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RESEARCH ARTICLE

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Evaluation of global niobium flow modeling and its market forecasting

Abstract Metal, as the indispensable material, is functioning the society from technology to the environment. Niobium (Nb) is considered a unique earth metal as it is related to many emerging technologies. The increasing economic growth exerts an increasing pressure on supply, which leads to its significance in the economic sector. However, few papers have addressed Nb sustainability, which forms the scope of this paper in order to start the process of Nb market forecasting based on some previous data and some assumptions. Therefore, this paper will discuss different thoughts in material substitution and the substance flow of Nb throughout a static flow using Nb global data to have a better understanding of the process of Nb from production to end of life. This shall lead to the identification of the market needs to determine its growth which is around 2.5% to 3.0%. Moreover, due to China's huge Nb consumption which comes from the continuous development that is happening over the years, it will also briefly mention the Nb situation as well as its growth which according to statistics will grow steadily till 2030 by a rate of 4.0% to 6.0%. The results show that there should be some enhancement to Nb recycling potentials out of steel scrap. In addition, there should be more involvement of Nb in different industries as this would lead to less-used materials which can be translated to less environmental impact.

Keywords niobium (Nb), sustainability, substance flow analysis, recycling, industrial ecology

1 Introduction

Niobium (Nb) is a gray-white rare metal with chemical and physical properties like tantalum, which must be processed at a bearable temperature. Nb is usually used to make high-temperature alloys because a slightly added amount of Nb can make other metals have a greater strength and a better resistance. Approximately 90% of all Nb productions are transformed into ferro-Nb which can be used in the steelmaking market [1]. Moreover, Nb contributes to many other smaller volume and higher value applications at the same time, for instance, superalloys, carbides, electronic units, and superconductors. One of the things that should be considered is that, if Nb is added to metals, it would increase the cost of production [2].

The dominant producer of Nb and its derivatives, the Companhia Brasileira de Metalurgia e Mineração (CBMM), controls the market share of Nb which is divided into many different categories, but the main use Nb is to make high-temperature resistance alloys and stainless steel. Nb addition is very beneficial to some metals that are normally exposed to low temperatures as it provides these metals with a better resistance [3]. The Nb demand is rising as it can replace many other elements, which can lead to dematerialization. The annual demand for Nb according to Cradle Resources Limited varies between 100 and 110 kt (1 kt = 1 Gg = 10^9 g) with stable prices in the global market [4].

In recent years, the demand for Ferro Nb has grown steadily, mainly in China, where the demand for high-strength low-alloy steel (HSLA) has increased. In addition to the increased demand, the implementation of new rebar standards in China in 2018 led to an increase in vanadium prices, prompting mills to replace vanadium with Nb for rebar alloy (see Electronic Supplementary Material). As a result, Nb has gained some additional market share in the process, although the recent fall in vanadium prices has prompted China's more price-sensitive mills to resume using vanadium [5]. That was one of the main reasons which made the market share for Nb increase.

Moreover, one of the great things about Nb consumption in different applications is that its unit is very low-weight percentage per ton of finished steel, which makes the

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outcome benefits great. Adding Nb to steel can increase its strength in an obvious way, which turns into less use of required steel, which means a huge reduction in cost. The intensity of Nb use in China has been increasing, but it remains low in several large steel-producing countries like India, and part of South-east Asia. The market share of Nb in the rebar fields has increased recently, although Nb is mostly used in flat steel products. The use of Nb will continue to increase in the years to come, driven by increased steel production, regulations involving higher micro-alloy cement, and the steelmaking economy. Besides expanding current applications, many Nb projects are underway, where some of which may be launched in the next few years to meet the high growing demand.

As environmental issues become increasingly intricate, it is more incompetent for people to address these issues directly or with regular market tools [6]. Many papers have been published on the sustainability of various metals. Nb, however, is an exception. Although some researchers have published a feasibility study, detailed work has not yet started. A previous initiative modeling study for Nb analysis [7] paved the way for further studies, not only for evaluation of the effect of Nb on different applications and industries, but for appraisement of its impact on the environment. This paper is seeking to discuss the current Nb and FeNb consumption and production rate globally, and more specifically in China due to its great industrial power and its enormous Nb market share. In addition, this paper intends to measure the current use and the future demand of the market, and to conduct a material flow analysis for Nb based on the previous papers and data. Moreover, it will give an estimation prediction of Nb and FeNb future demand till the year 2030 which would help predict the price of Nb among the other substitutions. This would assist the society in realizing that there should be some restrictions for the manufacturing territories regarding dematerialization if a sustainable future with less environmental impact is to be achieved. Furthermore, the designed analysis shows that the market needs to concentrate more on the recycling potential for the steel scrap that is coming from the automotive and building structure industries as they have approximately around 60% of the total Nb alloy steel out of the total 90% of the whole Nb production that goes into steel.

2 Materials and methods

2.1 Methods

The main way to accomplish a comprehensive study about the Nb market is by gathering all the data and trying to imply the data on a material flow modeling. This method is preferable as it helps to appraise the environmental assessment of Nb because it analyzes the substance flow from the early stage to its disposal and allows having a critical view of the use of Nb around the globe. In addition, the assistance of decision making based on the outcomes will help in planning and detecting any environmental problem that might happen [8]. On the other hand, some issues in this process have to be addressed to obtain enough input data and the ability to handle uncertainties.

2.2 Market

Global demand for Nb increased at a rate of 10% per year between 2000 and 2010. The energy, construction, and automotive industries are the largest consumers of FeNb. In 2000, the Nb production in Brazil was around 35 kt and in 2007 it reached 82 kt of Nb concentrate [9]. According to Roskill data, the compound annual growth rate (CAGR) of global Nb consumption from 2010 to 2019 caught up to 5% and the year-on-year growth of Nb productions reached 30%. With the introduction of the new standard for rebar in China, the demand and the prices for ferrovanadium have soared in 2018, which led to an unpredictable level of substitution. That was one of the reasons, where steelmakers in China began to use FeNb in grade 3 rebar, aligned with strong demand for FeNb in pipe, structure, and automotive applications, which was later defined as new high records in the Nb imports into China. The COVID-19 pandemic prevented the high demand for FeNb in early 2020, but some analysts reported that since the middle of 2020, as China has recovered from the effects of the pandemic, the demand is returning to more regular levels.

The World Steel Association has recently published a report that predicted that due to the COVID-19 pandemic, the global steel demand would fall to 6.4% in 2020, but it would rise again in 2021. Moreover, there is a noticeable increase in the demand and the growth of higher quality steel. Additionally, the use of Nb in the aerospace and automotive industries has also increased particularly in China, Japan, and India, which indicates that the demand for very pure Nb product would increase as well. Some studies show that the need for Nb will keep rising at CAGR for around 6% from 2020 to 2025 due to different causes [14]. Moreover, dynamics is a vital factor for car manufacturing as well as lightweight materials, so that cars would improve their fuel consumption efficiency, which is the main reason for the whole industry to look for Nb option. It was proven that one ton of steel containing only one kilogram of Nb would not only improve the durability and strength of steel but also reduce the weight of steel products. To learn more about the growth of Nb in different industries and applications including the steel market, it should be understood that while the market is run by the government, producer, and consumer (who has neither clue nor interest about the used technology behind the products) [6], the main two factors that drive the market to rise are cost and eco-friendliness. This is considered an essential reason for researchers to look more into how much the Nb market can increase side by side with saving the environment as well.

Based upon different studies, the global Nb economy (production) is estimated to be more than enough to meet the demand projects and applications. That is why the prices of Nb should be quite settled in the upcoming years with a hint of increase on yearly basis. Despite the low consumption of Nb due to the global economic crisis in 2008, the prices to investors were mostly beneficial [4]. Nb is mainly used for steel production. Either steel structure or superalloys, growth of consumption, counting price, is expected to follow the track of steel production growth. That is why the prices of Nb and FeNb are almost the same, because steel industry is the main course of Nb consumption (90%). On the one hand, Nb price growth does not always follow the steel prices growth, because only 10% of the world's steel production has Nb in its composition. The studies show that the price of Nb has been balanced around 42.0 USD per kg since 2015 [4,12,13]. On the other hand, FeNb prices vary between 41 and 46 USD per kg from 2012 to 2021, which is close to Nb prices because (as already mentioned) more than 90% of the whole Nb production is manufactured into FeNb (Fig. 1(b)).

2.3 Current applications

Currently, Nb is at the foreground of many cutting-edge technologies, including medical imaging, gas and wind turbines, space travel, manufacture of ultra-fast, high performance, particle accelerator, and ultra-safe ultra-rapid rechargeable batteries for electric vehicles (EVs) [14]. A large amount of Nb is used in cobalt, nickel, and iron-based super-alloys for many different applications such as rocket components, gas turbines, jet engines components, and heat resistant equipment and combustion. For instance, these superalloys were used in the advanced airframe system of the Gemini project, and the Apollo lunar module main engine. Nowadays, they

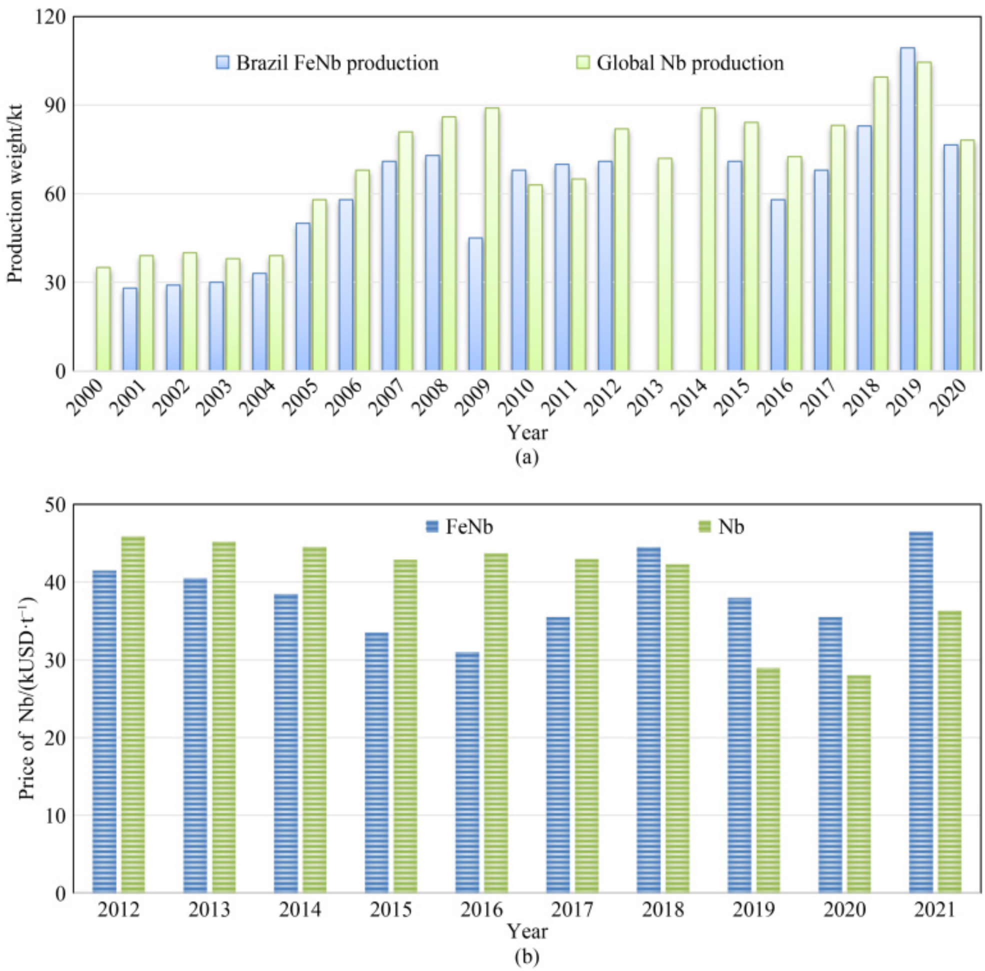

Fig. 1 Nb production and market in recent years.

(a) Brazil FeNb production and global Nb production (Data source from Refs. [9,10,11]); (b) FeNb and Nb price in global market (Data source from Refs. [4,12,13]).

are used in the liquid rocket propellant nozzle for the advanced Merlin Vacuums engines which are developed by SpaceX. Moreover, there are noticeable developments for the use of Nb in rechargeable batteries. Toshiba made an announcement regarding its next generation of rechargeable batteries for EVs using Nb anodes, which can achieve higher performance, faster charging, longer life, and safer batteries, which soon is expected to become industry standards [14].

2.4 Nb flow modeling

To design the right material flow analysis for Nb, the stages of Nb from mining and extraction to disposal should be defined precisely (Fig. 2) [15]. According to Vasconcelos [16], the applications and the process of Nb production from mine to market undergo four main steps. The first one is mining which is considered pyrochlore and tantalite, columbite, with pyrochlore as the primary deposit resources for Nb. The second step is the separation process through some floatation processes that remove undesired elements. The third stage is refining, which is to use the residual materials to produce different Nb products. The last step is the conversion, which is all about transforming Nb into different products specially FeNb.

Based upon the performed studies of Nb and its specific aspects related to different stages of the Nb production and transformation to different applications, a conceptual model of Nb flow could be established as shown in Fig. 3. An important modeling goal for subsequent steps related to the quantitative description of material flow is to consider the recovery of superalloys during the evaluation.

The established Nb flow analysis is a static flow designed for the year 2019 with an amount of global Nb

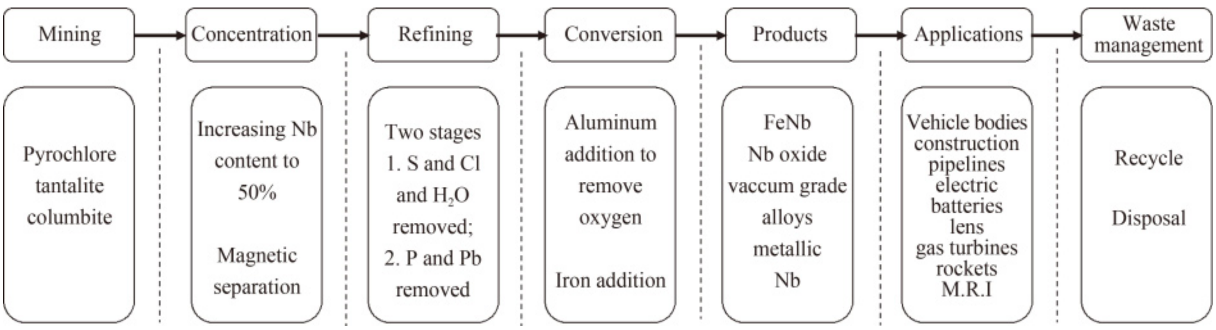

Fig. 2 Flow modeling of Nb stages.

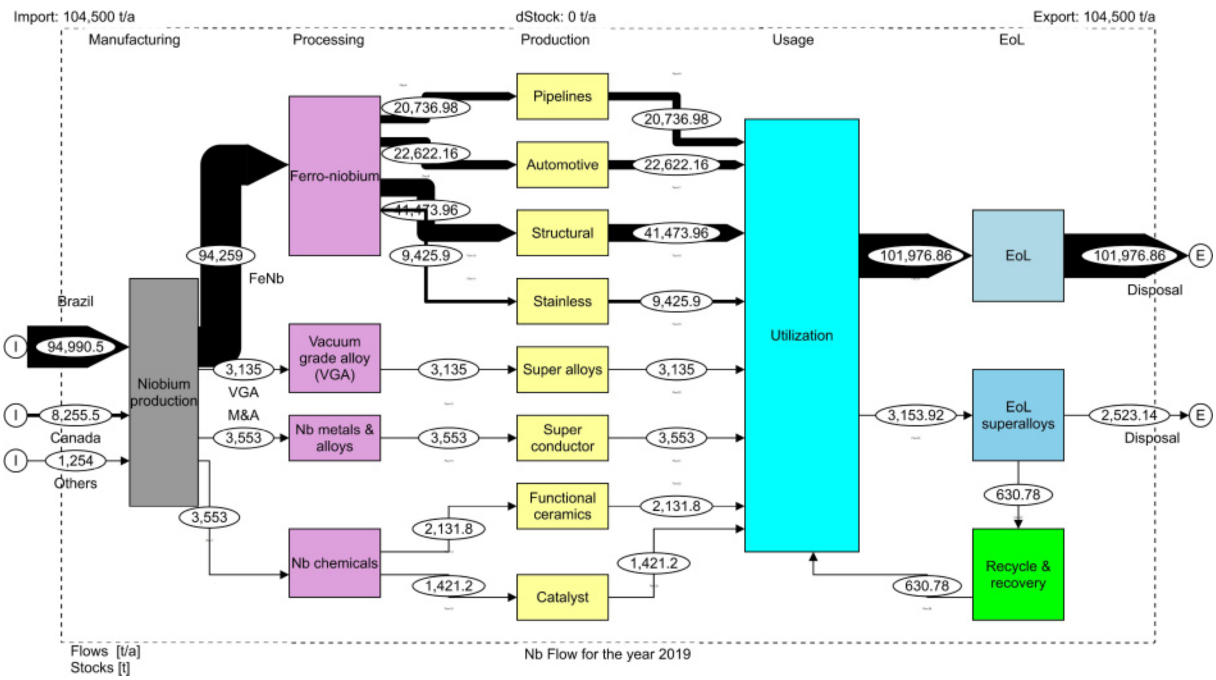

Fig. 3 Global substance flow analysis for Nb in 2019 (Data source from Refs. [11,13]).

production for this year of 104.5 kt (1 kt = 1 Gg = 10^9 g) (see Fig. 1(a)), assuming that the input rate equals the output rate without any stock in the market, with a Brazil exportation amount of around 90.9% in the whole Nb market, plus 7.9% and 1.2% goes for Canada and other producing countries, respectively [11].

The designed model is to analyze the Nb market in more of a mathematical way so that it would be easy to identify the current problem in the information of production and consumption flow, while looking for better chances to improve the Nb manufacture process so that it could be used more efficiently, and make a better decision for different industries to utilize it more often in their industry due to its huge beneficial outcome. This model is based on past existing data and some assumptions that were made to estimate the need and the average consumption of Nb in the mentioned different industries. This process in the STAN software also contains analyzing and verifying the inputs and the requirements to ensure that the outcome result has the least number of flaws.

Therefore, to simplify the process of the Nb flow model, for a starter, the main steps of the material flow have to be mentioned. The first step is the manufacturing process where Nb production is distributed to its main four categories forming the processing stage; Standard grade FeNb (steel with a Nb content of 60%) which possesses around 90.2% of Nb whole production, vacuum grade alloys (vacuum grade (VG) FeNb and VG NiNb) under 3.0% of Nb production, Nb metals and alloys and Nb chemicals both with a percentage of 3.4% of total Nb storage. Moving to the production step which comes from each category in the processing stage, starting with standard grade FeNb, its market share goes like 22%, 24%, 44%, and 10% for oil and gas pipelines, automotive, steel structure, and stainless, respectively [13]. In addition to that, vacuum grade alloy and Nb metals and alloys share their all percentage of their Nb portion to super-alloys and superconductors, respectively. The last process goes for Nb chemicals which are carved up according to the current market share into functional ceramic and catalysts with 60% and 40%, respectively. Moving forward to the utilization stage, where production components turn into commodities, could be used in the market such as heavy infrastructure and engineering, petrochemical sector, power plants, aircraft engines, power generation, electronics, and optical appliances. Then, it comes to the end-of-life (EoL) phase, where after the end of the utilization process [17], the EoL products go into two passes. The first one is direct disposal (landfill) which is the majority of the whole Nb products. The second pass could be recycled or recovered with a percentage of 3.0% which comes from EoL super-alloys products.

As the Nb market grows, more pressure is exerted on supply. That is why there are very great potentials and hopes for Nb recycling, as it would also reduce mining for production which probably would be needed to overcome Nb supply risk. So Nb recycling would not only reduce mining-based production but also mitigate the huge environmental impact that comes from Nb mining [18]. However, until now the only recycling work that has been made for Nb is for super-alloys, and there is not enough concentration to steel scrap which could be a better opportunity for Nb metal recycling [2].

According to the output data from the Nb flow model, it is very easy to monitor the amount of disregarded Nb production and waste that could be recycled and those that could not be recycled. So, this can be used as a way of evaluating the efficiency of the Nb market, which suggests that there should be more studies and researches on new technologies that can show how Nb can be increased in the market as a substitution for other materials, which leads to the efficiency of material resources. Moreover, this model permits assessing Nb versus other elements, as it shows the consumption rate of Nb in the most Nb used industries, which is considered very vital for industrial ecology as it shows the flow management of Nb and other metals such as vanadium or copper, and makes the choice of elements based on the consumption, production, recycling potentials, price rate for each of these metals.

Giving thought and attention to this idea might increase the production rate of Nb globally, which directly reduces the use of thousands of tons of other materials. For instance, if taking the Øresund Bridge in Sweden as a basic structural model, it can be clearly seen how much can be saved with a hint of Nb. This bridge was structured with 82 kt of steel, but with some Nb addition (around 0.02% of Nb (mass fraction)), a huge reduction could be made to the amount of used steel by 15 kt in weight, which could save the country around 25 million USD [19]. Another example could be applied to the automotive industry, according to Claude Dufresne, if only 10 USD of Nb were added, a load of an average-sized car by 150 kg could be deducted which would lead directly to a rise in fuel efficiency by 5%, that means less energy consumption, fewer materials, and better cost [19].

2.5 Nb situation in China

As China is considered around the globe as a major Nb consumer with most of its consumption coming from different new applications and end-user industries such as construction, oil, natural gas, and the aerospace industry, its consumption of FeNb has increased since 2019, partly due to the shortage of ferrovanadium and large price fluctuations, as some steel producers used Nb for HSLA steel as a substitute for ferrovanadium [20]. Moreover, the construction and building sector is currently a booming industry in different emerging economies of China. This would be the main key drive demand for

HSLA steel which would save the economic situation in China by reducing the weight of building which would accomplish cost reduction and prevent any failure in the infrastructure.

According to Mordor intelligence study, the Chinese government has launched a large-scale construction plan, involving the preparations for the migration of around 250 million people in the next ten years to the megacities, which would create an important influence in the research market [20]. Due to these changes in the Chinese market, the FeNb import growth curve is rising over the years, while the FeNb export curve is fluctuating according to the agreement between China and different countries. The reason for the high demand for Nb in China is that the needed Nb density for 1 cm^3 is 8.57 g, which is roughly half of tantalum (light refractory metal), plus the ratio of strength to weight for Nb is higher than those in titanium, nickel, and vanadium which are highly used metals in China. The FeNb market in China can be seen in Fig. 4(a) with the weight unit of import and export kilograms. In addition, China is mainly turning to the concept of raising the production of domestic EVs. To this end, the studied plans are to increase the manufacturing of EVs to approximately seven million vehicles per year by 2025 [20].

3 Results and discussion

3.1 Results

The study of the Nb flow model and the analysis of the Nb and FeNb market paved the way for some predictions for the future material growth and how would the potentials of Nb double this estimated growth rate if it is implemented well in various industries and applications. The outcomes of the designed model suggest that the utilized amount of Nb globally is not quite high as it is supposed to be, because the distinguished properties of Nb based on different studies and facts qualify it to substitute many other materials and save lots of cost and resources. Nevertheless, according to the model, there should be more considerations regarding the recycling issues, as at this rate the increasing cost might affect some industries which would stop using Nb if its price rises compared to its substitutions.

Concerning Nb growth rate, all these previous studies and facts indicate that the production and consumption for Nb and FeNb might increase till the year 2030 by a factor of 2.5% to 3.0% if the utilization of Nb kept growing constantly (Fig. 5), in case the global economy does not confront any crisis. There is a steady growth of

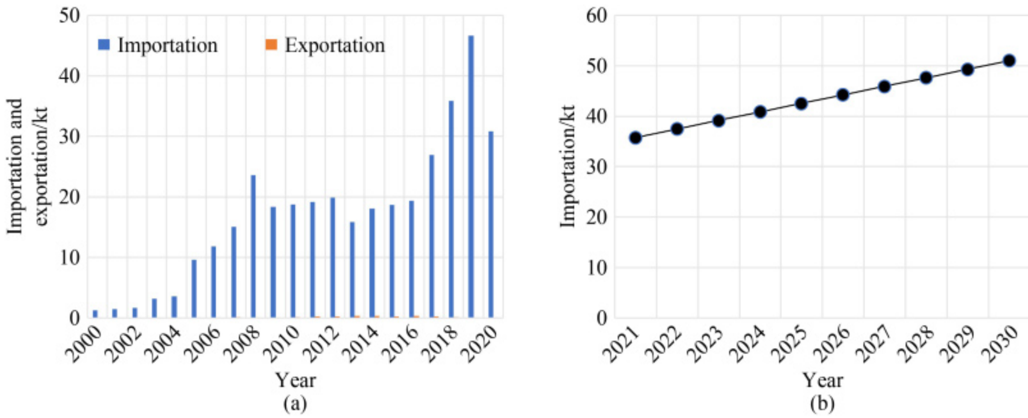

Fig. 4 FeNb importation and exportation in China.
(a) Historical importation and exportation (Data source from Refs. [9,21,22]); (b) future importation.

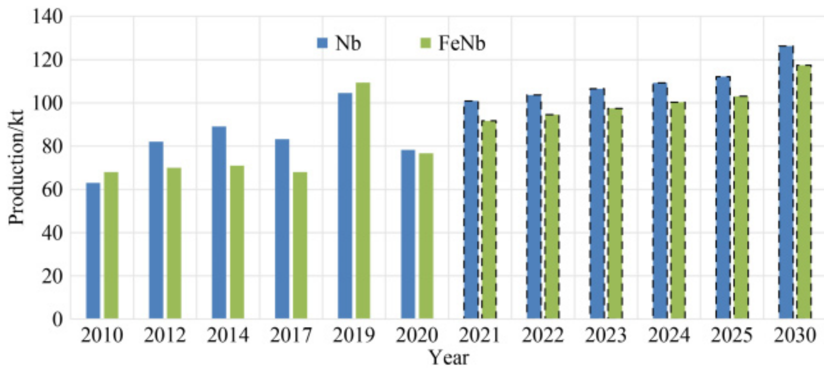

Fig. 5 Nb and FeNb global growth.

around 2.6% in both Nb and FeNb based on the production and the consumption rate over the years from 2010 to 2020, which is how the forecasting has been made till the year 2030.

So far as the Nb future in China is concerned, based upon the stated facts, a conceptual Nb flow analysis was made for China (see Electronic Supplementary Material) which can be a reference for further studies. As can be seen in the model, the Chinese government might depend on importing some waste that contains Nb super alloys to recycle it and reuse it again in the manufacturing stage which would be a huge benefit for the environment and the economy as well.

If this goal is accomplished, it would be better to use Nb in the manufacturing process of EV batteries, which will inevitably increase the demand for Nb in the Chinese and the world market share. If the Nb Chinese market keep increasing with the same rate, it would be easy to estimate the future FeNb import (Fig. 4(b)), which would be around positively 4.0% to 6.0%.

3.2 Discussion

Emergency services continue to work to face the growing environmental issues, especially climate change [23,24], but one of the main issues that need to be focused on is lowering the carbon emissions which comes from reducing mining and the excessive use of different resources, which is one of the points that is issued in this study. Based upon the analysis and different reviews, the demand for Nb will keep globally rising steadily. This is driven by three main factors: the first one is the higher demand of Nb consumption in structural steel due to the tensile strength and durability characteristics of bridges, buildings, and mega construction projects (Stadiums, Hangars). The second is the widely use of Nb-based alloys in automotive manufacturing, and high-performance engines. The last one is the development of different new technologies and military applications.

Furthermore, Nb cost might undergo some additional changes over the few upcoming years, according to a study made by the global metal organization [2], the increasing global demand for Nb metal as a substitution would cause a big rise in Nb price which would create more focusing on Nb recycling. On the contrary, if used as a substitution for several elements, the Nb metal would cause a huge cost reduction in the production process of different applications, and fewer materials used as well. Therefore, more studies should be conducted to deal with this matter as recycling would not only save the environment from continuously mining but also play an important role in keeping the Nb cost efficient for its use.

3.3 Toward carbon neutrality

Paying attention to the main critical raw materials and their importance and environmental impact is kind of a big concern to many countries that seek to achieve carbon neutrality in the near future. The results of this study and the previous ones show that there should be more concentration on Nb utilization and its recycling potential to reduce the use of other materials and minimize the harmful impact that urban mining generates. According to the current Nb industries and applications, not enough Nb is used in producing energy although many studies have shown that Nb should be focused more on clean energy production especially in solar cells as it can improve the quality of solar cells and their performance which would help in carbon emission cutback [25–27]. Moreover, this review demonstrates that if more research is conducted to grab attraction to the benefits of Nb addition to steel for the mobility industry to create a lightweight steel material (lower vehicle weight = lower fuel use) and for other steel industries such as construction, pipes, etc., there would be a huge reduction in the use of other materials which means a lower environmental impact. Lastly, the global growth of Nb and FeNb might increase (Fig. 5) if more awareness and actions are given to the benefits of Nb in different industries.

4 Conclusions

The whole world never stops looking for different substitutions for many materials to minimize the cost of any product, and to save the environment a little bit from waste generation, which is the reason for the current increasing need for Nb. Nb is now a part of many end-user industries and products such as oil, pipeline, steel structure, EV batteries, etc. One of the main reasons that many industries are switching to Nb is that its extreme heat resistance can be a huge benefit to several products. To this end, a material flow model was designed for Nb globally, to help in the process of predicting the demand of Nb for the upcoming next years which will be a steady increase of around 2.5% to 3.0%.

Based on the previous studies, no attention is paid to the recycling rate of Nb in steel scrap which is considered as waste because Nb recycling and recovery would be way better than mining which leads to an environmental impact reduction that comes out from this process. Only 80% of Nb super alloys products (e.g., jet and aircraft engines) is recycled, but this category only possesses around 3.0% of the whole Nb production which is very low compared to the other Nb products that should be recycled or recovered. Furthermore, another model was designed for China as it is the major country that consumes Nb the most in many different projects and products. Through forecasting, the Chinese Nb import amount would increase by 4.0% to 6.0% if no global economic crisis happens over the years till 2030.

The purpose of the modeling of Nb can be summarized in a few points, starting with the evaluation of Nb production, consumption, and waste management which is the key for understanding the material (resources) needs. Increasing the research technology in this area would be a great profit for the environment, which means a sustainable future with sufficient materials for the upcoming generation. Highlighting the great outcome to the market and the decision-makers so that more attention would be paid to this area as it shows that Nb can be added, recycled, used instead of other expensive elements, leading to less-use of new resources, which means a simple mining process, and would lead directly to a circular economy and less environmental impact as well.

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