CORPUS PUBLISHERS

Journal of Mineral and Material Science (JMMS)

ISSN: 2833-3616

Volume 4 Issue 2, 2023

Article Information

Received date : March 23, 2023

Published date: April 13, 2023

*Corresponding author

George J Simandl, School of Earth and Ocean Sciences, University of Victoria, British Columbia, Canada, Email: gsimandl@uvic.ca

Key Words

Critical Materials; Battery; Magnet; Photovoltaic; Transition to Low Carbon Economy; Development Opportunities

DOI: 10.54026/JMMS/1057

Review Article

Critical Materials - Global Outlook and Canadian Perspective

George J Simandl*

School of Earth and Ocean Sciences, University of Victoria, British Columbia, Canada

Abstract

Ongoing geopolitical tensions and armed conflicts are causing most governing bodies in the free world to become concerned with the availability of materials essential for the national security and economic well-being of populations within their jurisdictions. Overlapping with these concerns are commitments to combat climate change. Consequently, current critical material lists for these jurisdictions highlight materials that are at risk of supply disruption (or future shortage) and are essential for one or more of the following domains: national defense, economic health, and the fight against climate change. Battery, Magnet, and Photovoltaic (BM&P) materials are essential for all three of these domains. Therefore, projects involving these materials benefit from unprecedented interest from mineral producing and manufacturing industries, investors, the public, and governments. Technically and economically sound BM&P projects represent exceptional development opportunities.

Introduction

The importance of raw materials to humanity has been evident at least since the Stone Age, through the transition to Bronze Age, and subsequently the Iron Age.. The availability of raw materials becomes particularly important during armed conflicts [1]. For example, bronze (approximately 90% copper and 10% tin) church bells were confiscated by German forces throughout occupied Europe during the First and Second World Wars and melted down to make shell casings and armaments. Nearly 150,000 church bells were melted down during the Second World War alone [2]. During the Cold War era, the United States of America (USA) and other countries maintained strategic stockpiles of raw materials. In 1992, with the easing of tensions between the East and West, the US Congress authorized the accelerated disposal of 44 commodities from their stockpiles, and subsequently sold entire inventories of lead, zinc, copper, nickel, tin, bismuth, antimony, cadmium, and silver [3]. These authorized disposals were valued at US$5.5 billion. Simultaneously, the US government was reducing its involvement in most mineral-related activities. The prevailing view was that the mining industry and a progressive globalization of the mineral markets would solve most mineral supply problems [3]. During the same time period, China was already a major or dominant producer of a wide range of raw materials, including antimony, arsenic, barite, bismuth, cadmium, coal, feldspar, germanium, graphite, iron ore, pig iron, steel ingots, ferroalloys, lead, magnesite, magnesia, primary magnesium, mica, molybdenum, phosphate rock, rare earth elements, salt, pyrites and sulfur, talc, tin, tungsten, vanadium, zinc, and a few others [4]. Because of its centralized economy, and its need for hard currencies, China was a formidable competitor on international markets and as a result, many US, EU, Canadian, and Australian mineral producers had to close. China was frequently accused of 'dumping' raw materials into international markets (i.e., exporting them at prices below their cost of production). However, as China's industrialization advanced, the situation changed. More raw materials were required for China's internal use, and to support its domestic industry, China reduced its exports by introducing export quotas, export duties, and export licenses on select mineral commodities. Although these restrictions are incompatible with the principles of the World Trade Organization (WTO), given the current geopolitical situation and inability of WTO to enforce rules, they remain in place [5].

The vulnerability of Japan, and by extension the European Union (EU), USA, and other jurisdictions to possible disruptions in raw material supply chains, was highlighted by the 2013 standoff between China and Japan over a collision between a Chinese fishing vessel and a Japanese coast guard vessel in the East China Sea [6]. China controlled over 95% of global Rare Earth Element (REE) production at the time and threatened to interrupt REE shipments destined for Japan, endangering the Japanese high technology industry. The potential use of an abrupt supply chain interruption as an economic weapon served as an alarm bell for other countries heavily dependent on raw material exports from China.

Critical Material Studies

As the possibility of raw material supply disruptions became widely recognized, governments, international agencies, and major industrial users in Asia, Europe, and North America, started to urgently assess their dependence on mineral imports from China and from several politically unstable jurisdictions. As a result, they started to identify critical materials. Critical material lists published by the European Commission in 2011 and 2014 [7], US Department of Defense in 2013 [8], and the US Department of Energy in 2011 [9] were representative examples; these lists are compared and discussed in a 2015 paper by Simandl et al. [10]. At the time, the methodologies used to establish critical material lists were based on two main parameters: 1) the supply risk and 2) a material's importance for a country's economic health, national defense, or its transition to a low-carbon economy. The same principles apply today. Figure 1 illustrates the concept using three examples: barite, construction aggregate, and graphite. In this case, the vertical and horizontal dashed lines in the figure represent the critical risk and economic importance thresholds, respectively [11]. To be considered as a critical material, a commodity must be important for a country's economy and subject to a high risk of supply disruption. For the EU's critical materials list, the procedure used to quantify the risk and the importance of each material to the economy is quite complex, well-documented, and continuously evolving [e.g., 12-14]. Of course, critical materials lists created by different political jurisdictions differ based on the various factors considered [15]. These can include: 1) country-specific internal availability and production of raw materials; 2) the geopolitical distribution of individual materials; 3) whether the criticality analysis covered requirements for the jurisdiction's economy [e.g, 7,11,16]; 4) a focus on national defense [8], 5) an emphasis on the transition to clean-air technologies [9], 6) the methodology used to determine the criticality of materials, and 7) the level of recycling within the jurisdiction (circular economy aspect), and other factors. Many jurisdictions including Japan, India, and Canada (even some individual Canadian provinces) have developed critical material lists; unsurprisingly, China is not an exception [17]. The critical material lists of the USA, EU, and most industrialized jurisdictions have been updated several times since the early 2000s. For example, the EU with updates its critical materials list every three years. The most recent

(2023) critical material list for the EU [14] was released 2 days after the first draft of this document was completed; nevertheless, it was incorporated it into this study.

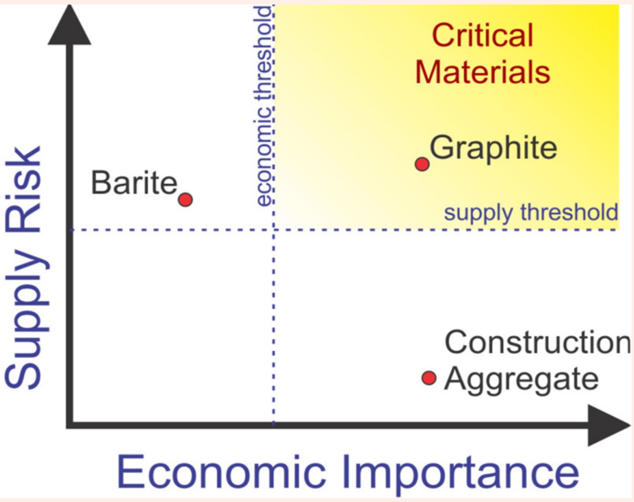

Figure 1: Determining which materials are critical using the European Commission's 2014 methodology [7]. Vertical and horizontal dashed lines correspond to the supply risk and economic importance thresholds. Barite exceeded the supply risk threshold, but it had low economic importance. Construction aggregate exceeded the economic threshold, but the risk of supply disruption was low. In 2014, only graphite was a critical material. Note that critical material lists evolve with time [10]; for example, in the European Commission's 2020 critical material list [11], barite is listed as critical material. Simplified from Simandl et al. [15].

Importance of Fully Documenting the Methodology Used to Produce Critical Material Lists

Objectives and documentation of the methodology used in the creation of a specific critical material list is important because these lists are increasingly used by the media, academia, civil servants, and politicians. If taken out of context, the term 'critical' could change meaning and, intentionally or not, become misleading. Hayes and McCullough [18] examined 32 criticality studies and determined that REE, Platinum Group Metals (PGM), In, W, Ge, Co, Nb, Ta, Ga, Sb, Bi, Tl, and Mg are materials most commonly perceived as critical, largely due to their use in high technology industries. The most influential critical material lists today are specific to the EU and USA (Table 1). They were produced based on the principle shown in Figure-1. The use of PGM and REE is seldom covered in detail because relevant data is sparce; however, we cover them in Tables 2 & 3. A non-initiated reader would assume that a standard methodology and the definition of the term 'critical' are used internationally (or at least by the EU, US, and their allies); however, this is not the case [19]. There are multiple possible reasons for this, such as a lack of understanding of mineral economics, the opportunity for the government to appear decisive or proactive, a need to interact or reach consensus between several (socially, geographically, politically, economically, or otherwise distinct) jurisdictions within the same country, an opportunity to take advantage of a country's vast resource base in materials to decarbonize energy production, a desire to attract foreign investment in all sectors of the critical materials supply chains (including mining, processing, refining, manufacturing and recycling) for long-term benefits to the country, or simply to remain competitive by matching initiatives provided to the industry, research organizations, and academia by its allies and economic partners. The 5th column of Table 1, Canada's critical materials list, is an example. This list was most likely produced by the Canadian government in consultation with Canadian provinces and territories. The list was widely distributed and elegantly marketed worldwide with the help of the Canadian maple leaf [20], the main icon on the Canadian flag (Figure 2). In Canada, provinces and territories have control of their mineral resources, and the Canadian government (Natural Resources Canada) provides a national umbrella. If we examine provincial and territorial mineral production summaries for 2020 or 2021, and provincial critical material lists (where available), it becomes evident that the Canadian critical material list is based at least in part on input from Provincial and Territorial governments about which materials are important to them. The remainder of Canada's critical material list largely mirrors the EU and US critical material lists (Tables 1-3).

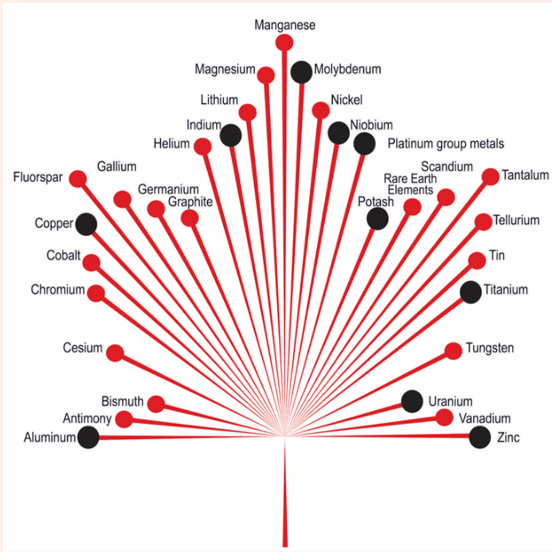

Figure 2: Canada's critical material list is marketed domestically and internationally in the form of a maple leaf. Materials shown by red circles (except helium) correspond to materials from the EU 2020 and USA 2022 critical material lists. Helium appeared on the EU 2023 list (Table 1). Canada is the world's largest producer of potash. Canada is also a major producer of niobium, platinum group elements, primary aluminum, indium, titanium concentrate, copper, molybdenum, zinc, and uranium. These materials, shown in black, contribute significantly to Canada's mineral exports [21]. Therefore, the reader should not assume that Canada is at risk of supply disruption as far as these materials are concerned. Aluminum is an exception because no significant bauxite deposits are known in Canada. Modified from Natural Resources Canada [20].

Table 1: Critical material lists specific to the EU, USA, and Canada. The EU and US critical material lists reflect potential risks of supply disruption for materials estimated as essential for economic health, national defense, and/or the transition to low carbon economy in respective jurisdictions [11,14,19]. Biotic materials covered in the EU [11,14] are excluded from this study (except coking coal). Canada's 'critical material list' from 2022 [20] is a hybrid (agglomerate of commodities). It lists materials critical to the EU and US (Canada's important allies); however, it also lists materials that represent a high proportion of Canada's exports [21]. These materials are identified by *. The last column lists examples of uses for each critical material, not necessarily in decreasing order of importance (no reliable source of information on use of individual REE and PGM in the public domain). The U.S. Geological Survey Mineral Commodity Summaries 2023 [22] and the references in the 2020 European Commission's document [11,14] provide additional information. Copper and nickel were not identified as critical by the European Commission [14]; however, they were referred to as strategic (Strat) on the EU 2023 list.

Critical Material	Critical Material Lists				Main or Selected Uses (Not Necessarily in Order of Importance Unless Specified)
	EU 2020	EU 2023	USA 2022	CAN 2021	
Aluminum		yes	yes	yes*	Transportation, construction, electrical and consumer goods, and other sectors
Antimony	yes	yes	yes	yes	Flame retardants, batteries, ammunition, ceramics
Arsenic		yes	yes		Semiconductors (photovoltaics cells, space, and telecommunications); preservatives
Barite	yes	yes	yes		Heavy media in drilling for oil and gas, radiation protection, brake pads, paint
Bauxite	yes	yes			Ore of aluminum (+/- gallium); also in refractories, abrasives, cement, and chemicals
Beryllium	yes	yes	yes		In alloys essential for aerospace, defense, automotive industries; electronics
Bismuth	yes	yes	yes	yes	Alloys, fire detectors, extinguishers, electric fuses, solders, and pigments
Borate / Boron	yes	yes			Glass, ceramics, fertilisers, boron in REE magnets, abrasives, semiconductors
Cesium			yes	yes	Cesium formate (oil drilling fluid); electrolytes, spectrometers, scintillators
Chromium			yes	yes	Stainless steel, other alloys, chromium chemicals
Cobalt	yes	yes	yes	yes	Batteries, super alloys, specialty magnets, cemented carbides for cutting
Coking coal	yes	yes			Mainly coke for steel making; in some cases, a variety of synthetic graphite
Copper		Strat		yes*	All industrial sectors - electrical wires, roofing, plumbing, alloys
Feldspar		yes			Mainly in glass and ceramics; also used as a filler in paints, and latex
Fluorspar	yes	yes	yes	yes	Flux for aluminum making, refrigeration, air conditioning, uranium processing
Gallium	yes	yes	yes	yes	Mainly in integrated circuits and photovoltaics; also in superalloys
Germanium	yes	yes	yes	yes	Solar cells for satellites, other photovoltaics, fiber optics, night vision instruments
Graphite	yes	yes	yes	yes	Batteries, refractories, lubricants, brake linings, fuel cells, steel making
Hafnium	yes	yes	yes		Nuclear reaction control rods, alloys, and high-tech ceramics
Helium		yes		yes	Inert gas (welding and instrumentation), balloons, cryogenics, leak detection
Indium	yes		yes	yes	Indium tin oxide coatings (liquid crystal displays, photovoltaics); soldering
Lithium	yes	yes	yes	yes	Batteries, ceramic and glass additives, lubricants
Magnesium	yes	yes	yes	yes	Light alloys (automotive and aeronautic industries), desulfurization of iron and steel
Manganese		yes	yes	yes	Steel production, batteries, fertilizers, and pigments
Molybdenum				yes*	Alloying component in steel, iron, and superalloys; high temperature resistant
Nickel		Strat	yes	yes	Stainless steel, batteries, specialty metal alloys, and electroplating
Niobium	yes	yes	yes	yes	Ferroniobium for steel industry, and superalloys for aerospace industries
PGM	yes	yes	yes	yes	See Table 2
Phosphate rock	yes	yes			Fertiliser and elemental phosphorus
Phosphorus	yes	yes			Chemical industry and defense applications
Potash				yes*	Mainly to produce potassium fertilizer; also other chemicals
REE	yes	yes	yes	yes	See Table 3
Rubidium			yes		Fiber optic networks, night vision, photoelectric cells, photomultiplier tubes
Silicon metal	yes	yes			Metallurgy (ferroalloy), silicones, photovoltaics, semiconductors
Strontium	yes	yes			Traditional sintered ferrite magnets, medical and pyrotechnical applications
Tantalum	yes	yes	yes	yes	Capacitors (in vehicles, phones, computers), superalloys for turbines
Tellurium			yes	yes	Photovoltaics, thermoelectric devices, and as an alloying agent
Tin			yes	yes	Protective coatings (tinplating), soldering, alloying agent, others
Titanium	yes	yes	yes	yes*	Light metal alloys (aerospace, armor, implants), and pigments (in oxide form)
Tungsten	yes	yes	yes	yes	Tungsten carbide, wear-resistant steel, alloys for aerospace and defence industry
Uranium				yes*	Source of nuclear energy and military applications
Vanadium	yes	yes	yes	yes	Alloying additive to iron and steel, vanadium redox flow batteries, and catalysts
Zinc			yes	yes*	Mainly in galvanized steel, batteries, and alloys (e.g., brass)
Zirconium			yes		Alloys for nuclear and chemical industries, (Zircon / abrasives and refractories)

Table 2: Platinum Group Metals. Osmium is not considered critical in the USA and is not assessed in the EU studies; however, it is not specifically excluded from the Canadian list.

Critical Material	Critical Material Lists				Main or Selected Uses (Not Necessarily in Order of Importance Unless Specified)
	EU 2020	EU 2023	USA 2022	CAN 2021	
Palladium	yes	yes	yes	yes	Catalytic converters; also, dentistry, hydrogen storage, jewelry, plating in electronics
Platinum	yes	yes	yes	yes	Catalytic converters, jewelry, crucibles, laboratory/dental tools, electrical contacts
Rhodium	yes	yes	yes	yes	Catalyst, hardening of platinum and palladium alloys, electrical components
Iridium	yes	yes	yes	yes	Crucibles, coating of anodes, in chlorine and caustic soda production
Osmium				?	Enhances wear resistance of PGM alloys; fuel cells, plating of electronic components
Ruthenium	yes	yes	yes	yes	Hardener in platinum group alloys, catalysts, electrical contacts, computer hard discs

Table 3: Rare Earth Elements. Lanthanides, yttrium, and scandium are included, following the 2005 IUPAC Recommendations. Promethium is exceedingly rare in nature; most of it is produced in nuclear reactors.

Material	Critical Material List				Main or Selected Uses (Not Necessarily in Order of Importance Unless Specified)
	EU 2020	EU 2023	USA 2022	CAN 2021	
Lanthanum	yes	yes	yes	yes	Anode additive in nickel metal hydride batteries, hydrogen sponge alloys, night-vision
Cerium	yes	yes	yes	yes	Catalytic convertors, ceramics, glass, metallurgy, batteries, polishing compounds
Praseodymium	yes	yes	yes	yes	REE magnets, batteries, aerospace alloys, high tech ceramics, glass/ceramic colorant
Neodymium	yes	yes	yes	yes	REE magnets, rubber catalyst, lasers, laser-range finders, military guidance systems
Promethium				?	Low natural abundance in Earth's crust; Promethium-147 derived from Uranium-235 in atomic reactors is used in atomic batteries
Samarium	yes	yes	yes	yes	Sm-Co (high temperature) magnets, infrared absorbing glass, stealth technologies
Europium	yes	yes	yes	yes	Fluorescents and phosphors in screens (including LEDs), monitors, and lamps
Gadolinium	yes	yes	yes	yes	Neutron radiography, nuclear reactor shields, gadolinium-Yttrium garnets for microwave use
Terbium	yes	yes	yes	yes	Magnets, trichromatic lighting, material-dopant in solid state devices, sonar systems
Dysprosium	yes	yes	yes	yes	REE magnets, nuclear industry (control rods), constituent of laser materials
Holmium	yes	yes	yes	yes	Magnetic flux concentrator, solid state surgical lasers, microwave equipment, colorant
Erbium	yes	yes	yes	yes	Dopant for laser and fiber optic applications, nuclear technology, colorant
Thulium	yes	yes	yes	yes	In active laser materials, superconductors, magnets for microwave equipment
Ytterbium	yes	yes	yes	yes	Dopant in solid state laser materials and in stainless steel, high stability atomic clocks
Lutetium	yes	yes	yes	yes	Limited use - catalyst for hydrocarbon cracking, scintillators and X-ray phosphors
Yttrium	yes	yes	yes	yes	Catalysts, lasers, plasma display panels, optical glass, batteries, ceramics, abrasive
Scandium	yes	yes	yes	yes	Aluminium-scandium alloys - aerospace & defence industries, sporting equipment

Canada is a reliable exporter of raw materials, with most of its 2020 mineral exports destined for the USA (54%), UK (10%), and China (7%). Canada is the largest potash producer in the world, and it ranks among the world's top 5 producers of diamonds, gold, indium, niobium, platinum group metals, titanium concentrate, uranium, and primary aluminum (Canada has large aluminum smelters; however, it does not have significant bauxite deposits) [21]. Furthermore, in 2021, Canada also exported CA$ 9.9 billion worth of copper and significant quantities of zinc (CA$ 2.3 billion) and nickel (CA$ 4.7 billion) [21]. Despite these high levels of production, potash, indium, niobium, platinum group metals, titanium, aluminum, copper, nickel, and zinc appear on the Canadian critical materials list. Creators of the Canadian critical material list recognized that Canada has a modest industrial base and is a key supplier of raw materials to USA and EU. If Canada opted for the same definition of the term 'critical' as USA or EU, the Canadian critical material list would have been much shorter. As a result, Canada would have missed an important opportunity to efficiently market its huge natural resource endowment. From the Canadian point of view, a broader definition of 'critical' [20] was desirable.

Competitive Advantages of Projects Involving Critical, Battery, Magnet, and Photovoltaic Materials Relative to Other Projects

Currently, battery materials (i.e, Li, Co, Ni, Mn, graphite, and to a lesser extent V), magnet materials (rare earth elements; more specifically, Nd, Dy, Tb, and to a lesser extent Pr) and photovoltaic materials (Si, Ge, Ga, In, Te, and to a lesser extent Cd, Se, As) are considered as essential for the electrification of infrastructure, the prosperity of the high technology industry, the national defense of many countries, and for addressing the climate crisis [11,15,23-28]. These materials, especially those appearing on recent EU and US critical material lists (Tables 1-3), are considered to be 'red hot' by exploration, mining, processing, and many high technology companies. Interestingly, after incorporating the 2023 data for the EU into Tables 1-3, we realized that the contents of Tables 2 & 3, covering PGM and REE respectively, remain identical. The main changes to Table 1, were the appearance of arsenic, manganese, helium, and feldspar as new critical materials for the EU. Indium has disappeared from the EU's 2023 critical material list. Although copper and nickel did not meet minimum criticality criteria [14], the European Commission added them to the critical material list under the designation 'strategic' materials. They defined strategic materials as: 'raw materials important for technologies that support the twin green and digital transition and defense and aerospace objectives' [14]. Obviously, there is significant overlap between 2023 'critical' and 'strategic' raw materials lists for EU. Selected projects involving these materials and/or related supply chains may benefit from government grants, loans, and other preferential treatment [e.g., 29,30]. Furthermore, large multinational manufacturing companies depending on these critical materials are becoming vertically integrated, or are contemplating, or forming, joint ventures with mineral explorers, miners, processors, and refiners to secure their future material supplies; the race is on.

Recent Programs Supporting Development of Critical Material Supply Chains

More recently, many jurisdictions have started to introduce policies aimed at facilitating the transition to a low carbon economy (i.e., the slowing down of climate change by reducing GHG emissions into the atmosphere). The Inflation Reduction Act (IRA) in the USA is probably the best-known example [31,32]. The IRA is helping to establish new battery, magnet, and photovoltaic (BM&P) materials-related supply chains and projects (including battery gigafactories) in the USA. To match the USA's success, the EU is expected to release its Green Deal Industrial Plan and Net-Zero Industry Act in early 2023. Other countries, including Canada, are also expected to upgrade their existing energy transition-related policies. Cumulatively, these new policies are promising to result in a global reduction of GHG emissions and have a positive impact on economies in countries who introduce low-carbon economy policies (e.g., new exploration and mine development projects, refining facilities, battery gigafactories, new electric vehicle plants, energy storage facilities). Furthermore, supply chains that are critical for the energy transition and the well-being of the economy (including defense, aeronautics, and spatial industries) are by extension also essential for national security.

Major Caveats

There is little doubt that in overall picture regarding the rapid market growth rates for BM&P materials (e.g., [22]) and these materials are essential for global reduction in GHG emissions. Recent governmental programs (e.g., IRA) provide additional credibility to these assessments. However, when we consider individual BM&P materials, caution regarding long-term market projections is required. Technological breakthroughs (e.g., nuclear fusion, discovery of superconductive materials able to operate at ambient pressure and temperature conditions, discovery of low-cost substitutes for high performance REE magnets for use in wind turbines, and EVs) may significantly alter long term market projections. Commercialization of new technologies (e.g., solid-state batteries and third generation photovoltaic cells), or the public's increased tolerance of nuclear energy-associated risks may also affect future markets for BM&P materials. A number of BM&P materials belong to the specialty materials category (i.e., have a small market base; less than 200,000 tonnes/year). In the short term, materials belonging to this category do not benefit from economy of scale in the same way as major commodities such as iron, phosphate rock, zinc, and copper [15,26]; unless they are recovered as by-products. For all materials, the early ranking of exploration and development projects is advised to limit the risk for investors, and to allow for the proper allocation of government resources; however, for projects targeting critical materials belonging to the specialty material category, early ranking of projects is absolutely essential [15,26]. It is also reasonable to expect that over the next few decades, the current geopolitical conflicts and tensions will ease and normal trade relationships between world powers will be reestablished. This type of international (geopolitical and economic) reconciliation has happened several times over the last 120 years. Under such market conditions, the projects with the highest ranking will have the best potential to remain profitable. Beyond traditional technical, economic, and environmental parameters, the relative merits of the projects in terms of their role in the circular economy, and carbon intensity are becoming increasingly important.

The peculiarities of some highly publicized critical material lists could generate undue expectations from the industry. For example, the Canadian critical material list includes Cu, potash, U, Zn and REE, among others (Table 1). This could be interpreted as indicating that in Canada, projects involving Cu, potash, U, Zn and related supply chains could benefit from the same advantages and fast-tracking procedures during mine permitting (relative to commodities that are not on the Canadian critical mineral list) as projects targeting REE, cobalt, or natural graphite, which are nearly universally accepted as critical by the world's largest economies. The history and track records of the exploration, mining and processing industries indicate that assuming price elasticity will compensate for declining grades, human ingenuity should be able to efficiently increase resource and reserve bases of most critical materials. However, a number of critical materials, including photovoltaic materials other than silicon (e.g., Ge, Ga, In, and Te), are currently extracted as by-products of base and precious metals. Because many older smelters currently do not recover these materials, the addition of relevant recovery circuits to existing smelters may be the fastest option to rapidly increase the supply [15,26].

Summary

Today, all major industrial powers, including the USA, EU, China, Russia, Japan, and many other jurisdictions have their own critical material lists. For a variety of reasons, the methodologies and definitions used to establish these critical material lists differ. Consequently, some countries, renowned for their mineral exports and having a modest internal industrial base (i.e., low domestic needs for these materials), such as Canada, may have 'critical' material lists comparable to, or longer than, the USA, or EU. Many materials are considered essential for global reduction of GHG emissions. If efforts to slow down climate change continue on a global scale, and if the long-term market projections are correct, then technically and economically sound BM&P material projects have exceptional development potential.

The early and impartial ranking of critical material projects as to their development potential is essential. In the short term, it minimizes the risk to industry investors and helps governments correctly allocate government support. In the medium term, the market base of some critical materials currently belonging to specialty materials category will increase sufficiently for the principle of the economy of scale to become applicable. In the long term, once current armed conflicts are resolved and ongoing geopolitical tensions ease, global trading relationships will normalize and the top projects/operations will thrive because of the global open market, while lower quality projects will become uneconomic. This cycle repeated itself several times over the last 120 years.

Critical material lists are highly influential, regardless of the methodology used to produce them. They are used by politicians, government civil servants, and members of scientific committees for providing grants and loans to industry and for awarding research grants to academia. Projects involving critical materials have a greater potential to benefit from government support, to be fast-tracked during permitting processes, and are easier to promote and finance. Consequently, critical material lists are commonly used as promotional tools, in the exploration, mining, processing, refining, and recycling segments of supply chains.

Acknowledgments

Suggestions from Dr. David Lefebure, adjunct professor at the School of Earth and Ocean Sciences, University at Victoria, BC, Canada, and Carlee Akam, geoscientist, Victoria, BC, Canada, greatly improved clarity of this document.

References

1. Smith GO (1920) Minerals as essential raw materials. The Annals of the American Academy of Political and Social Science 89(1): 99-102.
2. Freeman KO (2008) The bells, too, are fighting: The fate of European church bells in the second world war. Canadian Journal of History 43(3): 417-450.

3. Humphreys D (1995) Whatever happened to security of supply? Minerals policy in the post-Cold War world. Resources Policy 21(2): 91-97.
4. British Geological Survey (1998) World Mineral Statistics 1992-1996- production, exports, imports. Keyworth, Nottingham, England.
5. Wu M (2017) China's export restrictions and the limits of WTO law. World Trade Review 16(4): 673-691.
6. Bradsher K (2010) Amid Tension, China Blocks Vital Exports to Japan, New York Times, 22nd September 2010.
7. European Commission (2014) Report on critical raw materials for the EU (Report of the Ad hoc Working Group on defining critical raw materials). p. 41.
8. US Department of Defense (2013) Strategic and critical materials 2013 report on stockpile requirements. Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, p. 189.
9. US Department of Energy (2011) Critical Materials Strategy. Office of Policy and International Affairs, p. 190.
10. Simandl GJ, Akam C, Paradis S (2015) Which materials are 'critical' and 'strategic'. In: Simandl GJ, Neetz M, (Eds.), (2015) Symposium on strategic and critical materials proceedings, Victoria, British Columbia. British Columbia Ministry of Energy and Mines, British Columbia Geological Survey Paper 2015(3): 1-4.
11. European Commission (2020) Critical raw materials resilience: Charting a path towards greater security and sustainability, communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. COM (2020) 474 final.
12. Pennington D, Tzimas E, Baranzelli C, Dewulf J, Manfredi S, et al. (2017) Methodology for establishing the EU list of critical raw materials, European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs.
13. Blengini GA, Blagoeva D, Dewulf J, Torres de Matos C, Nita V, et al. (2017) Assessment of the methodology for establishing the eu list of critical raw materials - annexes, Publications Office of the European Union, Luxemburg, 978-92-79-70213-6.
14. Directorate General for Internal Market, Industry, Entrepreneurship and SMEs (2023) Study on the critical raw materials for the EU 2023 - final report.
15. Simandl L, Simandl GJ, Paradis S (2021) Economic Geology Models 5. Specialty, critical, battery, magnet, and photovoltaic materials: Market facts, projections and implications for exploration and development. Geoscience Canada 48(2): 73-92.
16. European Commission (2017) Communication from the Commission to the European parliament, the council, the European economic and social committee and the Committee of the regions on the 2017 list of Critical Raw Materials for the EU.
17. Andersson P (2020) Chinese assessments of "critical" and "strategic" raw materials: Concepts, categories, policies, and implications. The Extractive Industries and Society 7(1): 127-137.
18. Hayes SM, McCullough EA (2018) Critical minerals: A review of elemental trends in comprehensive criticality studies. Resources Policy 59: 192-199.
19. U S Geological Survey (2022) U S geological survey releases 2022 list of critical materials.
20. Government of Canada (2022) Critical Minerals: An Opportunity for Canada.
21. Natural Resources Canada (2022) Minerals and economy.
22. U S Geological Survey (2023) Mineral Commodity Summaries 2023.
23. Hund K, La Porta D, Fabregas TP, Laing T, Drexhage J (2020) Minerals for climate action: The mineral intensity of the clean energy transition: World Bank Group, Washington, DC, US, p. 112.
24. International Energy Agency (2017) Energy technology perspectives 2017: International Energy Agency Directorate of Sustainability, Technology and Outlooks, p. 441.
25. Simandl GJ, Paradis S (2022) Vanadium as a critical material: economic geology with emphasis on market and the main deposit types. Applied Earth Science 131(4): 218-236.
26. Simandl GJ, Paradis S, Simandl L (2023) Future of photovoltaic materials with emphasis on resource availability, economic geology, criticality, and market size/growth. CIM Journal.
27. U S Department of the Interior (2018) Final list of critical minerals 2018: Federal Register Document Number 2018-10667. 83: 23296–23297.
28. World Bank Group (2017) The growing role of minerals and metals for a low carbon future: World Bank Group, Washington, DC. US, p. 111.
29. Government of Canada (2023) Programs and funding for critical minerals projects.
30. U S Department of Energy loan programs office (2023) Sector spotlight: critical materials.
31. White House (2023) Building a clean energy economy: a guidebook to the inflation reduction act's investments in clean energy and climate action, version 2.
32. White House (2023) Treasury Releases Guidance to Drive Investment in Critical Minerals & Battery Supply Chains in America.