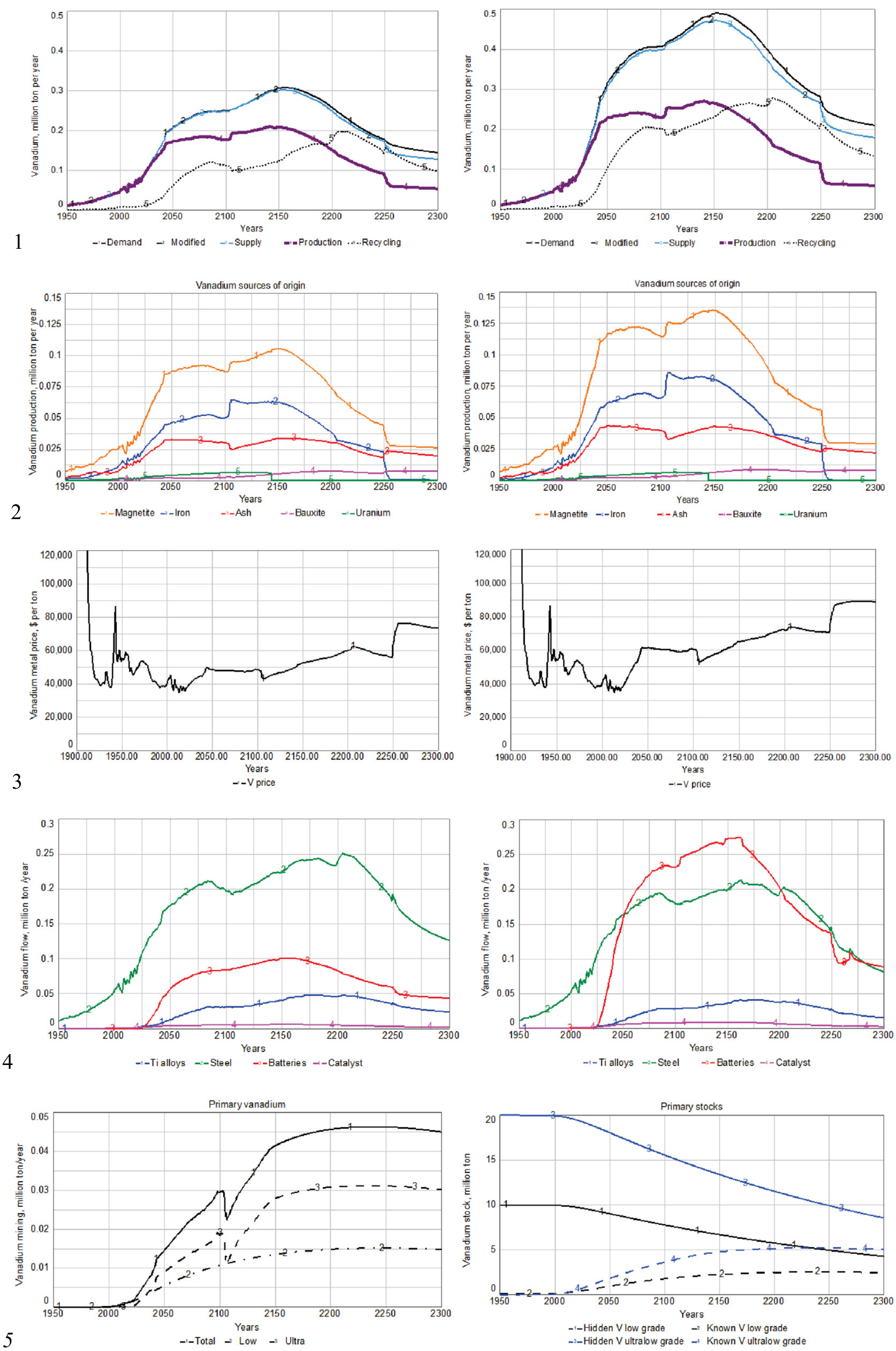


Fig. 5. Business-as-usual (Left side diagrams) and exploring a three times larger demand for vanadium caused by increased use in batteries after 2020 (Right side diagrams). The diagrams shown are from the top and down: (1) Demand, supply, production, recycling, (2) the source of the vanadium extracted, (3) the simulated price for vanadium metal. (4) the metal used in different product categories. (5) Rate of primary mining of vanadium.

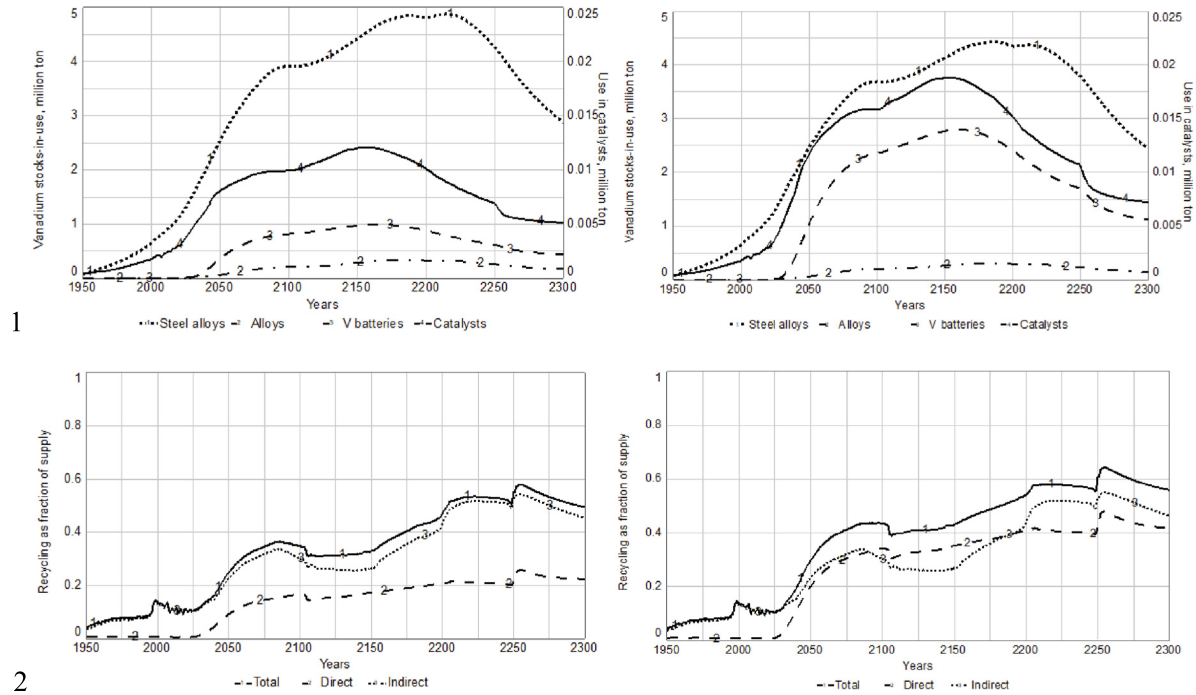


Fig. 6. Business-as-usual (Left side diagrams) and exploring a three times larger demand for vanadium caused by increased use in batteries after 2020 (Right side diagrams). (1) The amount vanadium provided to batteries and the initial demand, and stocks-in-use and planned stocks-in-use. (2) shows the degree of recycling with time when it is made to be vanadium and technology dependent.

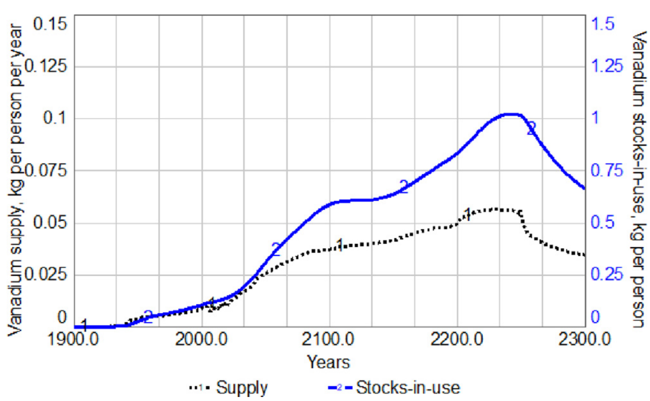


Fig. 7. The supply per person and year and the stocks-in-use per person. The diagrams are not significantly different between the two scenarios.

6. Results

6.1. Business-as-usual

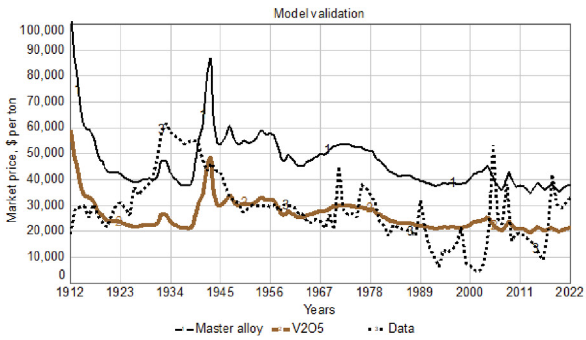
The results of the simulations for (1) business-as-usual including demand for vanadium to batteries for the period 1850 to 2200 to the left and (2) everything equal but with three times as much demand for vanadium to batteries to the right, are shown in Figs. 5–8.

Row 1 in Fig. 5 shows the vanadium demand, modified demand, actual supply from the market, total supply when including internal industrial recycling, the primary extraction of vanadium from primary and secondary sources, recycling and losses in million ton of contained vanadium per year. Note in the diagram how vanadium demand and modified demand separates, showing soft scarcity for vanadium after 2015. After 2040 modified vanadium demand and supply separates, suggesting that there will be hard scarcity for vanadium. There is a dependency of a part of the recycling on vanadium price in the model, it can be seen how the vanadium recycling increases after 2025. In 2175, the vanadium recycling is larger than the primary vanadium production. The recycling rate for vanadium is low today. Row 2 in Fig. 5 shows the production of vanadium from different secondary sources. Most vanadium comes from iron ore and titaniferous magnetite, smaller amounts come from uranium processing, bauxite processing and from extraction of hydrocarbon combustion fly-ash. A large vanadium potential is available in slag heaps around large steel mills, these slags can often contain 2%–4% vanadium. Row 3 in Fig. 5 shows the vanadium market price in $/ton. Row in Fig. 5 shows the metal used in different product categories.

Fig. 6 shows in Row 1 the amount vanadium provided to batteries and the initial demand, and stocks-in-use and planned stocks-in-use. Row 2 in Fig. 6 shows the increase in demand for batteries, shift how the vanadium will be allocated in the marked if allocation is proportional to the demand (Free market without intervention). Row 3 in Fig. 6 shows the degree of recycling with time when it is made to be vanadium and technology dependent. The increase in demand for batteries, shift how the vanadium will be allocated in the marked if allocation is proportional to the demand. Fig. 7 shows the supply per person and year and the stocks-in-use per person. The two scenarios are similar and the vanadium utility peaks in 2240. Higher total demand cause higher price and more pressure on extraction of vanadium. We have studied two scenarios: On called business as usual, where future demand is as traditional estimates for demand from 2015–2020 would be. The other scenario "Increased demand for batteries" we have applied where the demand would be 3 times larger than the business-as-usual.

6.2. Testing the model

The model was tested on available data for vanadium mine production for the period 1925–2018, and for market price for vanadium for the time period from 1909 to 2015. The principle is that the model is



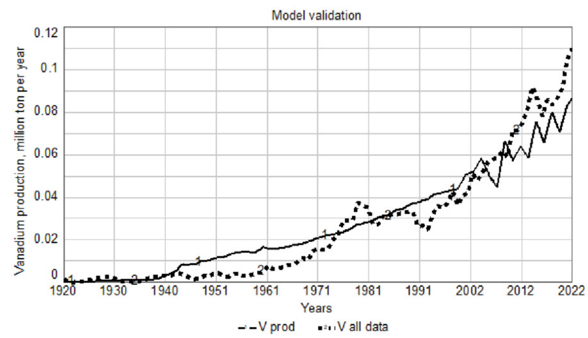


Fig. 8. (a) The cumulative production and extraction of vanadium for business-as-usual and new demand for vanadium to batteries (data from USGS ds140 series-vanadium (USGS, 2022, available on their website). (b). The price of vanadium was simulated and compared to the data extracted from the USGS ds140 series-vanadium, available on their website and from Petranikova et al. (2020).

set up to run with parameterization based on inputs and parameters independent of production rate and price data. The model output for price and production rate is then compared to the data. When the correlations between simulation and data is acceptable, we assume the model can be used to make reasonable forecasts. Caution was paid to the fact that some sources report the price per vanadium content, others per weight vanadium pentoxide. Fig. 8a shows the vanadium extraction simulation as compared to the observed data (USGS, 2022). Fig. 8b shows the simulated vanadium oxide price and the master alloy price as compared to the data. There is no historical price available for master alloy. The fit of the simulation to the data is reasonably good for both the vanadium price and the vanadium extraction rate. A better extraction fit can be obtained by adjusting the extraction rates down a bit, and by fiddling the curve showing the relationship between market amount and vanadium price, but then we deviate from the empirically observed market response curve and our philosophy of not fiddling parameterization outside observed values. We want to keep this simulation output, and then only adjust the specific extraction rate coefficient as to get the best fit for price and extraction simultaneously.

7. Discussion

The size of the vanadium resource as it can be detected in deposits do not really reflect how much that can be extracted. The vanadium extraction is secondary to iron and titanium-iron extraction, and dependent on the rate of extraction of those. Some of the extraction is active towards vanadium metals, whereas some is passive as some of the vanadium in the ore follows into the iron. This complicates the extraction calculations a bit. This implies that if there would be a shortage of vanadium, the price will go up. But that does not necessarily imply that the extraction would increase. Such an increase would probably be limited and slow to substantiate.

When evaluating the tests of the model, it must be remembered that the "data" is uncertain, and not really the truth. Plotting production timeseries for different USGS ds140 series editions show that the available production "data" is not internally consistent, and not consistent between the publishing years. This illustrates that there is no "true data", but different estimates using simple models based on pen-and-pencil calculations. Thus, "the data", are a result of simple estimation models. Thus, in Fig. 8, the production "data" make a broad band where the vanadium production most likely is to be found (see Fig. 9).

A simple scenario was simulated with where the standard scenario is based on the assumption that 80% of the vanadium goes to flow batteries and the rest goes to substitute for cobalt in Li–Vanadium units, and that the demand is 3 times larger than in the business-as-usual (Sverdrup, 2017). Translation of the available vanadium for vehicle battery packs and flow batteries, according to the scenario we have adopted is shown in Fig. 8. This is an arbitrary split and it is difficult to predict what the real future split will really be. In the "Business as Usual" scenario, 48 million ton of vanadium will be extracted and 83 million ton of vanadium supplied to 2300, under the "increased demand for batteries" scenario, 52 million ton of vanadium will be extracted and 118 million ton of vanadium supplied to 2300. The amount of vehicle battery packs based on vanadium substituting for cobalt will not be sufficient to replace the present fleet of fossil fuel cars running on the global roads (Sverdrup, 2019). Li–Co battery packs may maximum be able to support a fleet of about 300 million cars, and those supported by Li–Vanadium technology would appear to be a similar amount, under the assumption that all vanadium is used for vehicle battery packs. This is very unlikely to happen, and a number in the order of maximum of a fleet of 50,000 vehicle Li–Vanadium battery packs will be available. Fig. 9 shows the results of the simulations for business-as-usual and exploring a three times larger demand for vanadium caused by increased use of vanadium for batteries. The standard scenario assumes that 80% of the vanadium demand increase goes to flow batteries and the rest of the demand increase goes to substitute for cobalt in Li–V battery units.

The increased demand has limited effect on the extraction, but more on the price and the degree of recycling. Without the price response of recycling the vanadium price will become significantly higher. It can be seen that the extraction between the scenarios is nearly the same, resulting in a somewhat higher price in the high demand scenario. The vanadium supply per person and per year and stocks in use per person for the time from 1900 to 2200. Vanadium resources runs out in 2300, the available resources will be exhausted and the stocks in use depleted to insignificant. From then on, vanadium will be a rarity. It is visible in all simulations that vanadium will be in hard scarcity after 2030, unless recycling practices for vanadium are dramatically changed from what they are today. Specifically, this is seen where the lines for supply and demand separate. The vanadium that is recycled with steel far too often end up with scrap iron and is lost by dilution into the large global iron pool. From there vanadium recovery is practically not possible.

Uncertainties in the assessment process are mostly to be found in the estimation of future vanadium demand. At present, most analysts suggest a strong demand for vanadium in batteries. The battery technology is in rapid development, but the possibility of new disruptive discoveries make any prediction very uncertain. This is illustrated by the huge spread in predictions found on websites and in the literature. Future demand is especially difficult to predict for vanadium. There are a number of "experts" out there, making demand predictions, but these are mere guesses based on subjective market expectations. Some uncertainty arise from accuracy of the resource data and the degree of accessibility and extractability of the different sources of vanadium. The system dynamics model is largely self-confining within

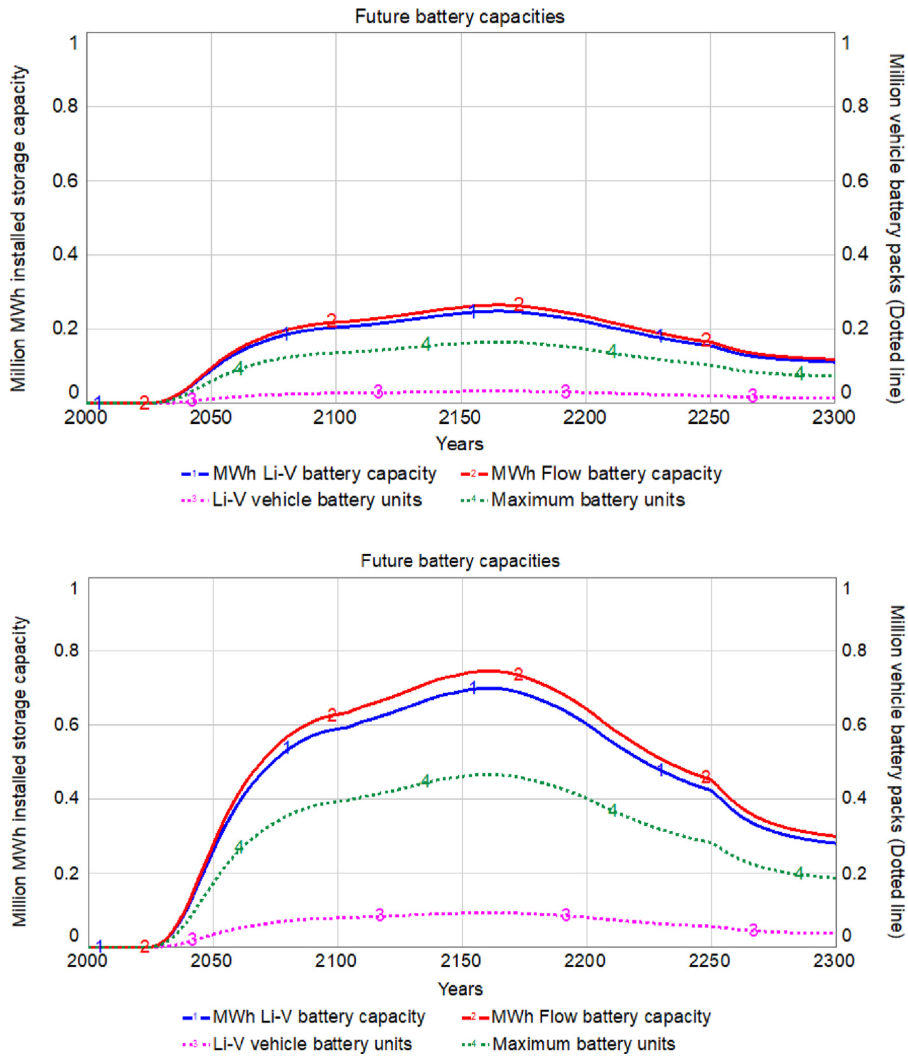


Fig. 9. The number of batteries and installed storage capacity for the two scenarios.

mass balance, and hold less of the uncertainty of the simulations. Important is to remember that a model forecast cannot be interpreted as what will happen in the future, it suggests what could happen in the future.

8. Conclusions

The following conclusions were made:

1. The extractable part of the global vanadium resource was much less that the geologically detectable amounts in geological deposits. The extracted amount is estimated to be about 60 million ton of vanadium to 2300, less that the ultimately recoverable resource estimate and far below what is geologically detectable.
2. Vanadium becomes a scarce commodity in the future. After 2015, vanadium is in soft scarcity, and the model outputs suggest risk for hard scarcity before 2045. How much depend a lot on estimates of future demand. This is significant enough to affect all sectors and may be a limitation for large scale application of some alternative energy technologies. Vanadium stocks-in-use in society peaks in 2100. The scarcity is less dependent on the size of the geological occurrence, and more on the context, the ability to mine a substrate that has good content and the ability to extract it in an economically sensible way.
3. The vanadium supply will not be able to respond to a large surge in demand and for new technology, less than half the expected demand can be satisfied by increased production. Vanadium will be vulnerable to demand variations in the market, since the production is to a large degree dependent on extraction of other metals.

The increase in price may stimulate better recycling and this partly can fill up some of the increase in demand that cannot be covered by increase in production. If recycling responds less to price increase than we have assumed in the model, then the vanadium market will experience scarcity and further price increases. Proactive mitigative measures against scarcity may be necessary such as enhanced recycling.

Vanadium may qualitatively substitute for cobalt in some technology applications, but this appears not to be a solution for cobalt scarcity, as vanadium is also a metal that soon will experience scarcity. Further possibilities of the vanadium dynamics needs to be explored with the WORLD7 model system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study contributed to the EU H2020 LOCOMOTION. Project under grant agreement 821105/H2020-LC-CLA-2018-2.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2023.100121.

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