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Original Research Articles

An assessment of the global supply, recycling, stocks in use and market price for titanium using the WORLD7 model

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ABSTRACT

The change in supply, price, extractable resources and recycling with time for titanium was assessed with the WORLD7 model. Demand for titanium is expected to increase in the future, and several future scenarios were investigated. The model is mass balance based and simulates the flow terms past from 1850 to 2023 and the flows in the future from 2024 to 2200. The recoverable mineral resources have been estimated at about 1800 million ton of titanium element after a review of the literature. Only 500 million ton of titanium mineral resources count as high grade, the rest is found in ores with low or very low content. Our findings are that for all scenarios, the WORLD7 model simulations shows that there will be no significant shortages in the short term (before 2050), but in the longer term there will be scarcity issues appearing after 2075 for both metal and oxide supply. If demand increase more than anticipated by market analysts, scarcity may develop decades earlier. The model makes estimates for titanium oxide and titanium metal demand, extraction, supply, recycling, losses and the development of major stocks in society.

1. Introduction

Titanium has important technical uses for modern technology. It is of growing importance in advanced civil and military technologies, and the supply security is of importance. The demand for titanium metal is high as compared to the production. Titanium is a material with very good technical properties and many new uses are being considered. One important question is if there is sufficient titanium available as oxide materials and for metal production. Titanium is very commonly occurring as a trace element in rocks and soils, and the presence in rocks and soils is enormous. However, the geological deposits that are suitable and available for mining is a much smaller amount, and titanium is a limited resource. Resource estimates have varied over time, and good estimates for extractable resources ate essential for making good assessments with WORLD7. Thus, we have identified that we must extract the best and latest estimates of extractable titanium resources and reserves.

Our mission with WORLD7 is to cover all the major metals in our global assessment of future metal supply security and sustainability. There are a substantial number of earlier studies for many metals by the authors and their colleagues that can be found in the reference list. Titanium is a metal of major future importance, titanium oxide is an important large volume industrial mineral as a filler and as a pigment. We may ask some questions: Will technology be the primary limitation or will there also be a resource limitation in the future? These questions have been posed by Perks and Mudd (2019) and that study provided a very good starting information for this study. Metal scarcity of natural resources in the future may cause trouble for continued technology development and the further development of the economy in the long term, and titanium have been important for the development of some specialized high technologies used in aviation and space technologies (Bardi, 2013; Sverdrup and Ragnarsdottir, 2014; Sverdrup et al., 2019a).

In this study there are two types of results, found in two places in the study. The first type is the assembly of the data required to parameterize, run the model, and for validating the model (Summarized in Tables 1–3). The second type is the model simulation outputs (Figs. 7–12).

The data is presented and processed before the model is put into use. These data are required for running the model, but they are also results in their own right. Important for the assessment is size of the titanium resource available. For this the data on the size of geological deposits with titanium and how the numbers are reworked into an assessment of how much of this it is actually possible to extract industrially. There is a

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Table 1

Titanium ilmenite ($FeTiO_3$) and rutile (TiO_2), reserves and resources, best available estimate by the authors, million ton. Take care that the amounts are in amounts mineral. Note that several slots have question marks, this indicate that we could find no good estimate.

Country	Ilmenite known reserves	Ilmenite hidden resources	Ilmenite sum	Rutile known reserves	Rutile hidden resources	Sum rutile
Australia	160	480	640	32	41	73
South Africa	63	190	253	8.3		
United Arab Emirates	15	45	60			
Russia	150	450	600			
Paraguay	30	670	700			
India	85	593	675	7.4	31	38.4
Sri Lanka	30	90	120			
China	200	600	800			
United States	2	108	110	0.2	12	1.4
Canada	31	100	131			
Kazakhstan	15	45	60			
Ukraine	6	40	46	2.5	10	12.5
Brazil	43	440	483	1.2	3.6	4.8
New Zealand	6	18	24			
Mozambique	14	42	56	0.5	2	2.5
Norway	57	252	309	1.0	4.9	5.9
Vietnam	2	30	32			
Madagascar	40	120	160			
Sierra Leone	?	?	?	3.8	12.2	16
Others	26	80	106	0.4	2.6	3.0
Sum mineral weight	975	4193	5227	57.3	117.3	174.6
Sum titanium metal			1480			99
Deduced from geology		2500	2500	12	83	95
Sum minerals	975	6593	7568	70	200	272
Ti content			0.283			0.568
Sum titanium metal contained	308	1866	2173	42	120	162

Table 2

Overview of resource estimates for titanium. Titanium occurs in ilmenite, rutile and in some regular iron ores. It is present in trace amounts nearly everywhere. Amounts in million ton.

Year	Ilmenite, rutile and other minerals	Titanium content	Mined to date	Titanium content URR	Refs.
1940	100	28	1	29	USGS older archives (1975)
1968	334	94	15	109	USGS (1975)
1970	485	137	30	177	USDoI (1980)
1993	883	250	50	300	Roper (1976a,1976b), USGS (1994), Arndt and Roper (1980)
1999	1230	348	52	400	USGS (2000)
2002	1250	350	54	404	USGS (2003), Roper (2006)
2006	2230	631	58	689	USGS (2005), Roper (2009)
2009	2250	637	60	697	USGS (2008)
2011	2120	600	62	662	Ragnarsdottir et al. (2011)
2013	4900	1372	65	1437	USGS (2012)
2014	3650	1033	70	1103	USGS (2016)
2014	3600	1000	70	1070	Sverdrup and Ragnarsdottir (2014)
2015	3690	1044	77	1121	USGS (2016)
2016	3900	1103	83	1186	USGS (2018)
2017	5227	1480	100	1570	Gambogi (2016) (USGS)
2021	5227	1480	100	1570	Gambogi (2022) (USGS)

Table 3

Estimated titanium resources and other model parameterization used as input data for the WORLD7 model. See Tables 1 and 2 for data extracted from literature. Rest is the fraction in each grade that would not be extractable. Perks and Mudd (2019, 2021a, 2021b) provided information for making the division into quality classes.

Ore grade (%TiO_2)	Titanium ore content, million ton					Field yield, %	Switch price
	Known	Hidden	Sum	Rest	Sum		
High grade (22–40%)	100	500	600	105	705	85	400 $/ton
Low grade (10–22%)	50	750	800	300	1100	73	1160 $/ton
Ultralow grade (2–10%)	50	350	400	900	1300	33	2000 $/ton
Trace grade (<2%)	100	100	200	1000	2000	10	4000 $/ton
Sums	200	1600	1800	2305	5105	45	

number of issues with the data, that will be evaluated in this part of the study, but discussed in the context of the modeling results at the end of the study.

The second type of results is the actual modeling outputs is discussed in the last part of the study, where the past and future supply dynamics of the titanium system is explored with the model. It is concluded with a

Table 4
Model parameterization and setting used as input data for the WORLD7 model to simulate the titanium system. The ore grades were taken from Perks and Mudd (2019, 2021a, 2021b). The price model parameters were derived as demonstrated by Sverdrup and Olafsdottir (2019).

Mining coefficient, titanium minerals, TiO_2	0.03
Prospecting rate	0.035
Average society retention	25 years
Recycling fraction of losses	0.2
TiO_2 price coefficients	$k = 116{,}000$, $n = 0.6$
Titanium metal price coefficients	$k = 81{,}000$, $n{=}{-}0.4$
Time step in numerical integration	1/256 year
Integration method	4-sep Runge-Kutta
High grade ore, TiO_2 content:	40–22%
Low grade ore, TiO_2 content:	22–10%
Ultralow grade ore, TiO_2 content:	10–2%
Trace grade ore, TiO_2 content:	<2%

discussion of diverse aspects of the results, and conclusions drawn from them about the future.

2. Objectives and scope

A number of research issues are pertinent for resources, also titanium (Bardi, 2013; Sverdrup and Ragnarsdottir, 2014). The study has several research objectives: (1) Estimate and compile the available global titanium resources distributed among different ore qualities that are available for extraction, the past and present annual global production and a review of the available literature on these topics. (2) To use a newly developed systems dynamics model to explore the dynamics of the supply system and its limitations for meeting future demands. Is there any risk for supply shortage of titanium within the next three decades, or in the next centuries? What would the price development of these metals look like according to a business as usual scenario or when the demand is strongly increased? How sensitive is the supply ability for TiO_2 and titanium metals to production and demand variations. In the WORLD7 model, the simulation of titanium, zirconium or hafnium supply systems have been developed as one internally connected module. This study describes the titanium part of that module.

3. Methods

The main methods used in this study are:

1. System mapping using systems analysis methods, causal loop diagrams and flow charts. The simulation model is based on system mapping using causal loop diagrams and flow charts (See a full description of the methodology in Senge 1990, Sterman 2000, and Sverdrup et al. 2022). The flow charts describe the mass balances used in the model. These are paralleled by energy balances (Not shown in this study). The causal loop diagrams show the causal links and feedbacks in the system. The flow charts and the causal loop diagrams are used for constructing the system dynamics model (Figs. 2 and 3).
2. Program the titanium system into a system dynamics tool (Fig. 5). The simulation model for the mass flows and economics of extraction, production and cycling of titanium in society, as a part of the WORLD7 model (Fig. 4). The model also involve energy balances, but these are not described here. The mass balance differential equations are numerically solved using the STELLA® Architect software. The titanium module was integrated into the WORLD7 model system (For a full explanation of the WORLD7 model, see Sverdrup et al. 2019a, 2019b, 2021 and Sverdrup and Olafsdottir 2019).
3. Parameterize the coefficients and constants of the titanium model (Tables 3 and 4 and Fig. 6). For the methodology of estimating the reserves and resources for metals, the works of Singer (2007) and Singer and Menzies 2010 was instructing. They use the geological characteristics of known and detected metal resources to predicts the amount of undiscovered resources, and estimating the amounts on a deposit by deposit basis.
4. Validate the total model performance on historical data 1900–2022 for titanium metal and titanium oxide (Fig. 8). The simulation model developed for titanium is not subject to extensive calibration, as would be the standard procedure with a statistical model. The WORLD7 model is confined by mass balance and energy balances, and all parameterizations have a real world connection. The parameterization is based on measured or estimated parameters, leaving small room for free adjustments.
5. Make model simulations for the titanium system. Run the Business-as-usual scenario as a basis (Fig. 9).
6. Make sensitivity analysis for increased demand in the future (Figs. 10–12). Interpret the results and draw out consequences for the future.

We interpret the simulations outputs and discuss aspects of the model simulations. We have employed tools and methods for assessments similar to earlier studies on other metals (Sverdrup et al., 2018, 2019a, 2019b; Sverdrup and Ragnarsdottir, 2014, 2016). There are several studies on assessment of geological deposits of titanium and attempts at estimating the extractable resources. These are described in the resources section. We have found no earlier system dynamics modeling of the titanium supply system and circularity. There are several simpler approaches available (Dodson et al., 2011; Sverdrup and Ragnarsdottir 2014; Busch et al., 2014). The results are of two types; (1) The compilation of data to support the modeling, and (2) the use of the simulation model to assess the future. The resource data is an important basis for initiating the model, the production and price data are important for validating how well the model recreates the past.

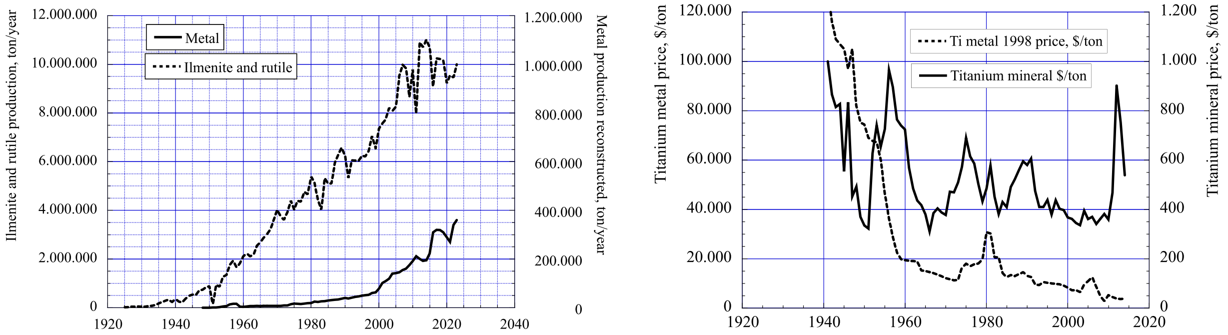
4. Titanium as a system

4.1. Background

Titanium and zirconium occur together in specific minerals like ilmenite ($FeTiO_3$), titanomagnetite, which is a solid mixture of ilmenite and magnetite ($FeO*Fe_2O_3$) and rutile (TiO_2) and in the carbonatite type of polymetallic ores. All minerals mentioned above are used for titanium oxide mining, but titanomagnetite is used for both iron-making and extraction of titanium and vanadium. In the common process used, 98% of the titanium and vanadium end up in the slag (Jena et al., 1995). Titanium is used as oxides in pigments (TiO_2) and as a refractory material (TiO_2). TiO_2 competes with ZnO as a white pigment in paint. It can also be used as a chemically inert and non-toxic filler in paper, toothpaste and a variety of products. Only a minor part of titanium is used in the metallic form at present (Jena et al., 1995). Titanium metals is valuable and sought after for its good chemical and technical properties such as in manufacturing of super-alloys, but it is expensive and complicated to manufacture (Kroll, 1940; Takeda et al., 2020). High titanium metal demand come from the great usefulness for advanced technologies. Titanium metal is used for a number of purposes, the main categories were as follows (van Toonder, 2010), Industrial equipment used 155,000 ton/year, aerospace applications: 165,000 ton/year, military hardware: 55,000 ton/year, other new technologies 95,000 ton/year, a total of 370,000 ton/year of titanium metal. The titanium metal has half the density of steel, is tough and strong, has a high melting point and excellent corrosion resistance.

4.2. Titanium production

The production of titanium in scale started as late as the 1950′íes for military purposes and for nuclear sciences, and titanium was not available for the civil markets until decades later. Titanium is mined



a; Metal and mineral production

b: Metal and mineral price

Fig. 1. The production of titanium as mineral concentrates and metals (a) and the corresponding prices for minerals and metal (b). Data from the British Geological Survey (BGS) (Brown et al., 2015; Idoine et al., 2022), (Perks and Mudd, 2019, 2021a, 2021b) and (USGS, 2022). a: Metal and mineral production. b: Metal and mineral price.

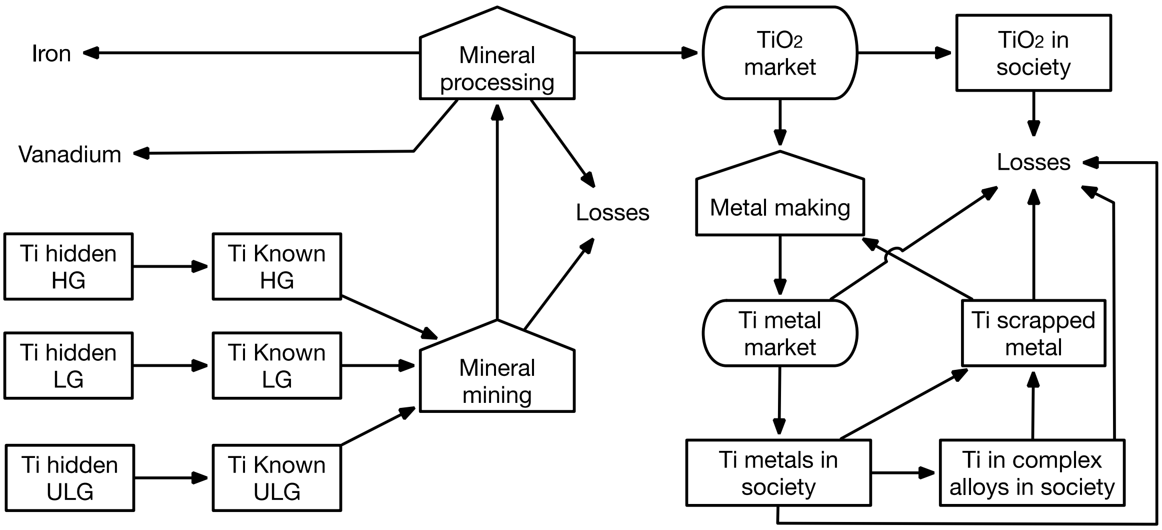


Fig. 2. Flow chart for the production of titanium in the sub-model built for inclusion in the **WORLD7** model. "Ti materials" are mostly titanium dioxide which is used as a filler material, in ceramics, foods, cosmetics and as a pigment.

47% from ilmenite ($FeTiO_3$), 40% from rutile (TiO_2) and the rest from other minerals and secondary ore concentrates (13%) (Jena et al., 1995). The titanium metal is produced with the Kroll process (Kroll 1937, 1940), but new methods are being explored (Chen et al., 2000). There is some recycling of titanium metal, but the low cost uses like chemicals, pigments and oxides are normally not recycled.

The complex production technology, high capital costs and high energy costs involved, pose significant challenges for producing titanium on industrial scale. Titanium extraction from low quality ores is a complicated process, and the costs in chemicals and energy are very substantial. Kroll (1937, 1940) describes the process to go from oxide to metal, Olbrich et al. (2009), Reed (2006), van Vuuren (2009), Fatollahi-Fard (2017), Martinez et al. (2010) discuss aspects of high costs, energy use and technical challenges of both mineral processing and metal production. The most important study of for titanium production is the study of Perks and Mudd (2019, 2021a, 2021b).

A very large amount is detected as present in a geological deposit, but this is not the same as an extractable resource. In very low contents, titanium is found nearly everywhere in the soils. The largest producers of titanium metal are China, Japan, Russia, United States of America and Kazakhstan. Data for titanium oxide and metal production to 2020 was taken from the United States Geological Survey website (USGS, 2022), under the Mineral Commodities Summaries programme (USGS 2022 mcs and USGS ds140–2022 report series) and from Perks and Mudd (2019). The titanium metal production data was assembled by the authors from industrial data and metal trading house websites and El Khalluofi et al. (2021), Moiseyev (2006), Industrial Business Publications (2013, 2015), Bedinger (2011). Prices and mineral prices are available from the USGS website.

For titanium, there was no real trading markets before the year 2000. Until then the production and price was determined by military needs and closed governmental contracts. The different sources for production show large differences. There is no consensus in the literature on reserves, resources and total global production (Perks and Mudd 2019, 2021a, 2021b). It is the most thorough and complete, they address some of the differences between the USGS and the BGS databases. They provide quantitative information of different ore grades in deposits. They make an overview of different methods for ore processing to titanium mineral concentrate. For rutile, the British Geological Survey (Brown et al., 2015; Idoine et al., 2022) and the United States Geological Survey (USGS, 2022) agree, for ilmenite the differ in amount extracted systematically the British estimate being 25% higher. The reason for the difference is discussed by Perks and Mudd (2019).

The metal price for titanium was assembled by the authors from business archives and notes and USGS (2022). There was no functioning trade market for titanium before 1960, outside the nuclear energy industry and the military. Titanium metal production amount were kept as state military secrets for a long time, and this may still be the case in

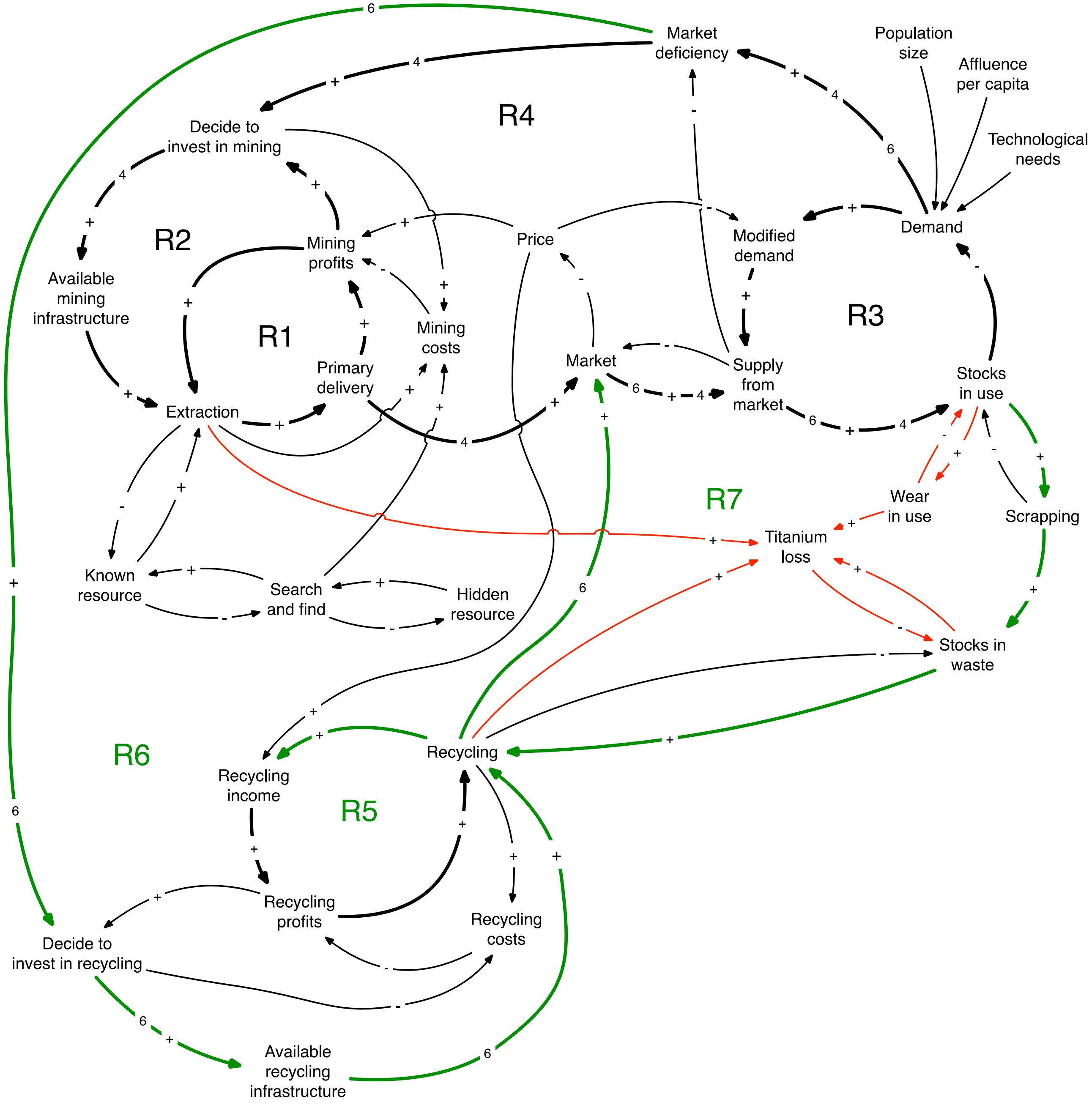


Fig. 3. The causal loop diagram for the titanium model. The different R's are reinforcing loops driving the system forward. The unmarked loops are balancing loops, slowing the system down. The green lines are links reinforcing recycling. Red links drive losses.

some countries. Overall, the titanium price has come down because of improved production processes and effects of a larger production volume.

4.3. Titanium reserves and resources

It appears from a review of the available literature references that the different resource assessment do not agree. Thus, all resource estimates made are approximate, and we have to extract the values we find most reliable and reasonable. We have in our calculations assumed that 1 ton of ilmenite was set equal to 0.283 ton of titanium, and 1 ton of rutile was set equal to 0.568 ton titanium, based on the chemical formula. Table 1 shows the size and country location of the titanium ores ilmenite and rutile, specified as reserves (known) and resources (hidden), in million ton for titanium. The reserves and resources estimates are based on classical geological estimates, and the allocation of extractable titanium amounts according to ore quality, stratified after extraction costs (Sverdrup et al., 2019). The data was collected from a number of references and pieced together into a whole overview.

The United States Geological Survey reports for 1993, 2009, 2014, 2015, 2017, 2019, 2022 and the British Geological Survey (Brown et al., 2015; Idoine et al., 2022) were used for the general overview, annual production rate and their estimates of reserves and resources. Older studies used for data extraction on resource size are for Table 2: Arndt and Roper (1980), Crowson (1996), Dixon (1979), Kimbell (1963), Meadows et al. (1974), Roper (1976a, 1976b), Safirova (2011, 2013), Taylor and Moore (1997) and Bedinger (2011). All of these made estimates for a certain year, and this was used to make Tables 1 and 2.

A number of newer studied were used to add to the general picture gained from the USGS material commodities summaries and the ds140

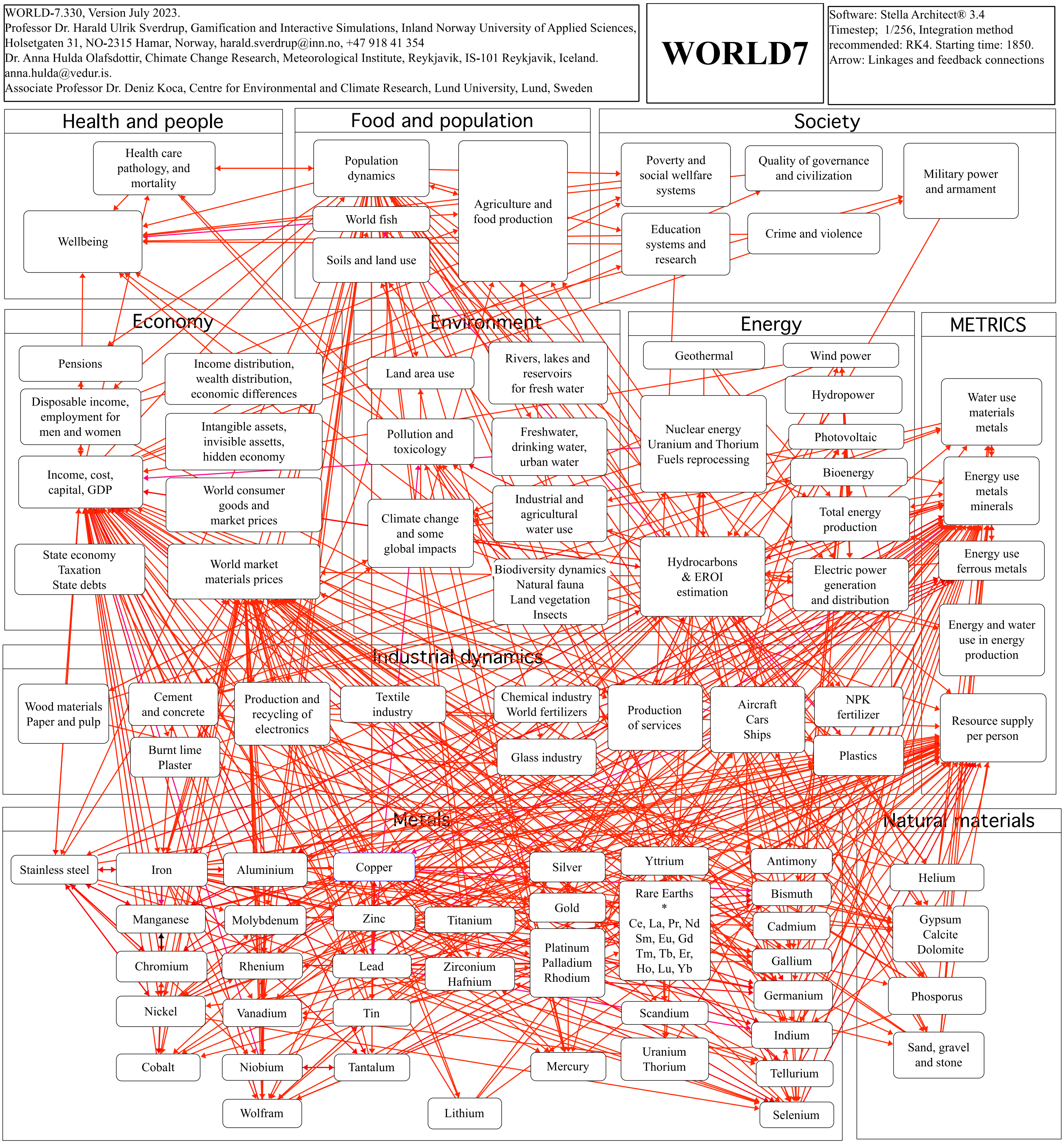


Fig. 4. An overview of the whole WORLD7 system. Every red line represents one of several flows, feedbacks or causal links in the model. Every box has one or several models inside, such as the one shown in Fig. 5 for titanium.

programme that ended in 2019 (USGS, 2022), Perks and Mudd (2019, 2021a, 2021b) and El Khalloufi et al. (2021), Britt et al. (2015), Boyd and Gautneb (2016), Norwegian Geological Survey (2016), International Business Publications (2013), Britt et al. (2015), International Titanium Association (2016), Kelly and Matos (2017), Korneliussen et al. (2000), Lele and Bhardwaj (2014), Tyler and Minnit (2004) and the Geological Survey of Finland (2013) supplied an estimate for either their national reserves, resources or both for a certain year or several years. In some of them, it is not transparent how geological occurrence was converted to available for extraction, or if this was considered at all.

We compiled the estimates into Table 2, organized chronologically to observe if the estimates converge on a limit or not. The total amount of rutile has been estimated at 82 million ton of rutile but there is more, and we think the real total resources (known plus hidden) is at least 270 million ton of rutile. That corresponds to 162 million ton of titanium metal content. Korneliussen et al. (2000) states that the mineable amount for 2017 was corresponding to 5497 million ton of ilmenite, or 1795 million ton of titanium.

Woodruff et al. (2017) published an assessment by the United States Geological Survey, saying the ilmenite resource is 4625 million ton

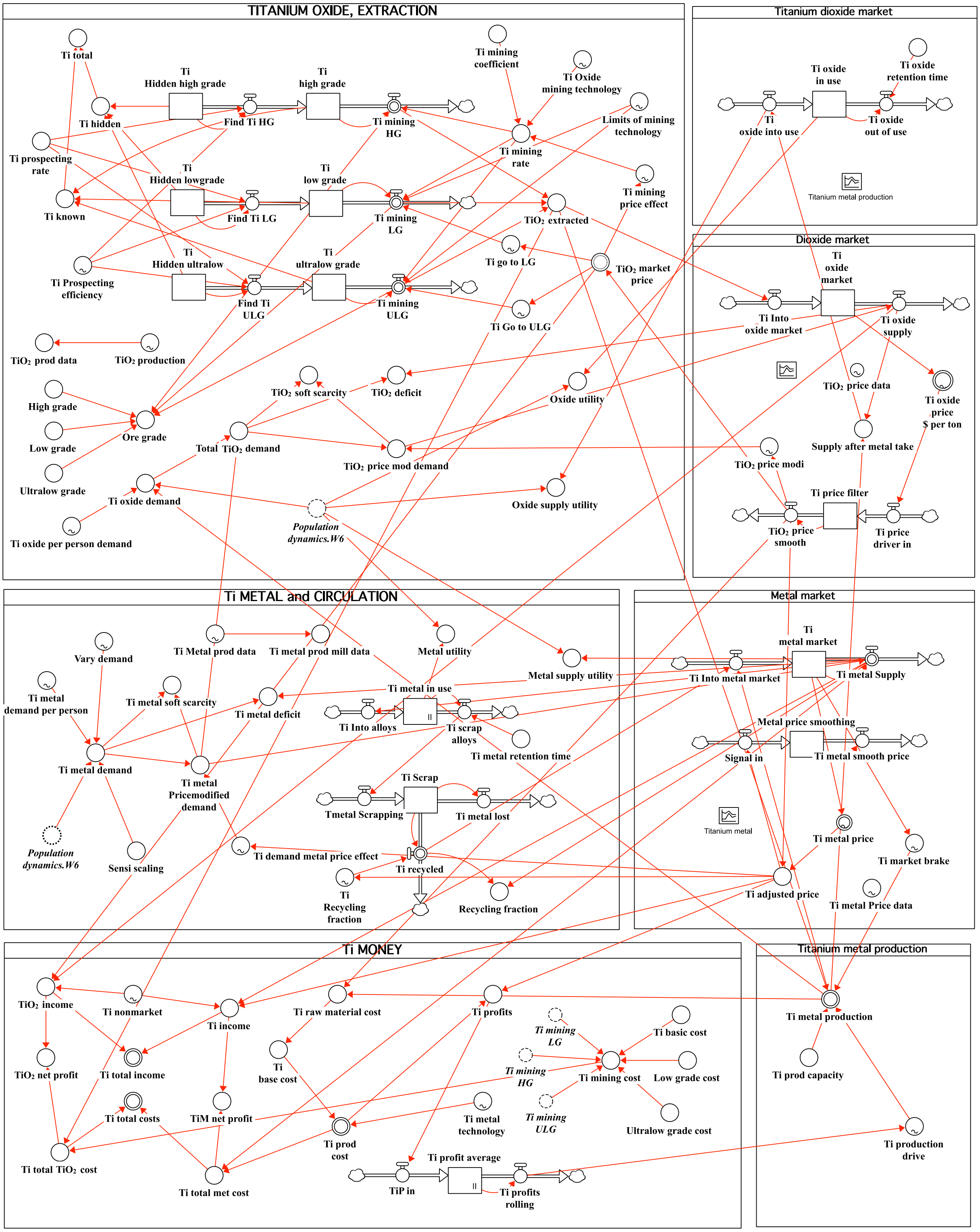


Fig. 5. The titanium module as it appears in the STELLA Architect system dynamics software. The system dynamics model was based on the flow chart shown in Fig. 3 and the causal loop diagram shown in Fig. 4.

mineral and about 367 million ton rutile mineral. Gambogi (2022) reported that the global ilmenite reserve is 700 million ton, the rutile reserve is 750 million ton and the total resources are at least 2000 million ton. Perks and Mudd (2021) and Perks et al. (2022) reports that the ilmenite, rutile and leucoxene total resource is about 2650 million ton of TiO_2 content. This is consistent with our estimates, using slightly different methodology. This can be can be interpreted so that the known ilmenite stocks are as follows: known ilmenite 700 million ton, hidden 1000 million ton, sum 1700 million ton of ilmenite, rutile known 750 million ton and hidden 1000 million ton, sum 1750 million ton of rutile. This would correspond to 1521 million ton titanium metal. The ore grades mined vary from 5% to almost 30% in the best deposits (Perks and Mudd, 2019). On average the ore grade is at present about 5–15%. The deposits are both in intrusive crystalline rocks and in

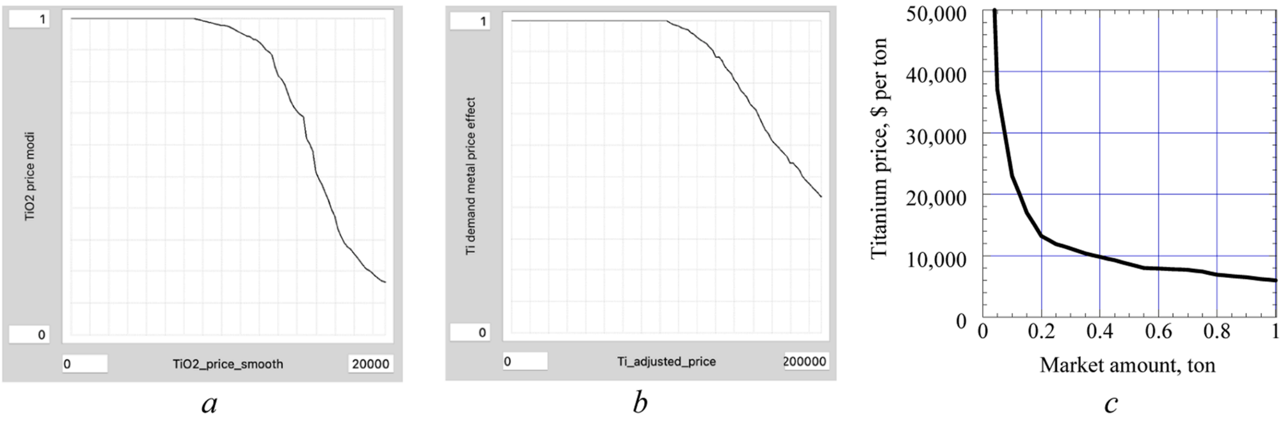


Fig. 6. The demand response to price functions for metal (a) and TiO_2 (b). The metal market amount to market price graph is shown in (c). A similar curve is used for TiO_2 price. These functions quantifies important feedbacks inside the model.

unconsolidated sediments. We estimated in 2020 that there are available extractable resources and reserves of approximately 2335 million ton titanium in all deposits. Producers use an extraction cut-off at 2–5% in the titanium mineral ore (Nordic Mining, 2020; Woodruff et al., 2017). By assuming an access yield of 80%, the extraction yield to be about 85% and the refining yield to be about 85% from concentrate to pigment, that gives an overall yield from deposit to pigment of 58%. We assume the refining yield from pure oxide (TiO_2) to metal to be about 90%, implying a yield from deposit to metal of about 52%. About 10 million ton of titanium in ore have already been extracted, corresponding to a deposit of 14 million ton TiO_2. This implies that the known deposits can be used to extract 2384 million ton of TiO_2 pigment or about 1200 million ton of titanium metal.

5. Modelling the titanium system

5.1. *The flow chart for the metals production, supply and market dynamics*

The basis of the titanium module is the flow chart for titanium in the system. The flow chart is shown in Fig. 2. Titanium originate from primary mining. The resources have been structured as “hidden”, which are transferred to “known” by prospecting and finding. We operate with three different qualities. Another important titanium source comes from slags from iron smelting. All stocks in the model have defined inputs and outputs, conforming to the principle of mass balance. The inputs are from recycling, and material produced from primary extraction.

Change-in-stocks is what is accumulated in society either as stocks in use or as scrap. Outputs will be what is lost or recycled. Recycling increases the flow through society. In the titanium system, titanium metal is frequently recycled, but titanium oxides are normally not recycled. To meet a certain supply to society, the larger the recycling, the smaller the primary extraction must be to meet the demand

5.2. *Simplified causal loop diagram for the titanium model*

The causal loop diagram is used to describe the main feedback loops of the system to be modeled. The causal loop diagram for the titanium model is shown in Fig. 3. The flow chart together with the causal loop diagram is the basis for the model structure as shown in Fig. 5 (Senge, 1990; Sverdrup et al., 2022). The different R’s are reinforcing loops driving the system forward. The unmarked loops are balancing loops, slowing the system down. There are six main loops driven by investment, infrastructure, prices, operational costs, financial costs and profits as well as recycling of material in the system driving the dynamics. Demand is driven from without the system. Two systems supply titanium into the system, primary mining and recycling of titanium from scrap. The recycling reinforcing links are shown in green, links driving losses are shown in red. Primary production is shown in black.

It can be seen how the titanium system is highly non-linear, and how the market dynamics is essential for capturing the system dynamics.

5.3. *The titanium simulation model description*

Fig. 4 shows an overview of the WORLD7 integrated assessment model. The model part for titanium was designed as a self-standing model, and then after testing, included as a sub-module in the WORLD7 model. This methodology has been described in earlier studies (Sverdrup and Ragnarsdottir, 2016; Sverdrup et al., 2019, 2021, 2022). Metals flow into the market, metal gets stored in products in society and are eventually scrapped or lost. WORLD7 model is a global integrated model that has different natural resources (metals materials, fossil fuels, human food production, forests, trace elements, phosphorus) simulations, an energy module, population module, economy module, society module, natural environment, agriculture and marine ecosystems.

When the profit is lower or goes negative, the mining rate is slowed down, leading to less material in the market, driving the price up. In practice, we have several sources of metal in society; the high, low and ultralow ore grades and the stocks of metal in society that can be recycled. The mining rate follows a first order rate equation depending on the mineable reserve. The rate coefficient is modified with ore extraction cost and ore grade. A technology-factor is accounting for the improvement of technologies used in mining, refining and extraction. Mining operational profit increase mining at higher price and lowering it at lower metal prices. Mining costs, refining costs and prospecting costs all include both variable operations costs and capital costs for infrastructures and equipment. The profit is driven by metal price and amount product sold, but balanced by the cost of operation. The size of the extractable ore body is determined by the deposit content, the technical cut-off in the extraction and the extraction yield. Successful prospecting adds to the known reserve, taking from the unknown, and adding to the known. The ore discovery is a function of how much prospecting that is done and how much there is left to find. The prospecting coefficient depend on the amount of effort spent and the technical method used for prospecting.

The causal loop diagram was used to map all significant causal connections in the system (Fig. 4). It is important that the links are true causal links and not just correlations or that titanium flow is modeled on chain of events. The extraction rate of titanium in the model is calculated as the primary mining rate of titanium oxide extraction rate. Metal is made from titanium dioxide already mined. Only a small fraction of the available titanium dioxide is used for metal production. The mining operation is driven by operations profit. The cost of the mining and extraction operation is mainly determined by two important factors

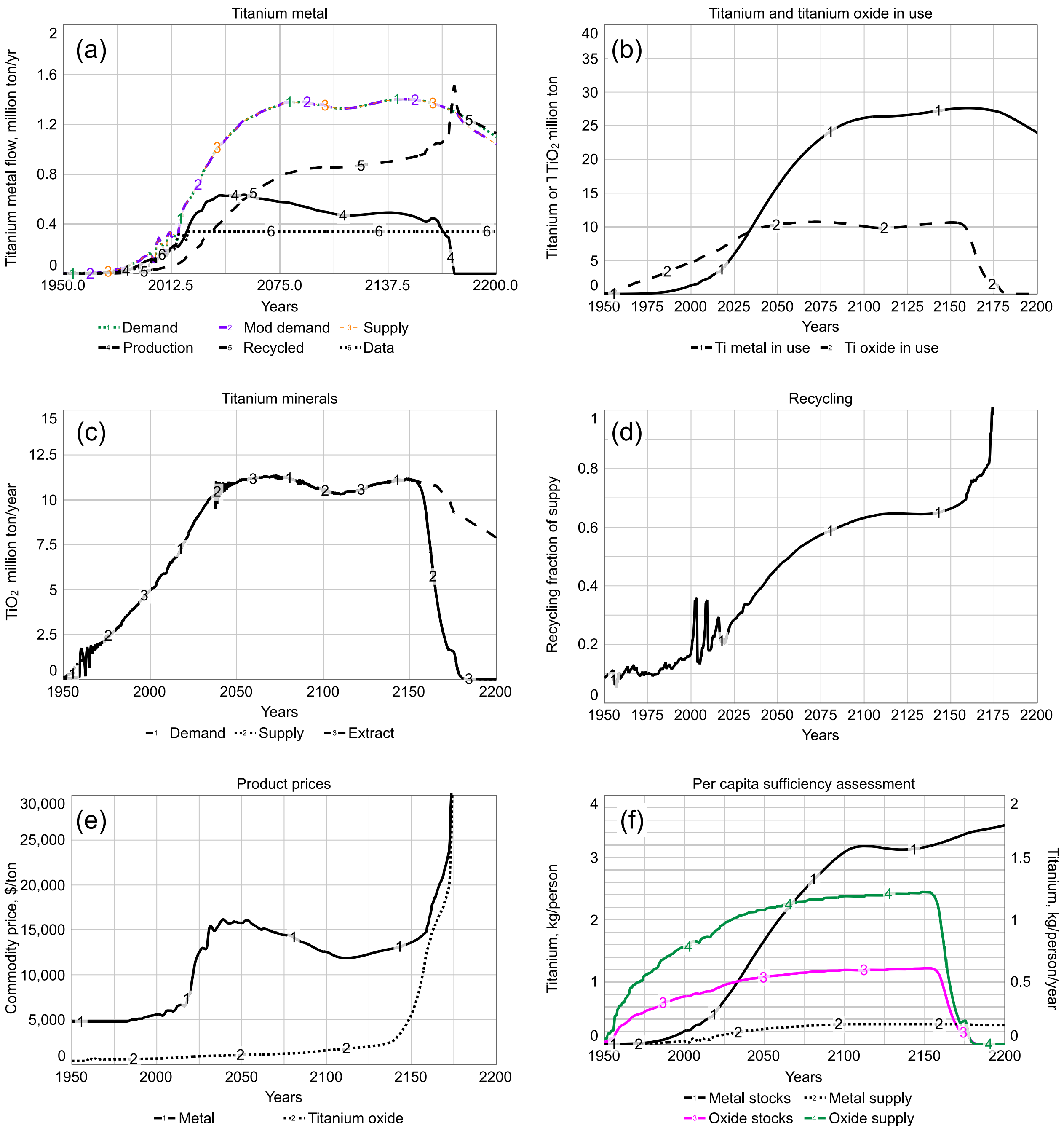


Fig. 7. (a) Comparison between primary extraction, supply, recycling, demand and demand after price adjustment for titanium metal. (b) Stocks-in-use for titanium metal and TiO_2. (c) Comparison of TiO_2 demand, demand after price adjustment and supply, expressed as titanium content. (d) The degree of titanium metal recycling. TiO_2 is not recycled. (e) TiO_2 and titanium metal price. (f) Supply per person and year and stocks-in-use.

beside the cost of investments, the energy price and the ore grade. The recycling fraction displayed in results were calculated as follows in this study:

$$\text{Recycling fraction} = \frac{\text{Supply to market} - \text{Primary extraction}}{\text{Supply to market}} \tag{1}$$

5.4. Modelling the market price

The price is determined by the amount in the market (Sverdrup and Olafsdottir, 2019; Olafsdottir and Sverdrup, 2021). (Fig. 6c) The price drives the urge for recycling of titanium stock from society. Higher price acts as a brake on demand. The profit is driven by metal price and amount extracted, but balanced by the cost of operation. The cost of operation is mainly determined by labour costs, cost of investments, energy cost and the ore grade (Fig. 4). The amount in the market depend on the balance between deliveries to the market and the shipments from the market in response to demand. The demand response to price functions for metal and TiO_2 are shown in Figs. 6a and b.

5.5. Input data, model parameters and model setting

The extractable amounts were set at the beginning of the simulation in 1900, stratified with respect to ore metal content (Sverdrup et al., 2019). Tables 1–3 show the estimated titanium reserves and resources in 2017, based on literature, corporate reports and the USGS. Table 3

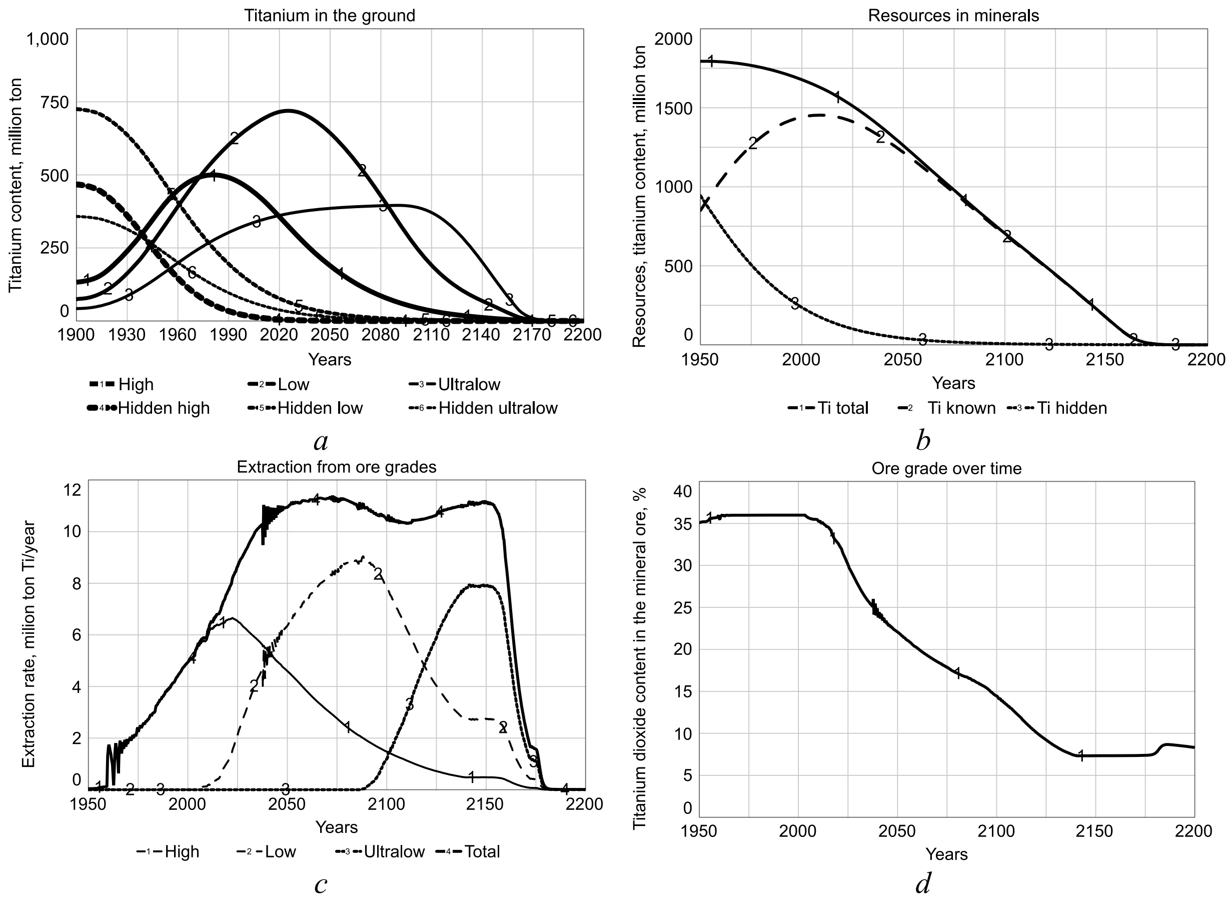


Fig. 8. (a) The amounts of known and hidden high, low and ultralow grade titanium ore as a function of time. (b) The amounts of total, known and hidden titanium content in all global deposits that can be extracted industrially. (c) The extracted amounts from different ore grades. (d) The simulated development of titanium ore grade with time.

shows the estimated titanium reserves and resources in 1850 when the simulation starts.

Reserves are the known and proven reserves, remembering that there probably is far more material in the ground, further in or deeper down, as well as in areas not yet investigated. Our estimates are based on information taken from a variety of sources, they have cited earlier in the text. Take careful note that the resource size is not a fixed size, it depends on both extraction costs and ultimately, society's ability to pay. Hidden resources are defined as that amount that can in due time be found and extracted, even if some of it would require a higher price and more effort (Attanasi and de Young, 1992; US Department of Interior, 1980; USEPA, 1994), how we model this can be found in Sverdrup and Ragnarsdottir (2014) and Sverdrup et al. (2019a). Some of it may require technological innovations and a significantly higher price to cover the extraction costs. The highest ore grades with the lowest extraction costs are consumed first in the model, the switch to a lower ore grade takes place when the price has passed a predefined price level. Reserves are the known and proven reserves. These we call "known". The yet undiscovered extractable amounts (Resources), which we call "hidden", represent what is called resources. Resources are defined as that amount that can in due time be found and extracted, even if some or much of it would require a higher price and more effort. Through prospecting "hidden" is converted to "known" when it is found. But technically it will sooner or later be available, provided we will take to effort to extract it. We have chosen to use an estimate of 1800 million ton of titanium in mineral ores to be available to industrial extraction. There are about 25 million ton titanium available in upgraded iron slags and 125 million ton titanium in iron slag that could be available for extraction, in total 150 million ton. This has been counted into the numbers for high grade ore. Because of the significant uncertainty in the available data, there are quite a broad range where the titanium resource size can be set. Tables 3 and 4 show the WORLD7 model parameterization used as input data for the WORLD7 model for these runs, using the values we find to be the most appropriate.

5.6. *Expressing supply*

In the simulation the soft scarcity is calculated as the difference between the demand and the demand after it has been modified with the price. The hard scarcity is simulated as difference between demand and supply:

$$\text{Soft scarcity} = \text{demand} - \text{price} - \text{modified demand} \quad (2)$$

$$\text{Hard scarcity} = \text{Modified demand} - \text{market supply} \quad (3)$$

These will be plotted as a result from the sensitivity runs (Figs. 10–12). One of the significant uncertainties for the future, is demand. The demand is modeled as being composed of two parts. A basic demand estimated from population and affluence, in principle making it dependant on GDP. And a more arbitrary part, based on guesswork on substitution and technological development. A sensitivity analysis was made by scaling up demand from the year 2000 and forward.

6. Results from model simulations

The simulation results were done in two steps. First the business-as-usual was done (Figs. 7 and 8), and the standard run compared to historical data for model validation (Fig. 9). This serves to secure the

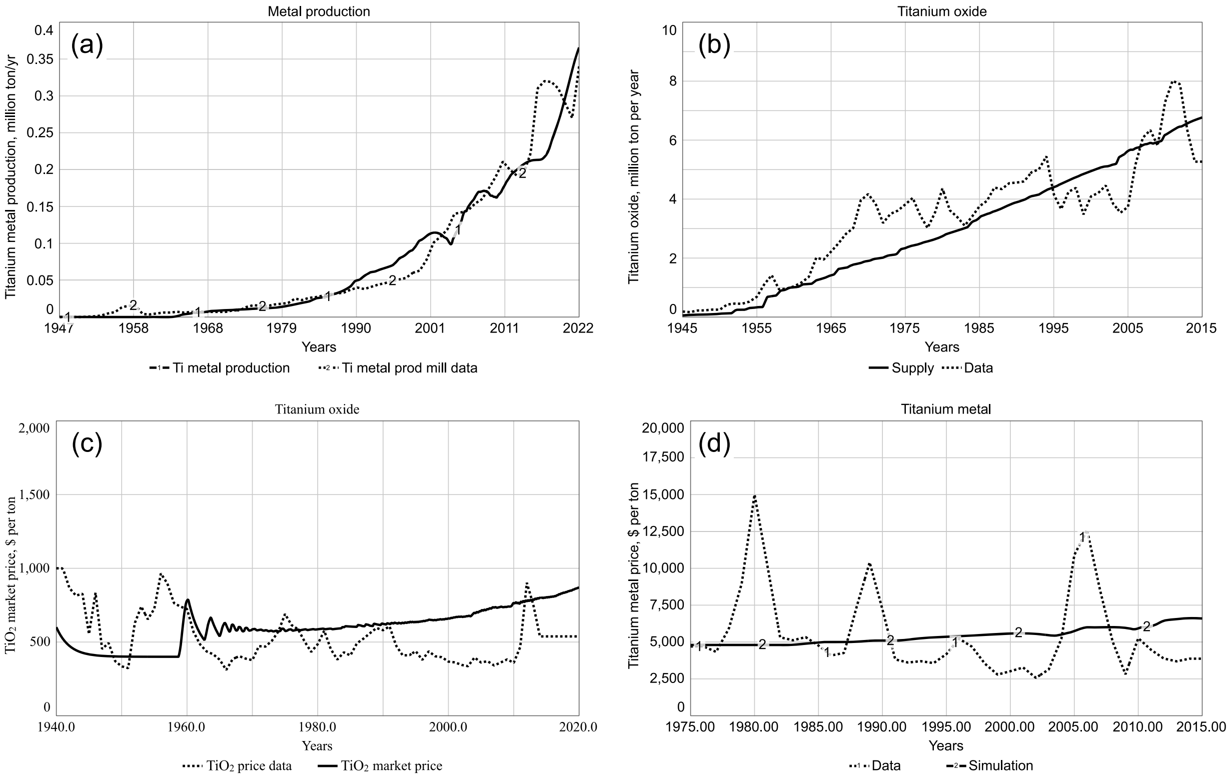


Fig. 9. The simulation of the past and future price dynamics for (a) titanium metal and TiO_2 price. (b and c) Test of the simulation of the prices of TiO_2 (b) and metal (c) on the observed data.

credibility of the model. Secondly, the model was used to make sensitivity simulations, using variations in demand, to have results helping us to understand future titanium system dynamics (Figs. 10–12). Finally, some aspects of the simulation results will be discussed in broader terms.

6.1. *The business-as-usual simulation*

The simulation results were taken straight from the WORLD7 model and has been plotted in Fig. 7. Fig. 7a shows the titanium metal dynamics, demand, modified demand, supply, extraction and recycling from the simulations. The simulation shows how the recycling picks up as a result of the price going sharply up when the extraction stops because of mine exhaustion. Fig. 7b shows the amounts in use in society for titanium dioxide and metal. The metal amounts plunge quite fast after titanium ore extraction has stopped. Fig. 7c shows the titanium oxide mining rates 1900–2250 as compared to the observed mining rate for 1950–2020, as TiO_2 demand, modified demand and actual supply. Fig. 7d shows the simulated recycling degree for titanium metal. There is no titanium dioxide recycling and everything used is lost. The metal recycling spikes up when the metal production stops and because a sharp increase in metal price. Fig. 7e shows the simulation of price for TiO_2 and titanium metal. Fig. 7e shows the metal and TiO_2 price. Note how the price for both spikes up when the mining resource runs out. Fig. 7f shows the amount per capita and amount per capita per year.

Fig. 8 shows further modeling results for the titanium resource base. Fig. 8a shows the amounts of known and hidden high, low and ultralow grade titanium ore. The term “known” is analogue with what the USGS calls “reserves”. “Unknown” are the “resources” in the USGS terminology. They are steadily declining all the time. Known rise from nearly nothing in 1850, to peak one by one, the best first and the poorest last. Fig. 8b shows the total resource, known and hidden, expressed as titanium content in all global deposits that can be extracted industrially. The resource is under business-as-usual exhausted at about 2260. Then only trace grade deposits will be left, and these are largely not minable.

Fig. 8c shows the rate of extraction from different ore grades with time. The simulation extract the best qualities first and then in declining order. In the model, the best grades are mined first and the poorest last, but the classes overlap some. The extractable titanium resources end in 2175. Then the global titanium reserves and resources will be exhausted. There will still be titanium in geological deposits and in soils, but these are not minable.

Fig. 8d shows the development of the average ore grade over time. The highest ore grade seen is about 52% titanium content, but the bulk of the ores have lower grades than that. The curves all show that under Business-as-Usual, the titanium global extractable resources will come to an end before 2200. An important diagnostic indicator would be the ore grade. When ore grade goes down globally, this is a hard proof of resource exhaustion going on. When declining ore grades are observed, all denial of resource exhaustion is futile.

6.2. *Testing the model on historical data*

For testing the model, data are available on historical prices and on historical amounts of mineral and metal production (See Fig. 1, with data from USGS (2022), BGS (2022) and other sources). This has been shown in a series of charts shown in Fig. 9. Fig. 9a shows the test on metal production data and Fig. 9b shows the test on TiO_2 production data. In both cases, the model simulation works fine, considering that the modeling is from basic physical causalities and market mechanisms, and no calibration to time series of the model used is done. The production over time in the past from 1947 to 2022 is reasonably reconstructed. The USGS data series stop in 2019, and data to 2022 was found in various sites on the web.

Fig. 9c shows the model test on TiO_2 data on price, and we can see that the model slightly overpredicts the price. Fig. 9d shows the model test on metal price. The metal price reconstruction is reasonable. It

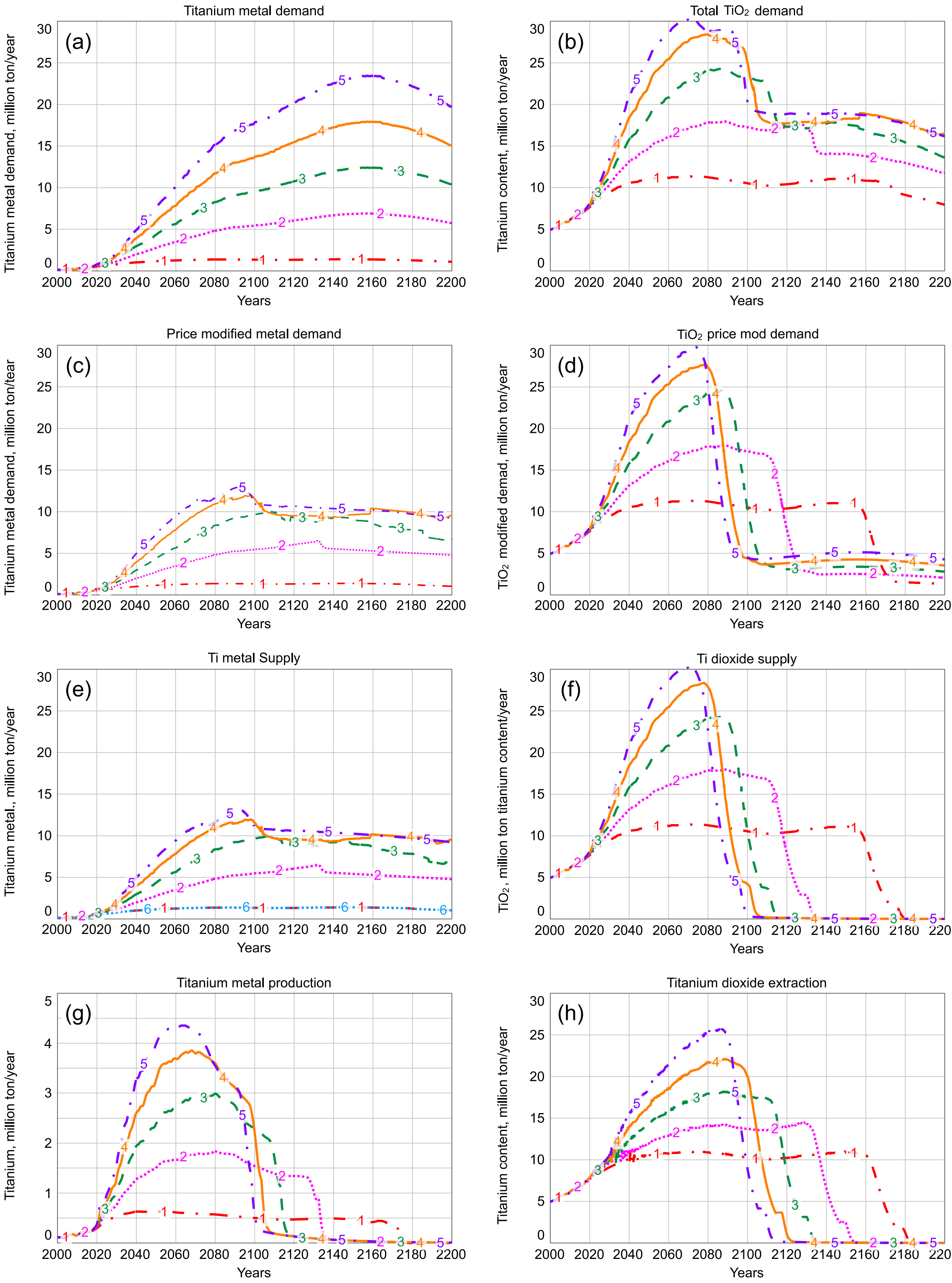


Fig. 10. Results from the sensitivity simulations. Metal on the left, titanium oxide on the right. The Business-as-usual scenario is represented by the line numbered 1. TiO_2 demand and titanium metal demand in the sensitivity runs. Titanium metal demand is independent, TiO_2 demand has one independent part and one that depend on metal demand. The difference between (a) and (c) is the soft scarcity for metal. From the top and going down, we have initial demand (a, b), demand after modification by price (c, d), the actual supply (e, f) and finally the extraction (g, h) for metal and oxide.

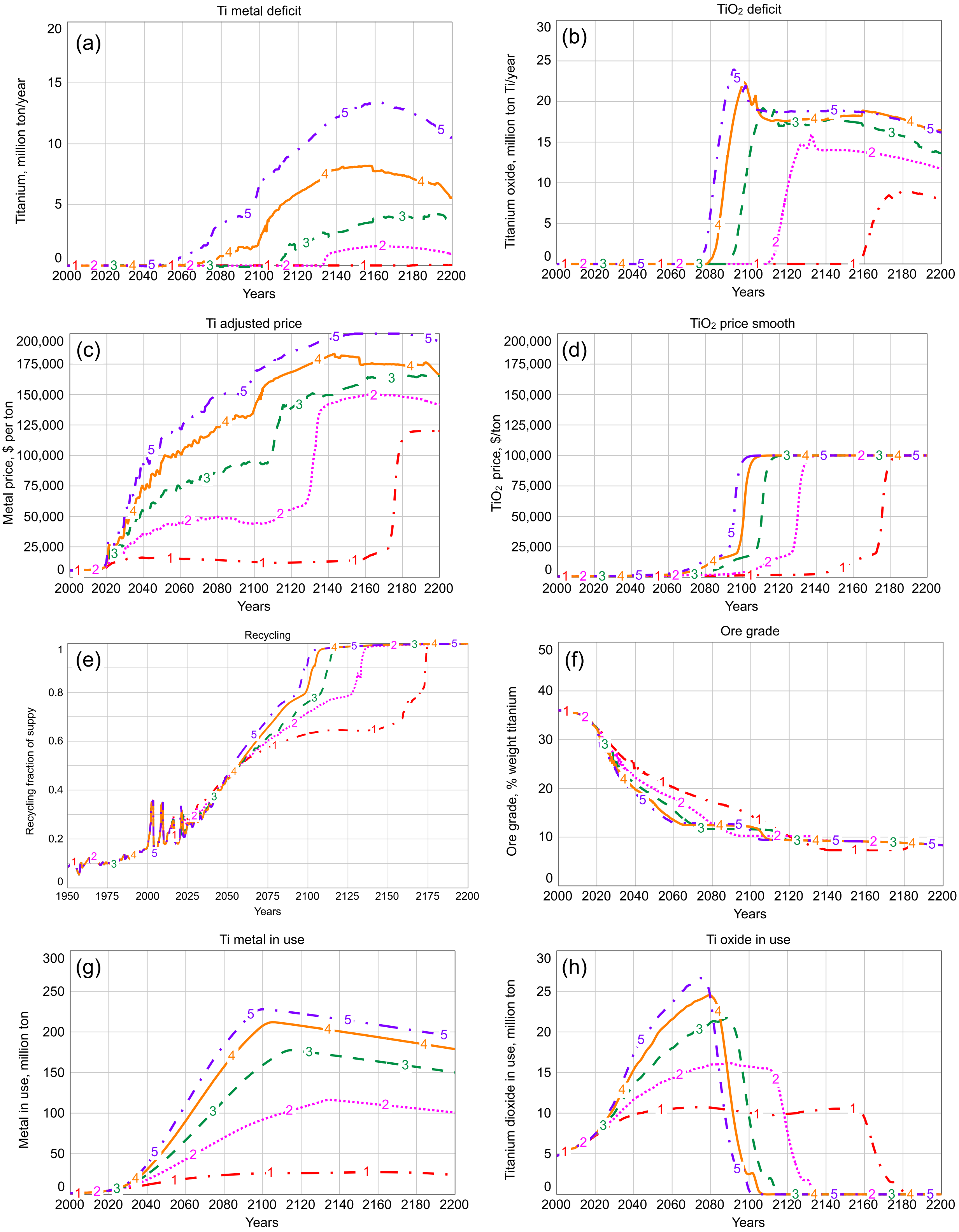


Fig. 11. Results from the sensitivity simulations. Titanium metal to the left and TiO_2 to the right. (a) and (b) shows the titanium soft scarcity as the difference between initial demand and modified demand for metal and TiO_2. (c) shows the titanium metal price and (d) the TiO_2 market price when demand changes. The price shoots up when scarcity occurs. (e) shows the recycling degree for titanium metal. (f) shows the mineral ore grade with time. (g) shows the stock of titanium metal in society in use, as million ton (h) shows the amounts of TiO_2 as titanium content in use in million ton.

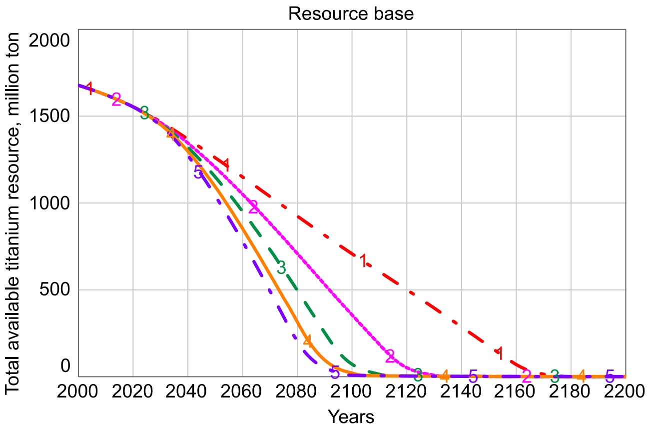


Fig. 12. The development of the total mineable resource over time for the different scenarios. Depending on the demand scenario, the available titanium resource runs out somewhere between 2090 and 2175. Business-as-usual runs out in 2165 (Line 1). It is evident how higher demand will be able to exhaust the extractable resource earlier.

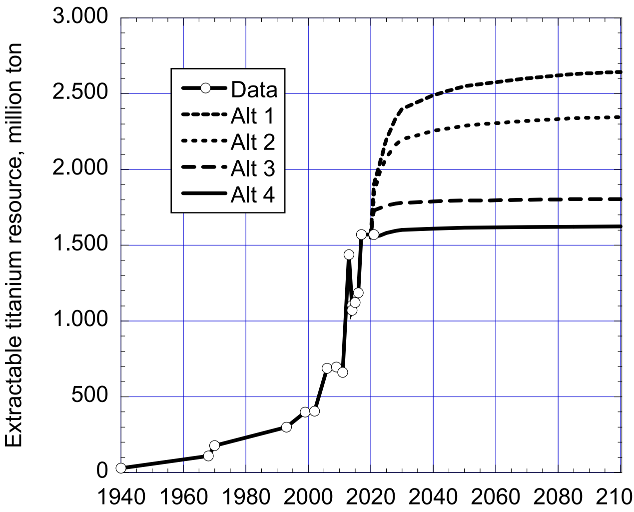


Fig. 13. The diagram shows the development of known titanium resources with time. In this study, we adopted alternative 3 for the scenarios.

appears that the model reproduces the observed long term pattern well. The conclusion drawn from the test is that the model reliably reconstructs the past and have a good probability that it can be used for reasonable future forecasts.

6.3. *Sensitivity of the titanium system to future demand changes*

Fig. 10 shows the simulated inputs to the sensitivity simulations and some of the results. These results have two parts: First the demand into the titanium markets, and then how the system responds to these demands. The demand itself is calculated as the result of different demands from different technical sectors in the WORLD7 model, driven by population increase, economic development and technological developments. The titanium oxide and metal demands under Business-as-usual is represented by line 1 in Fig. 10a. The titanium metal demand is shown to the left (10a) and titanium dioxide demand to the right (10b). First the demand for titanium as metal (10a) and as a mineral, and converted to TiO_2, expressed as titanium content (10b) is calculated, using the titanium module embedded in the WORLD7 model (Figs. 10a and b). The mineral demand is affected by the TiO_2 demand and the metal demand. Thus, the different demand curves. TiO_2 demand increase when the price is low and decrease when the price is high. The demand depends on several factors and thus is a dynamic variable in the model. Business-as-usual is a very conservative estimate, not counting in any new technologies, or new types of demands. Figs. 10c and d show the demand after modification by price for metal (10c) and oxide (10d). It is visible how the demand after modification of demand by price, is much smaller that the initial demand, this is reflecting the soft scarcity. When modified demand and supply have a difference, we have hard scarcity. Figs. 10e and f show the supply of metal (10e) and oxide (10f) by applying the demand scenarios discussed above. The metal supply responds to demand and cover the demand after modification by price, but after 2100, supply issues become apparent. This is further illuminated in the Fig. 11.

Figs. 10g and h show the extraction for titanium metal (10g) and titanium oxide (10h). After 2100, the extraction of titanium oxide and titanium metal declines because of decline of the extractable resource and increasing energy prices. This occurs for titanium metal and oxide progressively earlier in time depending on demand, the higher the total demand is, the earlier the price goes up and scarcity becomes apparent (Fig. 10g for metal and Fig. 10h for oxides). The metal supply is kept up for some time after this because of high price and increased recycling, but eventually, the titanium availability disappears. This is seen in the next Figs. 11 and 12. It is our opinion that Business-As-Usual is probably not the most likely future scenario.

Fig. 11 shows more results from the sensitivity simulations with the model, elaborating on what was shown in Fig. 10. Fig. 11 and 11 shows the titanium metal to the left and titanium dioxide to the right in all diagrams.

Fig. 11a shows the degree of soft scarcity as defined earlier for titanium metal soft scarcity as and 11b shows the degree of soft scarcity for TiO_2. It can be seen that for metal, soft scarcity sets in already in 2050 under the highest demand. For TiO_2 this occurs later, in 2075. This is the amount demand is reduced by, because the price is high. It can be seen that titanium metal supply is unimpeded until the price goes up and the price feedback kick in on the demand, reducing demand and thus supply responding to demand. The same thing happens with the TiO_2 supply, only a little later.

Fig. 11c shows the titanium metal price. It can be seen that the price shoots up when the deficit comes. Price and deficit is linked in a feedback system as explained earlier in the causal loop diagram in Fig. 4.

Fig. 11d shows TiO_2 market price. The oxide price shoots up for titanium oxide when the mineral resource is exhausted. Then the metal price shoots up because the raw material price goes up. Fig. 11e and f shows the actual metal supply and the dioxide supply, expressed as titanium content. The oxide supply plunges 2080–2100, because the demand is strangled by the increases in price, and that most oxide goes to make titanium, which earns more money. Titanium metal is more resilient, since the stocks-in-use can be recycled. After 2120, the titanium supply will be dominated by the amount of recycling. Fig. 11g shows the recycling degree for titanium metal. It goes up when the price goes up. Fig. 11h shows the ore grade with time. The differences are a reflection of the resource getting depleted faster at higher demand. Fig. 11g shows the stock of titanium metal in society in use, Fig. 11h shows the amounts of TiO_2 as titanium content in use. Peak titanium metal occurs in 2095 under high demand and 2130 for low demand. The TiO_2 peak occurs in 2160 for low demand and in 2075 for high demand. TiO_2 is used as a bulk commodity pigment, and is generally not recycled. For most TiO_2 uses, recycling is simply not possible. TiO_2 goes out of mass use when the price goes up.

Fig. 12 shows the development of the total mineable mineral resource over time for the different scenarios. Depending on the demand scenario, the titanium mineral resource available to mining runs out somewhere between 2100 and 2175. In the Business-as-usual scenario, titanium resources runs out in 2145. Under the highest demand, scarcity occurs in 2090.

7. Discussion

7.1. Can titanium really be a limited resource?

Titanium is an abundant element, and we will with certainty not run out of titanium for a long time at the present rate of extraction. The titanium resources are large when compared to the present rate of extraction for pigment and metal production, but take note that no finite resource is inexhaustible, not even titanium. There is a lot of titanium present in geological formations, but only a smaller part of this is accessible for mining and extraction. That means that even if we may ultimately find that there is 10,000 million ton of titanium element present in the geosphere as minerals in the reach of human technology, only minerals containing about 1800 million ton of titanium is actually minable and within our technical means. And of this 80% is can be extracted and 90% refined to TiO_2, and from TiO_2, metal can be produced with a yield of about 90–97%. The yield through to TiO_2 is thus about 72%. The yield all the way to metal is about 65%. This implies that of the 1800 million ton in extractable deposits, it can be expected that 1300 million ton will reach the markets as titanium oxide. And that if all is converted to metal, then that would be 1170 million ton titanium metal.

And that is only under the condition that there will be energy available to make such an amount, which is far from certain. Titanium metal production is very energy demanding, the equipment is complicated and expensive (The Kroll-process), and this is an important factor for the relatively high price of the metal.

If the titanium demand would increase significantly more that we have anticipated in the sensitivity analysis, scarcity would occur at an earlier date than business-as-usual. The sensitivity analysis illustrates this in Figs. 10–12. There are very many situations where titanium would be excellent for product quality and performance. If the titanium metal price could be significantly reduced, then demand would go up significantly. While metal production at present is about 370,000 ton/year, the oxide is 10 million ton/year and there is no immediate lack of materials for making titanium metal for the next 60 years. Scarcity takes time to develop as a result of resource depletion depending on future demand between 2100 and 2150.

There is a possibility that more titanium deposits will be found in the future, and some of these may be very substantial. There are still large uncharted areas in Canada and Northern Asia (Siberia), where such finds are likely, but had to access. In Greenland, the ice cover will reduce significantly during the next 300 years, giving new possibilities. Such finds will probably be gamechangers only is human population really would decline significantly, which do not seem likely. If not, the time to depletion will only be push a bit further ahead in time. But the challenge it will not go away.

7.2. Data quality

There is great uncertainty associated with the production and price data used for model validation. Titanium metal is seen as a militarily strategic metal and the internal production in the United States, Russia and China is classified information. There may be deliberately misleading formation placed in internet and in state agency publications, to make it unclear to adversaries what the real production really is. There is a civilian market for titanium after 2000 and there are still several military markets, where the sizes are not really known.

Earlier studies have shown that the WORLD7 model gives very accurate predictions when very good data is available (Sverdrup et al., 2018, 2019a, 2021, 2022). This suggests that the uncertainty associated with the large integrated model are less and not a significant limitation of the model performance.

7.3. Sustainable supply of titanium

The sustainable extraction rate for the next 10,000 years would be a total of 230,000 ton/year of titanium, for any use, oxide or metal. The diagrams shown in Fig. 1 are the only known data available on historical global flows and market prices at present. Perks and Mudd (2019) pointed out that the United States Geological Survey (USGS) and the British Geological Survey (BGS, 2022), give different production curves for TiO_2. The BGS (2022) production curve is about 25% higher than the USGS curve. Part of the difference come from estimates made for countries where there are no real data available, and that the estimates are made by indirect means. The simulations are sensitive to the resource size used as input and the production volume. Adopting the BGS (2022) estimate for production, implies that the time for scarcity comes earlier. Overestimating the total resource has the opposite effect. Adopting the BGS (2022) estimate for production but a larger resource, cancel the difference, making the conclusions of the present assessment stand.

7.4. Items for future research

There are some aspects we could not cover in this study. The size of the total extractable resource plays an important role in whether there will be a titanium shortage in the near or far future. It would beyond what would get space here to go through the possibilities for future discoveries, and to what degree they would be available for industrial extraction.

Fig. 13 shows the development of known titanium resources with time 1940–2021. In the WORLD7 model, resource exploration and discovery is modeled as a function of how much there is left to find and the prospecting effort put in. Such curves are at the fundamental level s-shaped, and reach on a finite planet a final value (Sverdrup and Ragnarsdottir, 2014; Singer, 2010). For some resources, the nearly whole shape is known (for example for gold, platinum, copper, Sverdrup et al., 2013; Sverdrup and Ragnarsdottir 2014), for other metals the full shape is not yet observable. For titanium, it seems like we have reached an inflection point, but this is far from certain. Different future scenarios are possible. If the inflection point is now, then Alternative 1 or Alternative 2 would seem reasonable. In this study, we adopted alternative 3, which is 15% above the latest USGS assessment (Gambogi, 2022). In a future study, we would investigate the probable potential discoveries based on available information, and then run a sensitivity assessment based on different alternatives. The assessment of all available geological surveys and an assessment of future resource discovery potential is a major undertaking, requiring more resources that what we at present have.

8. Conclusion

The extraction, supply, price, extractable reserves, total resources, recycling and losses of titanium was modeled with the WORLD7 model. The model has been successful in reconstructing the mining and price patterns 1900–2015 when tested on the available data. We estimate that the model makes reasonable projections for business-as-usual based on such tests and can be used for policy analysis. The assessment shows that titanium oxide and titanium metal will not become limited by physical availability before 2200. The obstacle to increased titanium metal use is mainly the high energy input needed for metal production and the relatively work intensive production process. Future energy shortage, may send the titanium price further upward. The titanium oxide pigment is a large volume, low price and low margin commodity, and is not likely to run out before 2200. In the longer run, the time horizon for titanium oxide as we know it is after 2200, when only ultralow ore grades are left. A high titanium metal price will prevent titanium metal being used for mass market products. It is important to point out that the planet earth does not run out of titanium, but that the extractable amount in known deposits may be exhausted.

For future studies, more work on the industrial dynamics of the WORLD7 model needs to be done, in order to link future titanium demands to future forecasts for technical uses of titanium in society. Most future predictions for titanium available in the scientific literature are based on naive economic forecasts, based on eternal growth of GDP, and a lack of understanding of future resource limitations in multiple dimensions. Thus, most analysts forecast are no better than guesses, and sometimes worse. Titanium will be important for aeronautics industry and for military advanced hardware, in high performance turbines and for speciality alloys. Technical estimates of demand based on a good analysis of these used would be a good improvement.

Research ethics

This work, assessments, data processing, model development and model simulations is original research done by the authors. All text herein come from the hands of the mentioned authors and collaborators and nowhere else.

CRediT authorship contribution statement

Harald Ulrik Sverdrup: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Antoniy Elias Sverdrup:** Formal analysis, Writing – review & editing.

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.

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