The Hague Centre for Strategic Studies

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Mapping European industry needs

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Summary

The energy transition and digitalization have brought critical raw materials (CRM) to the forefront of international politics. However, little is said about the fundamental role that CRM play in the defence sector and the possible impact of CRM supply chain disruptions on the military domain. This report provides a risk assessment of the short and long-term CRM supply security and geopolitical risks, specifically focused on the defence sector.

The defence sector makes use of a significant amount of raw materials across the air, sea and land domains. A selection of 40 materials is deemed critical or 'soon-to-be' critical in this report. Each material's value chain analysis determines specific geopolitical threats and supply chain risks. For instance, graphite and aluminium are the materials most commonly used across military applications and are also subject to considerable supply security risks that stem from the lack of suppliers' diversification and the instability associated with supplying countries.

The risk assessment is developed based on the correlation between impact and probability of supply disruptions. Probability is measured through an analysis of short and long-term CRM supply security and geopolitical risks, while impact is operationalized into the frequency of CRM use across defence applications. Exploring the different degrees of criticality of each material allows for the creation of four categories: 1) Very High-Risk Materials; 2) High-Risk Materials; 3) Medium-Risk Materials; 4) Low-Risk Materials. The analysis provides an initial overview of the risks of supply disruption for CRM in the defence sector.

The criticality of materials varies considerably across military domains. Materials deemed very critical for aircrafts, helicopters, and missiles might not be as critical to build corvettes, aircraft carriers and submarines. Graphite and gold are categorised as very high-risk and low-risk, respectively, for the air domain but are instead judged as high-risk and medium-risk for their applications in the sea domain. Thus, specific vulnerabilities for each military domain that should be taken into account when formulating appropriate responses to CRM supply security risks in the defence sector. Moreover, the analysis reveals notable differences to the categorization provided by the EU in the context of the green and digital transitions.

Securing supplies for CRM for defence requires attention to domain-specific vulnerabilities, but also an all-encompassing strategy on the national, European, and transatlantic level. Coherence across national security, industry, and CRM strategies is fundamental to ensure the alignment of interests and policies. Cooperation between the civil and military sectors should be the pillar upon which European CRM supply security is built. In the coming years, competition for the procurement of CRM will increase and with it the need to cooperate in producing coherent policies and strategies to secure CRM. Cooperation at the European level is also important to overcome obstacles related to the supply chain security, as demonstrated by the war in Ukraine. Further, Europeans must not forget their military dependencies on the United States and their military technology supply. CRM supply security strategies should be developed from the perspective of transatlantic cooperation.

Supply risk for critical raw materials in military applications

Application	Very high risk	High risk	Medium risk	Low risk
Fighter Aircraft	Aluminium, Graphite	Beryllium, Chromium, Cobalt, Copper, Dysprosium, Germanium, Iron/Steel, Lanthalum, Nickel, Neodymium, Platinum, Praesodymium, Samarium, Tantalum, Titanium, Tellurium, Terbium, Tungsten, Vanadium, Yttrium	Barium, Borates, Cadmium, Gallium, Indium, Lead, Lithium, Manganese, Molybdenum, Niobium, Silver, Tin, Thorium, Zinc, Zirconium	Gold, Hafnium, Selenium
Main Battle Tank	Aluminium, Graphite	Beryllium, Chromium, Copper, Germanium, Iron/Steel, Neodymium, Nickel, Tantalum, Tellurium, Titanium, Tungsten, Vanadium, Yttrium	Borates, Cadmium, Gallium, Indium, Manganese, Molybdenum, Selenium, Thorium, Zinc	Hafnium
Missile	Aluminium	Chromium, Cobalt, Copper, Dysprosium, Iron/Steel, Neodymium, Nickel, Praesodymium, Samarium, Silicon Metal, Tantalum, Titanium, Tungsten	Borates, Lead, Lithium, Niobium, Molybdenum, Zirconium	
Submarine	Aluminium, Graphite	Chromium, Cobalt, Iron/Steel, Platinum, Samarium, Titanium, Tungsten, Vanadium	Barium, Lead, Lithium, Manganese, Niobium, Silver	Hafnium
Corvette	Aluminium, Graphite	Cobalt, Chromium, Copper, Iron/Steel, Nickel, Samarium, Titanium, Tungsten	Barium, Lead, Lithium, Molybdenum, Manganese	Gold
Artillery	Aluminium, Graphite	Beryllium, Chromium, Copper, Germanium, Iron/Steel, Neodymium, Nickel, Tantalum, Tellurium, Vanadium, Yttrium	Cadmium, Indium, Molybdenum, Manganese	
Ammunition	Aluminium, Graphite	Beryllium, Copper, Germanium, Neodymium, Tantalum, Tellurium, Titanium, Yttrium	Cadmium, Indium	
Torpedo	Aluminium	Chromium	Lead, Lithium, Manganese, Zirconium, Silver	
Assault Rifle		Iron/Steel, Vanadium		

Legend

- Very high risk
- High risk
- Medium risk
- Low risk

1. Introduction

Critical raw materials (CRM) have grown in importance in the last years due to their role in the energy transition and digitalisation. CRMs are both essential for Europe's strategic sectors and prone to supply risks. In the next decades, the supply of CRMs will become increasingly strained as the world moves toward similar goals: climate neutrality, digitalisation and strategic autonomy. Geopolitical competition for CRMs is fuelled by Europe's dependence on a small number of unstable and/or unreliable suppliers such as China, Russia, the Democratic Republic of Congo and Kazakhstan.

Less attention has been placed on the role of CRMs in defence applications. This paper focuses specifically on the European defence sector, providing a risk assessment for critical and 'soon-to-be' critical raw materials used in defence applications for light and heavy weapons operations. By analysing short and long-term supply security risks, geopolitical challenges and the frequency of use of a certain material across applications, a qualitative risk assessment is made for European CRM in defence. Such an assessment is essential in Europe's path toward strategic autonomy as it offers defence-specific insights into the type of materials, components and applications most at risk from a supply security perspective. It becomes clear that the critical minerals for defence do not fully coincide with the ones most critical for the energy transition. As such, targeted CRM policies to mitigate supply risks for defence are necessary.

Nonetheless, European defence should work together with the energy and digital sectors to mitigate some of the supply risks associated with CRMs. Some minerals are used across civil and military technologies, so efforts to secure supplies should be coherent across the energy, digital and defence sectors. Moreover, dual-use green technologies like electric cars or solar panels will be needed to decarbonise defence, meaning that the civil and military sectors will face similar challenges in terms of raw materials. Strong support for Europe's industrial base, financial incentives, strategically using trade relations, and responsible sourcing are central themes for the future supply of CRMs.

2. Methodology

This paper seeks to assess supply security risks of raw materials in defence applications, taking the European Union's critical raw materials list of 2020[1] as a starting point and enriching it with other (non-critical) raw materials that are important for the defence sector. Defence applications are divided into three domains, namely air, sea, and land, and the required materials for manufacturing selected applications for each domain are mapped. Cyberspace and space related raw material requirements are not included because their cutting-edge nature makes it difficult to carry out an in-depth analysis with public information and because some of these applications are not per se defence specific . A list of defence applications and materials was compiled using the EU's Joint Research Centre report "Raw materials in the European defence industry"[2] as the main source of reference. Appendix I includes a list of the defence applications and materials considered.

The risk assessment conducted in this study measures the impact and probability of supply chain disruptions. Probability is operationalised by looking at the long and short-term supply chain security and geopolitical risks to which materials are subject (see section 3). Impact is weighed as the frequency with which materials are used across defence applications, i.e., in how many defence applications a material is used. Finally, the risk assessment leads to the division of the materials in four categories: 1) Very High-Risk Materials; 2) High-Risk Materials; 3) Medium-Risk Materials; 4) Low-Risk Materials.

Probability is assessed based on the indicators in Table 1, which serve to analyse the short and long-term supply security risks as well as geopolitical challenges. This framework is consistent with the one used in the 2022 HCSS report "*Scenariostudie kernenergie*"[3]. Two out of the nine criteria used in the aforementioned report, "Substitutes" and "Dutch needs", are not applied to the present study. These criteria have been excluded from the analysis because of the limited relevance and availability of this information for the scope of this research. Given that this is a qualitative study, the quantitative assessment of the future demand for materials in defence applications specifically for the Netherlands is out of scope. Moreover, given the high sensitivity associated with substituting critical minerals in defence applications with (possibly) less effective alternatives, substitutes are not considered in this study.

Short-term supply security depends on the extent to which a material has a diversified supply base and on whether potential supply chain bottlenecks can be identified. In the long-term, new mines can be established, processing facilities opened, and supply chains partly altered to be more (or less) secure. The extent to which short and long-term supply risks can materialize is not just dependent on logistics but also on geopolitical challenges. For that reason, the supply risk analysis incorporates the stability of a supplier state, the extent to which the Netherlands can rely on it as measured in the Dutch Foreign Relations Index (DFRI),[4] and

1 European Commission, "Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability," 2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474.

2 Claudiu C. Pavel and Evangelos Tzimas, "Raw Materials in the European Defence Industry" (LU: Publications Office of the European Union, 2016), https://data.europa.eu/doi/10.2790/0444.

3 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie," 111-112.

4 Hugo van Manen et al., "The Dutch Foreign Relations Index: Version 2" (The Hague Centre for Strategic Studies, 2020), https://hcss.nl/report/methodological-note-the-dutch-foreign-relations-index-version-2/.

pre-existing geopolitical issues. The results of this analysis are then qualitatively aggregated to form the 'Probability' indicator of the risk assessment matrix.

Table 1. Probability Indicator Framework

	Indicator	Definition of indicator	Measurement of indicator
Short-term supply security *The ability of the system to respond to disruptions in the supply chain in the short-term*	Supplier diversity	To what extent does the material have a diversified supply base?	Diversity of supplier and processing countries
	Supply chain bottlenecks	To what extent are there (potential) bottlenecks in the supply chain?	Potential bottlenecks (economic or geopolitical) in different stages of the supply chain
	Substitutes	Can the material be replaced in times of supply disruptions?	Available substitutes
Long-term supply security *The ability of the system to respond to disruptions in the supply chain in the long-term*	Worldwide reserves	How large are global reserves?	Global reserves in tonnes
	Future global supply	What are important future sources of the material?	Existing global resources, new mines in exploration, reserves discovered, recycling methods etc.
	Dutch needs	What is the future demand of the Netherlands?	Netherlands' demand for material in 2035 measured in kilograms and/or gigawatt hour (GWh). Based on calculation in scenarios.
Geopolitical challenges	Stability	To what degree are the main suppliers stable countries?	Use Fragile States Index to determine whether suppliers are considered stable countries. Scores range between 1-120, with higher scores indicating more instability and fragility.[5]
	Reliability	To what degree are the main suppliers reliable partners?	Use Dutch Foreign Relations Index (DFRI)[6] to determine whether suppliers are reliable partners for the Netherlands. Scores on three levels: low, medium, and high. A high score indicates a more reliable partner.
	Geopolitical problems between Europe and suppliers	To what extent are there/ could there be geopolitical issues between Europe and the supplier country to prevent the delivery of materials?	Examples: sanctions to Russia due to war in Ukraine, issues with China due to competition for technological superiority, China owning mines in DRC etc.

The 'Impact' indicator is operationalised by looking at the frequency with which materials are used in defence applications. It is very challenging, if not impossible, to gather publicly available data on the precise quantity of each material used in all the considered defence applications. Therefore, the fact that a material is used across multiple components of several applications is regarded as the best proxy of how severely disruptions along the supply chain would impact the defence sector. The more applications the material is used in, the more significant the impact will be.

Finally, the risk is measured as Probability X Impact by cross-analysing frequency of use and long/short-term supply security risks and geopolitical challenges. Figure 1 summarises the matrix used for the risk assessment of each material, while Table 2 explains the definitions of the risk categories deriving from the risk assessment.

5 "Fragile States Index | The Fund for Peace," Fragile State Index, 2022, https://fragilestatesindex.org/.

6 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index."

Figure 1. Risk Assessment Matrix

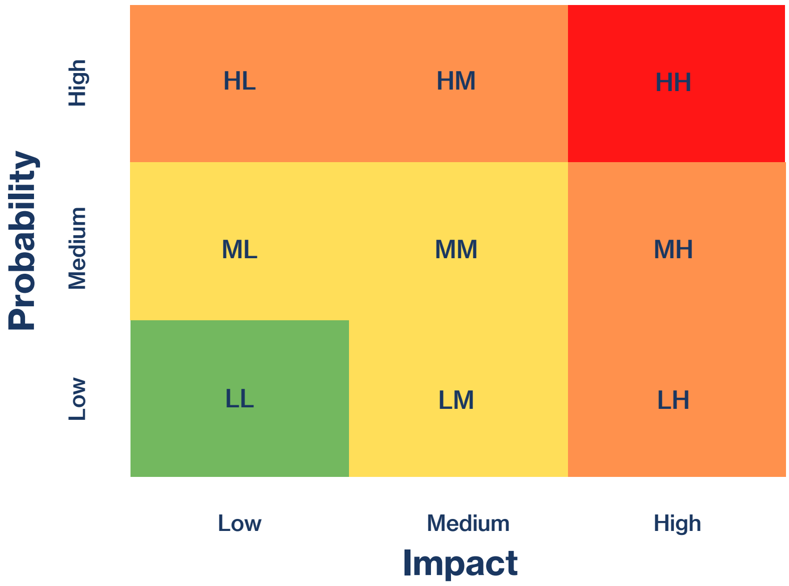


Table 2. Definitions of risk categories

HH	It is **very likely** that the risk will materialise and its impact would be **significant**.
HL	It is **very likely** that the risk will materialise and its impact would be **limited**.
HM	It is **very likely** that the risk will materialise and its impact would be **medium**.
MH	It is **likely** that the risk will materialise and its impact would be **significant**.
LH	It is **unlikely** that the risk will materialise but its impact would be **significant**.
ML	It is **likely** that the risk will materialise and its impact would be **limited**.
MM	It is **likely** that the risk will materialise and its impact would be **medium**.
LM	It is **unlikely** that the risk will materialise and the impact would be **medium**.
LL	The risk is **unlikely** to materialise and its impact would be **limited**.

The analysis has a few limitations. First, data regarding defence applications is somewhat limited and difficult to collect. Second, several materials are combined in the form of alloys, which can contain up to a dozen materials. For the scope of this study, only materials composing at least 10% of said alloys have been accounted for.

The study is divided into two parts, which allow for the identification of the overall impact of supply chain disruptions on the European defence industry as a whole, as well as for the air, sea, and land domain specifically.

1. Part I consists of a classification of the raw materials used in European defence, based on which a supply risk assessment is carried out for the sector as a whole.
2. Part II illustrates how the previously mapped materials are used in each of the three defence domains identified (air, sea, land), detailing which components of defence applications employ the materials. It then proceeds with a more specific risk assessment, looking at the impact and probability for each domain.

3. Geopolitical and supply chain risks for European defence industry

Part I. Materials risk assessment

The results of the assessment (Table 3) show significant variation in the supply chain risks faced by the defence industry depending on each of the considered materials. Still, a few key general points can be extrapolated.

Most of the analysed materials have a medium-risk of incurring supply security disruptions, and only two are very high-risk materials. Interestingly, the European Union's criticality categorisation is partially consistent with our own. For instance, the EU lists REE as very high criticality materials, given their fundamental role in the energy transition. However, their limited use in the defence sector means that they are assessed as of medium criticality in the present research. Graphite and aluminium, which the EU categorises as 'moderate criticality' or that 'may become critical' respectively, resulted as the most critical materials in our assessment. The difference between the EU categorisation and this analysis highlights the importance of having a defence-specific assessment when looking at the criticality of raw materials.

Furthermore, the risk assessment reveals that supply diversification and the reliability of suppliers are fundamental mitigators of supply chain and geopolitical risk. Thus, if the supply of a widely used material across defence applications is diversified and is sourced in reliable countries, the risks of supply chain disruptions are significantly reduced. This is the case, for instance, of copper. The following sections offer a deeper dive into the specifics of each material's assessment. The sections' structure is based on the degree of risk, starting with very high and ending with low-risk materials.

Table 3. Assessment of risk categories of critical military equipment necessary for operational effectiveness[7]

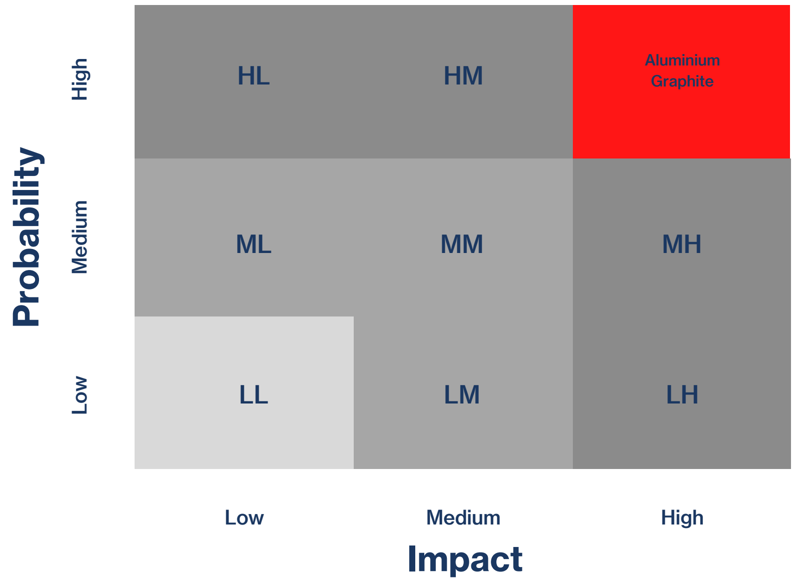
Defence Application	European Union's list of Critical Raw Materials (2020)																					
	Very high criticality						High criticality			Moderate criticality				Low criticality								
	HREE			LREE																		
	(Dy) Dysprosium	(Y) Yttrium	(Tb) Terbium	(La) Lanthanum	(Pr) Praseodymium	(Nd) Neodymium	(Nb) Niobium	(Ge) Germanium	Borates	(Be) Beryllium	(Pt) Platinum	(Co) Cobalt	Graphite	(In) Indium	(V) Vanadium	(Li) Lithium	(W) Tungsten	(Ta) Tantalum	(Ti) Titanium	(Ga) Gallium	(Si) Silicon Metal	(Hf) Hafnium
Aircraft (fighter, transport, maritime patrol and unmanned)	Orange	Orange	Orange	Orange	Orange	Orange		Orange	Yellow	Orange	Orange	Orange	Red	Yellow	Orange	Yellow	Orange	Orange	Orange	Yellow		Green
Helicopter (combat and multi-role)		Orange				Orange	Yellow		Yellow	Orange		Orange	Red	Yellow		Yellow			Orange	Yellow		
Aircraft and helicopter carrier, amphibious assault ship												Orange	Red			Yellow	Orange		Orange			
Corvettes, offshore patrol vessels and frigates												Orange	Red			Yellow	Orange		Orange			
Submarine							Yellow				Orange	Orange	Red		Orange	Yellow	Orange		Orange			
Torpedoes																Yellow						
Main battle tank								Orange		Orange			Red		Orange		Orange	Orange	Orange			
Infantry Fighter vehicle, armored personnel carrier and self-propelled artillery		Orange				Orange		Orange	Yellow	Orange			Red	Yellow	Orange			Orange	Orange	Yellow		Green
Towed Artillery		Orange				Orange		Orange		Orange			Red	Yellow	Orange			Orange				
Ammunition		Orange				Orange		Orange		Orange			Red	Yellow				Orange	Orange			
Assault rifle															Orange							
Missiles	Orange				Orange	Orange	Yellow		Yellow			Orange				Yellow	Orange	Orange	Orange		Orange	

Defence Application	Materials included in European Commission's foresight study (2020)																Additional		
	May become critical																		
	(Mo) Molybdenum	(Mn) Manganese	(Sn) Tin	(Cr) Chromium	(Zr) Zirconium	(Ag) Silver	(Al) Aluminum	(Te) Tellurium	(Ni) Nickel	(Fe) Iron/Steel*	(Se) Selenium	(Zn) Zinc	(Cd) Cadmium	(Au) Gold	(Cu) Copper	(Pb) Lead	(Ba) Barium	(Sm) Samarium	(Th) Thorium
Aircraft (fighter, transport, maritime patrol and unmanned)	Yellow		Yellow	Orange	Yellow	Yellow	Red	Orange	Orange	Orange	Green	Yellow	Yellow	Green	Orange	Yellow	Yellow	Orange	Yellow
Helicopter (combat and multi-role)				Orange		Yellow	Red	Orange	Orange	Orange		Yellow	Yellow		Orange		Yellow		
Aircraft and helicopter carrier, amphibious assault ship			Yellow			Yellow	Red		Orange	Orange		Yellow		Green	Orange	Yellow	Yellow	Orange	
Corvettes, offshore patrol vessels and frigates	Yellow			Orange			Red		Orange	Orange				Green	Orange	Yellow	Yellow	Orange	
Submarine		Yellow		Orange		Yellow	Red			Orange						Yellow	Yellow	Orange	
Torpedoes		Yellow		Orange	Yellow	Yellow	Red									Yellow			
Main battle tank	Yellow	Yellow		Orange			Red	Orange	Orange	Orange			Yellow		Orange				
Infantry Fighter vehicle, armored personnel carrier and self-propelled artillery	Yellow	Yellow		Orange		Yellow	Red	Orange	Orange	Orange		Yellow	Yellow		Orange				Yellow
Towed Artillery	Yellow	Yellow		Orange			Red	Orange	Orange	Orange			Yellow		Orange				
Ammunition							Red	Orange					Yellow		Orange				
Assault rifle										Orange									
Missiles	Yellow			Orange	Yellow		Red		Orange	Orange					Orange	Yellow		Orange	

7 The materials under the 'Additional' category are materials that did not figure in the European Union's list of critical raw materials nor in the European Commission foresight study nor in HCSS previous assessments but were still widely used in defence applications and hence judged of interest to the study.

Very high risk materials

Figure 2. Very high risk materials



High probability, High impact (HH)

These materials are not only the most used in defence applications, but also the most likely to suffer from geopolitical and supply chain disruptions. Aluminium and graphite belong to this category. They are the two most used materials in the defence industry and can be found in aircrafts (fighter, transport, maritime patrol, and unmanned), helicopters (combat and multi-role), aircraft and helicopter carriers, amphibious assault ships, corvettes, offshore patrol vessels, frigates, submarines, tanks, infantry fighter vehicles, artillery, and missiles. These materials are used in components such as airframe and propulsion systems of helicopters and aircrafts as well as onboard electronics of aircraft carriers, corvettes, submarines, tanks, and infantry fighter vehicles.[8] The impact of supply security disruption would hence be very significant, given the multiplicity of aluminium and graphite's applications.

The materialization of supply security risks for aluminium and graphite is very likely too. Europe relies on China for its supply of both materials, given that the latter produces most of the world's aluminium and graphite. In the case of graphite, China dominates 69% of the global production, with the second biggest producer being India (12%) and the third one Brazil (8%)[9]. Moreover, China is the top global supplier of synthetic graphite, which could practically be used to replace natural graphite in various applications. China and the European Union are already engaged in tit-for-tat sanctions.[10] Further tensions between the two could endanger European supply of this metal, with the alternatives being two states subject to high internal

8 Information regarding the use of materials in defence application is taken from Pavel and Tzimas, *Raw Materials in the European Defence Industry,* unless differently indicated.

9 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

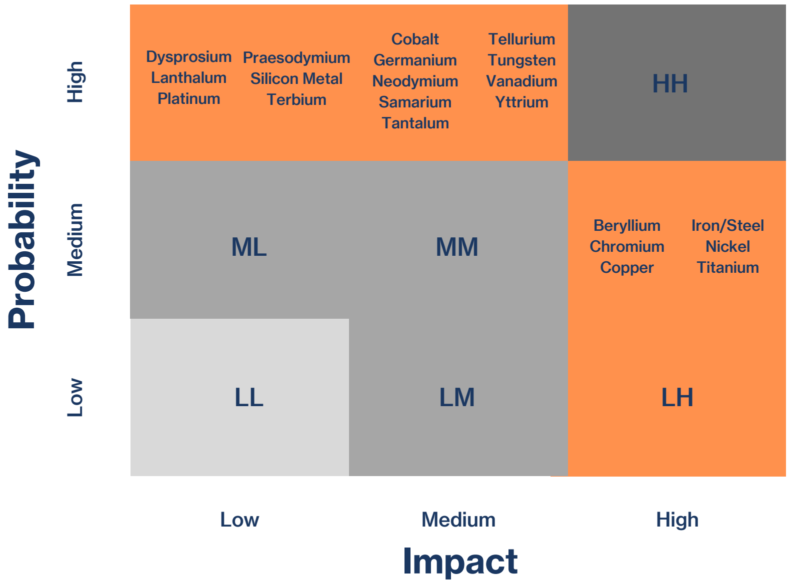
10 Vincent Ni, "EU Parliament 'Freezes' China Trade Deal over Sanctions," *The Guardian*, May 20, 2021, sec. World news, https://www.theguardian.com/world/2021/may/20/eu-parliament-freezes-china-trade-deal-over-sanctions.

instability and corruption levels.[11] Other supply risks are related to the growing demand for graphite, which could soon exceed supply capabilities, as well as the environmental concerns related to graphite production.[12]

For aluminium, the story differs only slightly. China is still the dominating producer, with a 46% share of global production.[13] Considering that the second biggest producer of aluminium is Russia (almost 7%)[14], the supply security for this material is also hindered by instabilities regarding both the reliability and internal unrest of supplier countries. The US already considers Chinese production of aluminium as a threat to its production capacity and has branded it a matter of national security. At the same time, Russia's current endeavours in Ukraine put a further strain on aluminium supply.[15] The geopolitical challenges threatening the supply of aluminium and graphite are hence not only very tangible and very likely to materialise but also already currently ongoing.

High risk materials

Figure 3. High risk materials



High probability, Medium impact (HM)

Cobalt, germanium, neodymium, samarium, tantalum, tellurium, tungsten, vanadium, and yttrium are materials subject to considerable geopolitical risk but used to a medium extent in the defence industry. Yttrium, germanium, neodymium, tellurium, and tantalum are used principally for onboard electronics of infantry fighter vehicles, armoured personnel carriers, and self-propelled and towed artillery. Vanadium's main application is in submarines' onboard electronics,

11 "Fragile States Index | The Fund for Peace."

12 van den Brink et al., "Identifying Supply Risks by Mapping the Cobalt Supply Chain," 6.; Ritoe, Patrahau, and Rademaker, "Graphite: Supply chain challenges & recommendations for a critical mineral," 18-19.

13 Pavel and Tzimas, *Raw Materials in the European Defence Industry, 52*.

14 Ibid.

15 "The Effects of Imports of Aluminum on the National Security" (U.S. Department of Commerce, January 2018), https://www.commerce.gov/sites/default/files/the_effect_of_imports_of_aluminum_on_the_national_security_-_with_redactions_-_20180117.pdf.

while tungsten can be mainly found in propulsion systems of aircraft and helicopter carriers, amphibious assault ships, corvettes, offshore patrol vessels, and frigates. Cobalt and samarium are primarily used in cobalt-samarium alloys employed in aircrafts, helicopters, and missiles' propulsion systems.[16] The alloy is also used in electronic components and countermeasures equipment like the Tail Warning Function.[17] A disruption of the supply chain would have a medium impact.

The geopolitical risks related to these materials mainly concern China's near-absolute market monopoly. For all the above mentioned materials, except tantalum and cobalt, Chinese production dominance is staggering, and in some cases, it nears 80%: yttrium and neodymium (86%), samarium (86%), germanium (76%), and tungsten (82%).[18] Furthermore, for many of these materials the second or third-highest producer is Russia, which also represents a geopolitical challenge. Cobalt is mined for 53% in the Democratic Republic of Congo (DRC) but Chinese companies own or have a financial stake in 15 out of 19 Congolese cobalt mines as of 2020.[19] Neither the DRC nor China are considered reliable partners of Europe,[20] and, as tensions between Europe and China are rising, the probability of supply security disruptions is high. Tantalum is mined mainly in Rwanda (46%), the DRC (19%), and Brazil (15%).[21] While it is excluded from China's dominion, the internal instability of these countries makes it highly vulnerable to supply chain risks. For instance, in Rwanda, the lack of investments in the mining sector means scarce capacity in mineral processing recovery, mine planning, efficient mining, and mitigating mineral price fluctuations.[22] In the DRC, the money derived from tantalum mining is often used to fund war.Severe concerns regarding child labour and overall working conditions create national instability and concern for importers over human rights violations.[23] The reliability of these materials' suppliers is hence shaky at best. Taking all of the aforementioned supply security risks and geopolitical challenges together, the probability of supply chain disruptions for cobalt, germanium, neodymium, samarium, tantalum, tellurium, tungsten, vanadium, and yttrium is high.

High probability, Low impact (HL)

Dysprosium, lanthanum, platinum, praseodymium, silicon metal, and terbium's use in defence applications is very limited. Dysprosium is mainly used in aircrafts and missiles' propulsion systems and frame. Praseodymium is used exclusively in propulsion and electronic systems of aircrafts, platinum in the propulsion of submarines and aircrafts, and silicon metal in missiles' radome.[24] Their use is hence considerably limited across defence applications.

Nonetheless, geopolitical and supply chain risks are highly likely to materialise. Dysprosium, terbium, lanthanum, and praseodymium are rare earth elements (REE), which means they are

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16 Claudiu C Pavel and Evangelos Tzimas, "Raw Materials in the European Defence Industry" (European Commission Joint Research Centre, 2016).

17 Hurst, Cindy, "China's Ace in the Hole: Rare Earth Elements," 123.

18 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016, 52–55.

19 Eric Lipton and Dionne Searcey, "Chinese Company Removed as Operator of Cobalt Mine in Congo," *The New York Times*, February 28, 2022, sec. World, https://www.nytimes.com/2022/02/28/world/congo-cobalt-mining-china.html.

20 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index."

21 Pavel and Tzimas, "Raw Materials in the European Defence Industry, 55."

22 Written Jordon Kuschminder, Matthew Bliss, and Chiwanza Kasanga, "IGF Mining Policy Framework Assessment: Rwanda" (The International Institute for Sustainable Development, 2017).

23 Lindsay Dodgson, "On the Trail of Tantalum: Tracking a Conflict Mineral," Mining Technology, April 20, 2016, https://www.mining-technology.com/analysis/featureon-the-trail-of-tantalum-4831288/.

24 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

almost exclusively mined in Chinese territories (86% of global production)[25]. Through vertical integration in the REE sector, six state-owned integrated companies were assigned 90% of national production quotas by 2016.[26] This gives China the capacity to manipulate REE's market to benefit Chinese companies. Given that China previously relied on trade protectionism, the probability of supply chain disruptions is very high.[27] Silicon metal is also predominantly mined in China (70%), with the second biggest producer being Russia (6%) and the third one in Brazil (6%).[28] Platinum is instead mainly mined in South Africa (71%), Russia (12%), and Zimbabwe (7%).[29] South Africa is prone to internal instability fuelled by union militancy and upheaval due to inequalities, potentially leading to geopolitical challenges.[30] The fact that Russia is the second-largest producer does not help, given the current tensions with Europe over the war in Ukraine. The overall reliability of these materials' producers is hence low, which makes the probability of the materialisation of geopolitical and supply security risks very likely.[31] However, the limited use of dysprosium, lanthanum, platinum, praseodymium, silicon metal, and terbium would mitigate the adverse effects of supply disruption on the European defence industry.

Medium probability, High impact (MH)

Beryllium, chromium, copper, iron/steel, nickel, and titanium are materials significantly used in the defence industry (albeit less than graphite and aluminium) but subject to only medium degrees of supply chain and geopolitical risks. These materials can be found in applications across air, sea, and land domains. For instance, titanium and iron/steel are fundamental components of airframes, propulsion systems, ships' hulls, and missiles' frames. Copper is often used in electronics and control systems, while chromium can be mainly found in propulsion systems. Beryllium is utilised in landing gears, electronic systems, and connectors of aircraft and helicopters, in the armour and armaments of battle tanks, as well as on the onboard electronics of infantry fighter vehicles, towed artillery, and ammunitions. Nickel is mainly employed in the propulsion systems of aircrafts, helicopters, aircrafts and helicopter carriers, amphibious assault ships, corvettes, offshore patrol vessels and frigates. It can also be found in electronic systems of aircrafts and armaments of battle tanks, infantry fighter vehicles, and towed artillery.[32] Beryllium, chromium, copper, iron/steel, nickel, and titanium have thus quite considerable use in the defence industry, making the impact of supply chain shocks significant.

Some supply chain and geopolitical challenges affect the supply security of these materials. For instance, Russia's role in titanium's supply chain recently led to an increase in the price of titanium and, at the same time, shrunk the market for this material.[33] Furthermore, introducing tariffs on iron/steel from the EU and the US to protect local producers might bring instability to the market.[34] Corruption and social unrest might represent a problem in countries where

25 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 52.

26 Irina Patrahau et al., "Securing Critical Materials for Critical Sectors: Policy Options for the Netherlands and the European Union," HCSS Geo-Economics (The Hague: The Hague Center for Strategic Studies, 2020).

27 Yufeng Chen and Biao Zheng, "What Happens after the Rare Earth Crisis: A Systematic Literature Review," *Sustainability* 11, no. 5 (March 1, 2019): 21, https://doi.org/10.3390/su11051288.

28 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

29 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 54.

30 Ed Stoddard, "Analysis: World's Platinum Lies on African Political Faultlines," *Reuters*, May 10, 2012, sec. Business News, https://www.reuters.com/article/us-platinum-risks-idINBRE8490NR20120510.

31 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index."

32 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

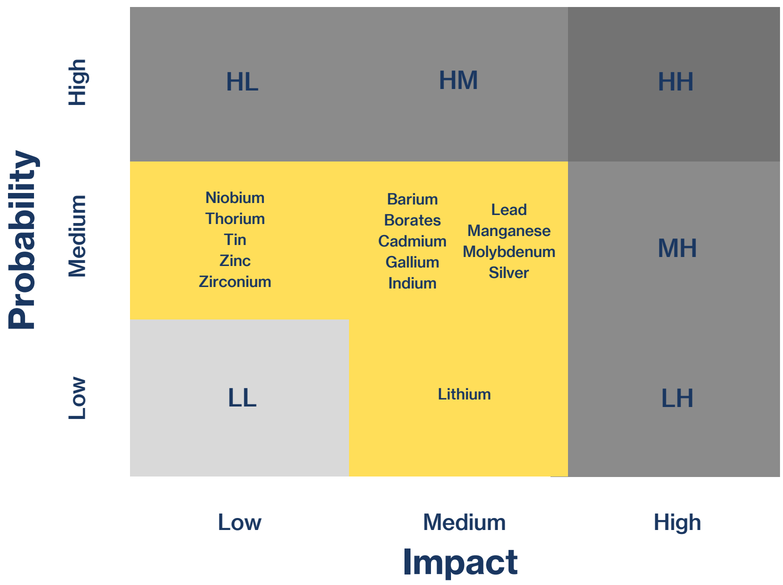
33 Felix Thompson, "Supply Chains: Grappling with Autocratic Risk," Global Trade Review (GTR), August 15, 2022, https://www.gtreview.com/supplements/gtr-scf-2022/supply-chains-grappling-with-autocratic-risk/; "Titanium Supply Threatened by Ukraine Conflict: Update | Argus Media," February 28, 2022, https://www.argusmedia.com/en/news/2304842-titanium-supply-threatened-by-ukraine-conflict-update.

34 "Steel Import Tariffs Extended for Two Years," *BBC News*, June 29, 2022, sec. Business, https://www.bbc.com/news/business-61982431.

copper is mainly mined, namely Chile and Peru.[35] In Chile, corruption problems regard especially the granting of mining concessions and the environmental approval of mining projects.[36] Big mining companies' tax evasion is also a recurrent problem causing social unrest in Chile.[37] In Peru, the mismanagement of copper mines and the mistreatment of local communities in mining sites often lead to community protests that halt the functioning of mines for several weeks.[38] However, the supply of these materials is relatively diversified, with no country controlling more than 45% of the global production and the suppliers varying for each material, which dilutes the risk of supply chain disruptions. Titanium's main producer is Australia (15%), chromium's is South Africa (45%), iron/steel is China (30%), nickel is Indonesia (32%), and copper is Chile (31%).[39] Beryllium represents the exception since it is produced for 90% in one state. However, the country in question is the United States, which is considered a reliable partner for Europe. Given the diversification and relative reliability of these materials' suppliers, the probability of materialisation of supply security and geopolitical risks are assessed as medium.

Medium risk materials

Figure 4. Medium risk materials



35 Emmanuel Hache, Charlene Barnet, and Gondia-Sokhna Seck, "Copper in the Energy Transition: An Essential, Structural and Geopolitical Metal!," IFPEN, December 2020, https://www.ifpenergiesnouvelles.com/article/copper-energy-transition-essential-structural-and-geopolitical-metal.

36 "Chile Transparente's Research on Corruption in Mining," CESCO, 2022, https://www.cesco.cl/en/2019/06/03/chile-transparentes-research-on-corruption-in-mining/.

37 Reuters, "Chile Plans to Raise Copper Mining Royalties and Reform Tax System," *Reuters*, July 1, 2022, sec. Americas, https://www.reuters.com/world/americas/chile-plans-raise-copper-mining-royalties-reform-tax-system-2022-07-01/.

38 Marcelo Rochabrun and Marco Aquino, "Copper Mine Protests Spread in Peru, Target Glencore and BHP's Antamina," *Reuters*, October 26, 2021, sec. Commodities News, https://www.reuters.com/article/peru-mining-idUSKBN2HG2QS.

39 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016, 52–55.

Medium probability, Medium impact (MM)

Barium, borates, cadmium, gallium, indium, lead, manganese, molybdenum, and silver are part of this group. While they are used in some defence applications, they are not as commonly employed as other materials. Borates, indium, gallium, and cadmium are all used in the electronic systems of aircrafts to produce sensors, avionics, and electro-optical systems. They are also found in onboard electronics of infantry fighter vehicles, armoured personnel carriers, self-propelled or towed artillery. Molybdenum, cadmium, and lead are employed in airframes, while barium is used in electric propulsion for aircrafts, helicopters, aircraft carriers, corvettes, and submarines. Landing gears and electronic systems of aircrafts make use of silver, which is also found, together with manganese, in submarines and torpedoes' propulsion systems. The use of lead extends to airframes, armaments, torpedoes, and missiles' propulsion systems.[40] The impact of supply security risks would be medium, considering the extent to which these materials are used.

Geopolitical and supply chain risks associated with this category of materials have medium probability of materialising. On the one hand, the leading producer of indium (56%), gallium (63%), molybdenum (38%), cadmium (32%), lead (53%), and barium (42%) is China.[41] On the other hand, most of these materials' second and third-biggest producers are states with stable relations with Europe and are deemed reliable, such as South Korea, Japan, the US, and Australia.[42] The fluctuating ties between the EU and Turkey are also to be taken into account, given that the latter mines the most borates globally (39% of the world's production).[43] While the supply of silver is diversified, with the biggest producers being Mexico (12%), Peru (14%), and China (14%)[44], these three countries are not the most reliable or stable, which might translate into geopolitical challenges.[45] The same goes for the two biggest producers of manganese, South Africa (24%) and China (20%), while the third largest producer is Australia (17%), whose closeness to Europe is undoubted.[46] Silver mining is also associated with several environmental risks: government crackdowns on mines that do not respect certain environmental standards could affect its supply chain.[47] Overall, there are some supply security and geopolitical risks associated with barium, borates, cadmium, gallium, indium, lead, manganese, molybdenum, and silver's supply security, but the probability of their materialisation is medium, in that it is mitigated by other factors such as diversification of supply and suppliers with affinity to Europe.

Medium probability, Low impact (ML)

Niobium, thorium, tin, zinc, and zirconium have a relatively scarce use in the military industry. Niobium can be found in propulsion systems of aircrafts, helicopters, and submarines, and in missiles' radome and frames. Tin's employment is limited to aircrafts' body and carriers' Browning machine guns, while zirconium is utilized for aircrafts, torpedoes' propulsion

40 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

41 Pavel and Tzimas; Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

42 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016; Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

43 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

44 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 52.

45 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index"; "Fragile States Index | The Fund for Peace."

46 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016; van Manen et al., "Methodological Note - The Dutch Foreign Relations Index"; "Fragile States Index | The Fund for Peace."

47 Neal R. Haddaway et al., "Evidence of the Impacts of Metal Mining and the Effectiveness of Mining Mitigation Measures on Social–Ecological Systems in Arctic and Boreal Regions: A Systematic Map Protocol," *Environmental Evidence* 8, no. 1 (February 21, 2019): 9, https://doi.org/10.1186/s13750-019-0152-8.

systems, and missiles' radome. Zinc and thorium are used in the electronic systems of aircrafts and helicopters and infantry fighter vehicles' onboard electronics. Zinc can also be found in aircraft and helicopter carriers' Browning machine guns.[48] Given the limited use of these materials across defence applications, the impact of supply chain disruptions is deemed low.

Regarding geopolitical and supply security risks, the challenges to the supply security of niobium, thorium, tin, zinc, and zirconium are varied, albeit not immediate threats. Indeed, 92% of the world's production of niobium comes from Brazil, and India dominates the thorium market with an 81% share. Brazil and India have price-setting power over the two materials. These two countries are not hostile to Europe. Nonetheless, they cannot be defined as trustworthy either, given that they are subject to internal instability that might cause supply chain volatility.[49] The global production of tin is in the hands of China (43%), Indonesia (27%), and Peru (6%)[50], which do not have immaculate human rights records. This influences supply security, given that European countries must comply with legislation mandating the ethical sourcing of this material.[51] While China is the primary producer of Zinc (37%)[52], the challenges lie in the refinement process, which is mainly conducted in the region at the centre of the Russia-Ukraine conflict.[53] South Africa and China produce respectively 15% and 10% of the world's zirconium.[54] Despite their mixed record of reliability and stability, zirconium's supply chain is considered relatively stable, as the leading producer is Australia (46%)[55]. Overall, niobium, thorium, tin, zinc, and zirconium face some supply security and geopolitical risks, but they are of medium entity.

Low probability, Medium impact (LM)

Lithium is the only material belonging to this category. It is mainly utilised in lithium-ion (Li-ion) batteries for electric motors and propulsion in aircrafts, helicopters, aircraft and helicopter carriers, amphibious assault ships, corvettes, submarines, torpedoes, and missiles.[56] Thus, lithium is mainly used in one form but one that is diffused across multiple defence applications. A disruption in this material's supply security would have a medium impact.

Lithium is especially coveted for its use in commercial applications such as electric vehicles and ICT devices, which drive its demand to increasing heights.[57] Nonetheless, the diversification of suppliers and the constant progress in recycling technologies for this material curb the probability of severe disruptions to the supply chain.[58] These circumstances might change in the future, but at the moment, the likelihood of supply security disruptions is deemed to be low.

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48 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

49 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index."

50 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 55.

51 Geopolitical Monitor, "Conflict Minerals and Global Supply Chains: The Tin Market," *Geopolitical Monitor* (blog), October 27, 2017, https://www.geopoliticalmonitor.com/conflict-minerals-and-global-supply-chains-the-tin-market/.

52 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 55.

53 Camille Erickson, "'Hold onto Your Wallets': Low Zinc Supply Hints at Market Shocks Ahead," April 13, 2022, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hold-onto-your-wallets-low-zinc-supply-hints-at-market-shocks-ahead-69615330.

54 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 55.

55 Ibid.

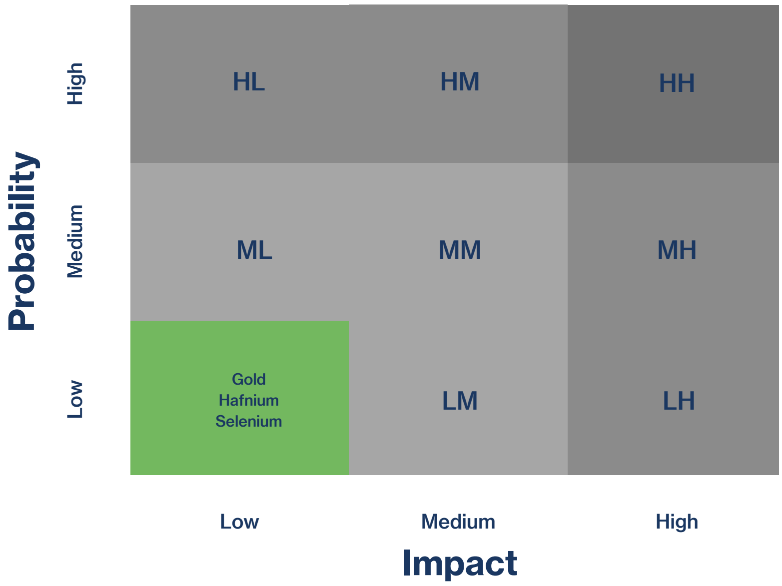
56 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

57 Patrahau et al., "Securing Critical Materials for Critical Sectors: Policy Options for the Netherlands and the European Union."

58 Patrahau et al.

Low risk materials

Figure 5. Low risk materials



Low probability, Low impact (LL)

There are only three materials used in the defence industry with low geopolitical and supply chain risks; gold, hafnium, and selenium. Gold is limitedly employed in producing onboard electronics for a selected number of warships and in a few components of airframes. Selenium is only used for electro-optical systems in aircrafts, and so is hafnium, which can also be found in phased array radars.[59] The limited use of these materials means that the impact of supply chain disruptions is established as low.

The supply of gold is diversified, with the largest global producers being China (15%), Australia (9%), and the US (8%).[60] None of these countries holds a monopolising market share, and two out of three states are reliable partners for Europe. Hafnium's production depends on the US and France, which account for 46% each of the world's share. Germany (31%), Japan (9%), and Belgium (8%) are the largest selenium producers.[61] The leading suppliers of hafnium and selenium are considered stable and reliable countries.[62] The probability of supply chain disruptions is hence minimal.

59 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016.

60 Ibid, 53.

61 Ibid, 53-54.

62 van Manen et al., "Methodological Note - The Dutch Foreign Relations Index"; "Fragile States Index | The Fund for Peace."

Part II.
Materials' applications in defence domains

The employment of raw materials changes from one military domain to the other. The domain-specific variations are vital tellers of each defence sector's vulnerabilities. The risk assessment sheds light on some key points that should be kept in mind when evaluating the defence needs of raw materials. The results of Part I apply to the defence sector as a whole. The domain-by-domain analysis provides further details on the vulnerability of each sector based on each domain's dependency on given materials. Furthermore, air, sea, and land domains have different needs and while certain materials are of high criticality across the three sectors, important differences must be noted. For instance, the air domain uses a greater variety of materials concerning the sea and land sectors, which influences the impact of geopolitical and supply chain risks. As such, the categorisation of certain materials varies from one domain to the other. For example, this is the case of graphite and gold. These two materials are respectively categorised as very high-risk and low-risk for the air domain but are instead judged as high-risk and medium-risk for their applications in the sea domain.

An analysis of these differences is carried out in the sections below, to facilitate understanding the needs and vulnerabilities of specific defence applications with regards to raw materials.

Air: critical raw materials in aeronautics

The air domain uses all of the analysed materials, and it is the most subject to geopolitical and supply security risks.[63] The most used materials across this domain are aluminium, graphite, copper, and titanium. These materials have several applications in aeronautics. In aircrafts (fighter, transport, maritime patrol, and unmanned) and helicopters (combat and multi-role), aluminium, graphite, and titanium find their main application in the airframe, where they are used in the body, wings, tail, nose, and axis of the aircraft. They are also employed in the production of propulsion systems' components such as combustors, nozzle, drive shaft, and propellers, as well as in landing gears, connectors, and electronic systems. Titanium is furthermore used for sensors, avionics, and electro-optical systems. Copper is instead used primarily in electro-optical and control systems. Other materials often used in the production of both aircrafts and helicopters' components are beryllium, nickel, iron/steel, and cadmium, which are employed in the airframes, landing gears, connectors and electronic systems. Interestingly, dysprosium is used in the turbines and control systems of aircrafts but not in helicopters.

Missiles make substantial use of iron/steel for their warhead, body frame, control actuator section, and propulsion systems. Dysprosium, given its high resistance, is also extensively used in the latter two components, as well as in guidance systems. Tantalum and copper can be found in missiles' fuses, propulsion arming and firing, and body frame. Neodymium is used in the propulsion and electro-optical systems of aircrafts, and in missiles' control actuator section and propulsion. Niobium is principally employed in aircrafts' turbines, helicopters' combustors, and, together with borates, missiles' guidance sections and body frames. Borates can also be found in sensors, avionics, and electro-optical systems of aircrafts and helicopters. Cobalt is mainly utilised in combustors and electronic components of aircrafts

63 Information about the application of materials across air domain application is taken from Pavel and Tzimas, "Raw Materials in the European Defence Industry," unless differently indicated.

and helicopters, as well as in missiles' propulsion arming and firing and motor pump actuators. Lastly, electronic systems such as sensors and avionics, communication and identification, and electro-optical systems of air domain applications make use of gallium.

The other materials (yttrium, terbium, lanthanum, praseodymium, germanium, platinum, indium, vanadium, lithium, tungsten, silicon metal, hafnium, molybdenum, manganese, tin, chromium, zirconium, silver, tellurium, selenium, zinc gold, lead, barium, samarium, thorium) are used to a lesser extent for defence applications of the air domain and are therefore not expanded upon in this section.

Figure 6 shows the categorization of materials according to Probability X Impact for the air domain while the detailed breakdown in components can be found in Figure 7. Lastly, Figure 8 exemplifies the use of raw materials in a fighter aircraft.

Figure 6. Risk assessment matrix for the air domain

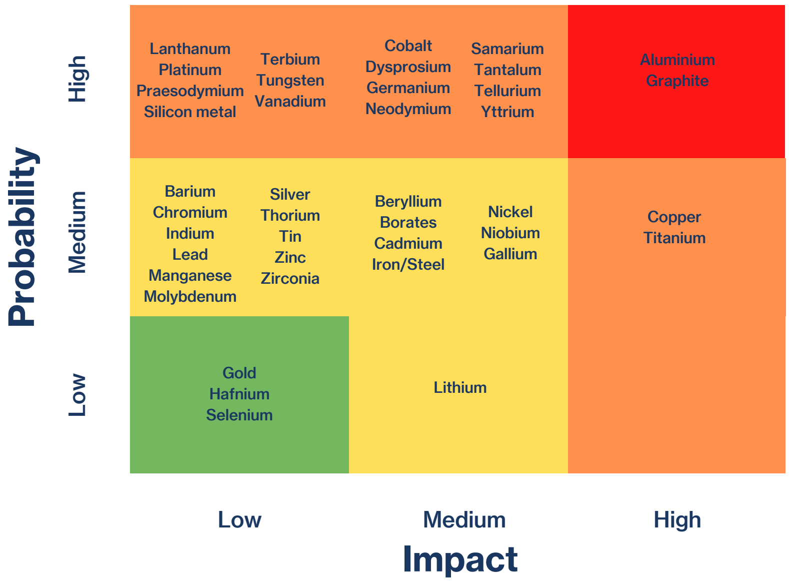


Figure 7. Use of selected materials across air domain applications

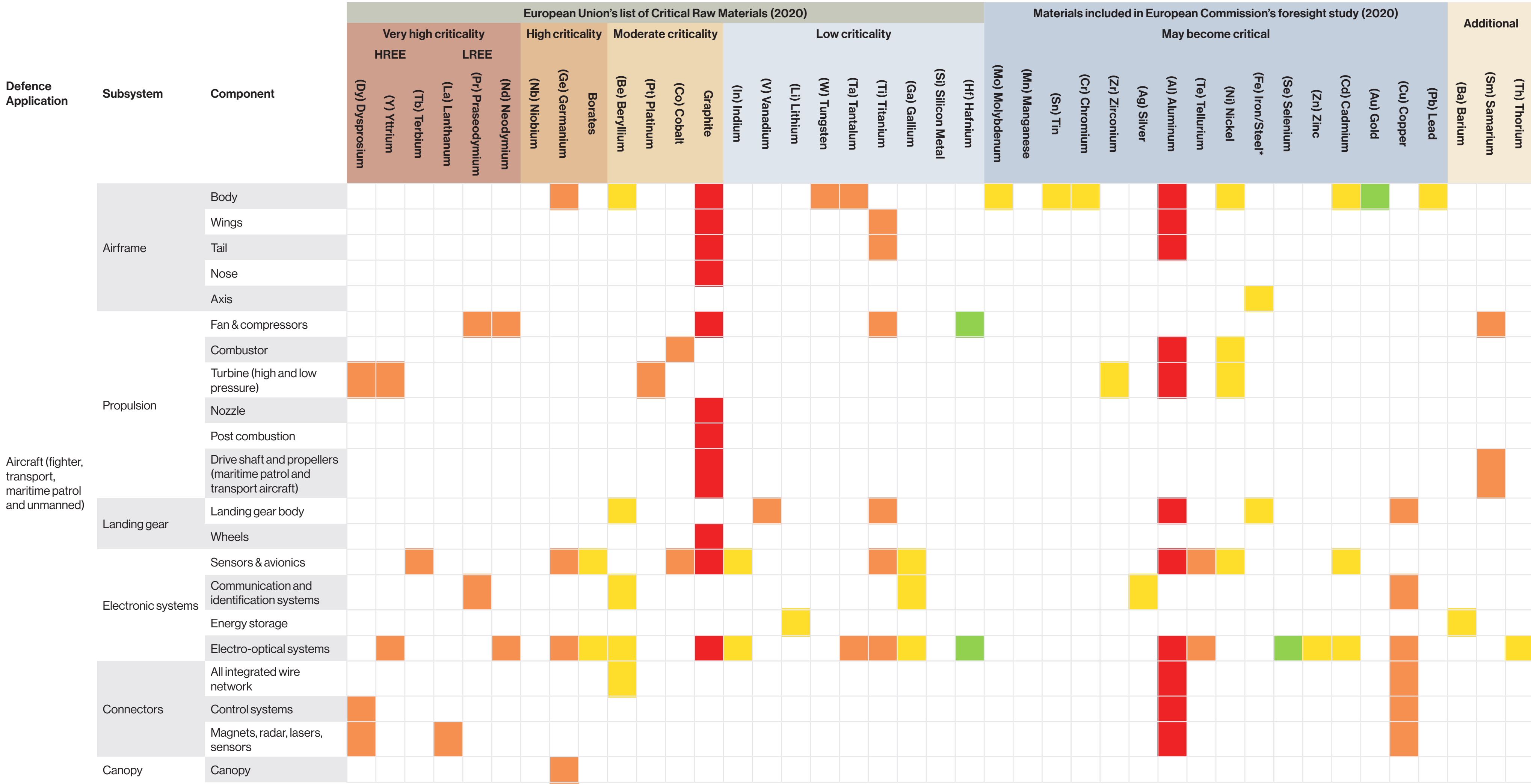


Figure 7. Use of selected materials across air domain applications (continued)

			European Union's list of Critical Raw Materials (2020)																						Materials included in European Commission's foresight study (2020)																Additional		
			Very high criticality						High criticality			Moderate criticality				Low criticality									May become critical																		
			HREE			LREE																																					
Defence Application	Subsystem	Component	(Dy) Dysprosium	(Y) Yttrium	(Tb) Terbium	(La) Lanthanum	(Pr) Praseodymium	(Nd) Neodymium	(Nb) Niobium	(Ge) Germanium	Borates	(Be) Beryllium	(Pt) Platinum	(Co) Cobalt	Graphite	(In) Indium	(V) Vanadium	(Li) Lithium	(W) Tungsten	(Ta) Tantalum	(Ti) Titanium	(Ga) Gallium	(Si) Silicon Metal	(Hf) Hafnium	(Mo) Molybdenum	(Mn) Manganese	(Sn) Tin	(Cr) Chromium	(Zr) Zirconium	(Ag) Silver	(Al) Aluminum	(Te) Tellurium	(Ni) Nickel	(Fe) Iron/Steel*	(Se) Selenium	(Zn) Zinc	(Cd) Cadmium	(Au) Gold	(Cu) Copper	(Pb) Lead	(Ba) Barium	(Sm) Samarium	(Th) Thorium
Helicopter (combat and multi-role)	Airframe	Body																			Orange										Red												
		Wings													Red																Red												
		Tail																																					Orange				
	Propulsion	Compressors																			Orange										Red		Yellow	Yellow									
		Combustor		Orange					Yellow					Orange																	Red												
		Turbine																										Yellow					Yellow										
		Drive shaft													Red						Orange																						
		Rotors													Red																												
	Landing gears	Landing gear body										Yellow																											Orange				
		Communication/ identification systems																				Yellow								Yellow	Red								Orange				
		Energy storage																Yellow																							Orange		
		Electro-optical systems													Red	Yellow																					Yellow						
	Electronic systems	Sensors		Orange				Orange			Yellow	Yellow			Red																Red	Orange				Yellow	Yellow		Orange				
		Avionics																																									
		Communication/ identification systems										Yellow										Yellow								Yellow	Red								Orange				
		Energy storage																Yellow																									
		Electro-optical systems										Yellow			Red	Yellow																Orange					Yellow						
	Connectors	All integrated wire network										Yellow																			Red								Orange				
	Canopy	Canopy													Red																												
Missiles	Radome	Sensors/seeker					Orange		Yellow														Orange						Yellow				Yellow										
	Warhead section	Fuse																		Orange					Yellow														Orange				
		Warhead																																Yellow									
	Propulsion system	Propulsion arming and firing unit	Orange					Orange			Yellow			Orange				Yellow		Orange								Yellow						Yellow					Orange	Yellow		Orange	
	Control actuator section	Motor pump actuator	Orange					Orange			Yellow			Orange																				Yellow								Orange	
	Frame	Body frame							Yellow										Orange	Orange	Orange				Yellow						Red			Yellow					Orange				
	Guidance section		Orange						Yellow																																		

Figure 8. Use of raw materials in a fighter aircraft

Sea: critical raw material in the naval sector

The sea domain uses the least amount of materials compared to the other sectors.[64] Aluminium, iron/steel, graphite, nickel, titanium, copper, lithium, silver, and lead are the most used materials in naval defence applications. Aluminium is used for constructing the shafts (driving controllable pitch propellers), decks, and naval guns of corvettes, offshore vessels and frigates. It is also found in the diesel turbines, five-bladed propellers, decks, navigation radar, and naval guns of submarines.

Torpedoes also employ aluminium to build batteries, contra-rotating direct-drive brushless motors, and Sundstrand gas turbines with a pump jet. Iron/Steel is used to construct the hull and naval guns in submarines and corvettes and to build the super-structure and armaments of aircraft and helicopter carriers. Graphite can be found in the super-structures of submarines and in onboard electronics such as bow sonar in corvettes and radars in carriers. Nickel is employed in the shafts and decks of corvettes and diesel and gas turbines, propellers, super-structure, and Browning machine guns found in carriers.

Titanium is used in the belt and upper belt of the corvettes, submarines, and carriers' hulls, as well as in gas turbines and navigation systems of carriers. Copper is utilised in constructing diesel turbines, thrusters, propellers, and Browning machine guns for carriers and corvettes' shafts. Lithium is used for batteries in submarines and torpedoes, in the electric propulsion system of carriers and in the electric motors of corvettes. Silver is utilised to construct batteries in submarines and torpedoes, with the former also employing the metal for its turbine. In carriers, lead is found in the electric propulsion system and in Browning machine guns. Corvettes use lead to construct electric motors, while in submarines, it is utilised for batteries and torpedoes. Other materials, namely platinum, cobalt, vanadium, tungsten, molybdenum, manganese, tin, chromium, zirconium, zinc, gold, barium, and samarium, are employed in the sea domain, albeit to a lesser extent than the above mentioned ones.

Figure 9 shows the categorization of materials according to Probability X Impact for the naval domain while the detailed breakdown in components can be found in Figure 10. Figure 11 shows a breakdown of the materials used at the component level for a naval surface vessel.

[64] Information about the application of materials across air domain application is taken from Pavel and Tzimas, "Raw Materials in the European Defence Industry," unless differently indicated.

Figure 9. Risk assessment matrix for the sea domain

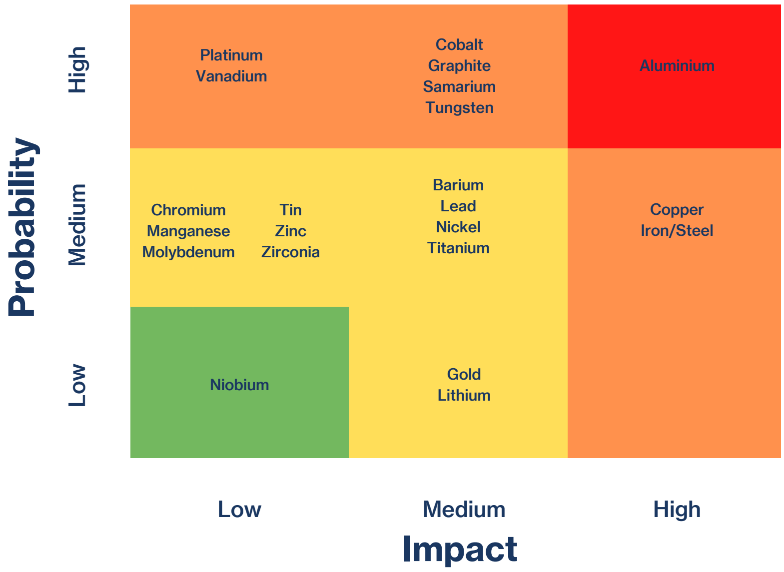
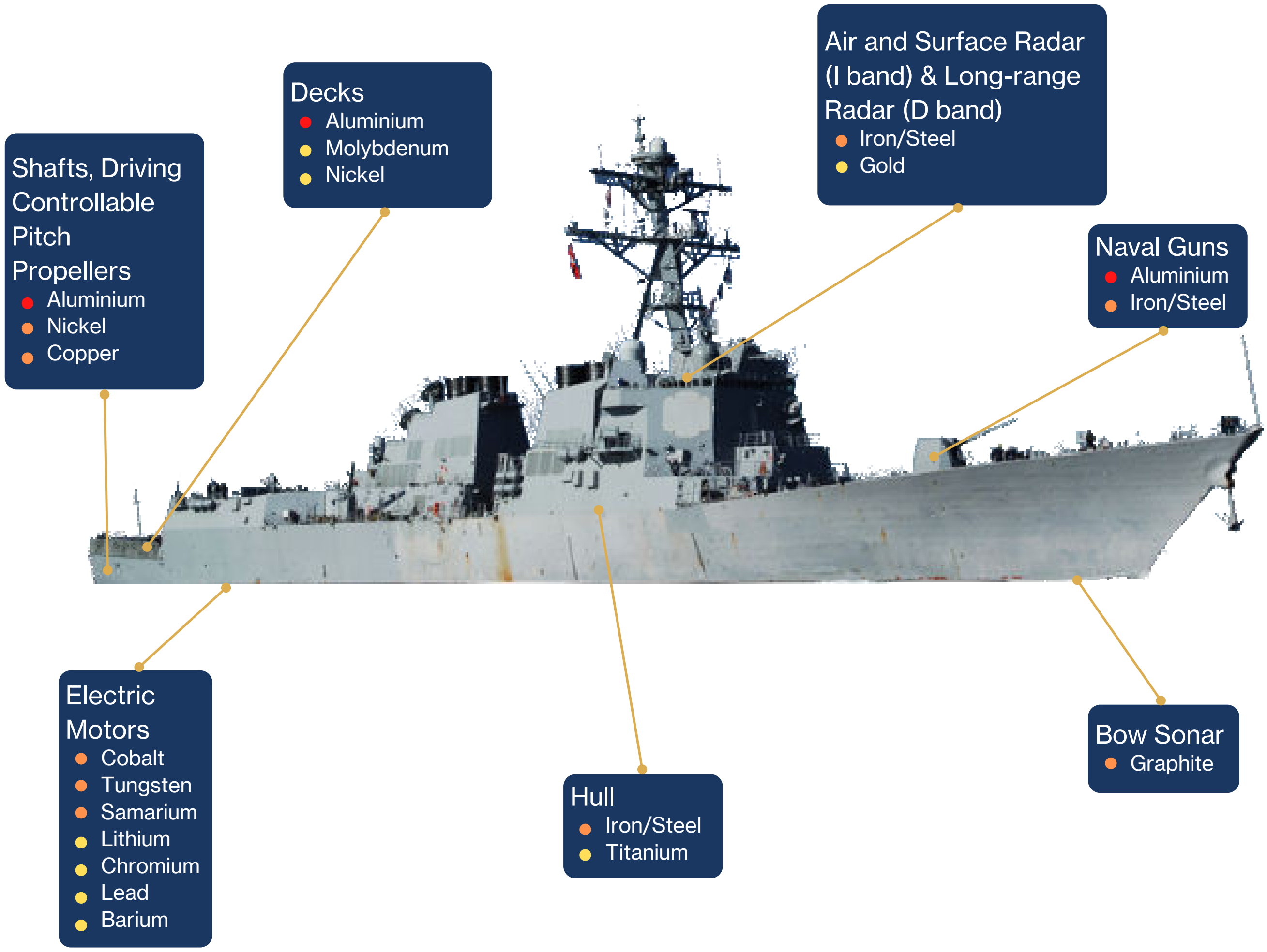


Figure 10. Use of selected materials across sea domain applications

Defence Application	Subsystem	Component	European Union's list of Critical Raw Materials (2020)								Materials included in European Commission's foresight study (2020)													Additional	
			High criticality	Moderate criticality			Low criticality				May become critical														
			(Nb) Niobium	(Pt) Platinum	(Co) Cobalt	Graphite	(V) Vanadium	(Li) Lithium	(W) Tungsten	(Ti) Titanium	(Mo) Molybdenum	(Mn) Manganese	(Sn) Tin	(Cr) Chromium	(Zr) Zirconium	(Ag) Silver	(Al) Aluminum	(Ni) Nickel	(Fe) Iron/Steel*	(Zn) Zinc	(Au) Gold	(Cu) Copper	(Pb) Lead	(Ba) Barium	(Sm) Samarium
Aircraft and helicopter carrier, amphibious assault ship	Hull	Belt								Yellow									Orange						
		Upper belt								Yellow									Orange						
	Propulsion	Integrated full electric propulsion (IFEP)			Orange			Yellow															Yellow	Yellow	Orange
		Gas turbine							Orange	Yellow								Yellow							
		Diesel turbine															Red	Yellow				Orange			
		Advanced induction motors																							
		Azimuth thrusters																				Orange			
		Five-bladed propellers															Red	Yellow				Orange			
		POD (propulsion with outboard electric motors			Orange																			Yellow	Orange
	Super-structure	Deck															Red		Orange						
		Flight deck																	Orange						
		Hangar																Yellow	Orange						
	On-board electronics	Long-range radar																			Yellow				
		3D medium-range radar																			Yellow				
		Navigation radar				Orange				Yellow							Red		Orange						
	Armament	Naval guns															Red		Orange						
		Browning machine guns											Yellow			Yellow		Yellow		Yellow		Orange	Yellow		
Corvettes, offshore patrol vessels and frigates	Hull	Hull								Yellow									Orange						
	Propulsion	Electric motors			Orange			Yellow	Orange					Yellow									Yellow	Yellow	Orange
		Shafts, driving controllable pitch propellers															Red	Yellow				Orange			
	Super-structure	Decks									Yellow						Red	Yellow							
	On-board electronics	Long-range air and surface surveillance radar																	Orange		Yellow				
		Air and surface detection, tracking and guidance radar (I band)																	Orange		Yellow				
		Bow sonar				Orange																			
		Naval guns															Red		Orange						
Submarine	Hull	Hull					Orange		Orange	Yellow									Orange						
	Propulsion	Diesel engine	Green																Orange					Yellow	
		PEM fuel cells		Orange																					
		Electric motors			Orange							Yellow													Orange
		Seven-bladed skewback propeller				Orange								Yellow											
		Batteries						Yellow								Yellow							Yellow		
	Super-structure	Decks				Orange																			
	On-board electronics	Sonar				Orange																			
		Periscope				Orange													Orange						
		Torpedoes						Yellow								Yellow	Red						Yellow		
Torpedoes	Propulsion	Sundstrand gas turbine with pump jet						Yellow				Yellow		Yellow	Yellow	Yellow	Red						Yellow		
		Contra-rotating direct-drive brushless motor															Red						Yellow		
		Battery						Yellow								Yellow	Red						Yellow		

Figure 11. Use of raw materials in a naval surface vessel



Legend

- Very high risk material
- High risk material
- Medium risk material
- Low risk material

Land: critical raw materials in the land sector

The land domain uses most materials considered in the analysis. Despite not employing as many materials as the air domain, it remains subject to geopolitical risks and potential disruptions in its supply chain. [65]

The most used materials in defence applications pertaining to land are beryllium, graphite, aluminium, iron, and copper. These materials are used in several defence applications, from the construction of main battle tanks to their use in ammunition. Beryllium is utilised in main battle tanks to build the hull, turrets, and tank floor, which constitute the armour of the weapon system. In infantry fighter vehicles, beryllium is utilised to manufacture electronic systems such as SIT communication equipment, combat identification equipment, and inertial navigation systems. For the construction of tank guns, Howitzer machine guns in infantry fighter vehicles, and GPS/SAL guidance systems in ammunition, graphite is found in combination with other materials to construct these components.

Aluminium is used to build phased array radars and artillery systems. It is also employed to manufacture navigation equipment and guidance systems found in infantry fighter vehicles and guided ammunition. Iron is an essential material for constructing the body and the barrel of assault rifles. It can also be found in other military equipment, such as main battle tanks, infantry fighting vehicles (turrets and cannons), and the split trail of towed artillery. On-board electronics in artillery systems, navigation systems, communication equipment, and radar in infantry fighting vehicles rely on copper. This metal can also be found in the binoculars used in main battle tanks' wire systems and circuits. Other relevant materials in the land domain are yttrium, neodymium, germanium, indium, tantalum, tellurium, and cadmium, which are mainly used for on-board electronic systems in main battle tanks and infantry fighting vehicles, as well as in guidance systems in ammunition. Vanadium and Titanium are used alongside other materials to manufacture tank guns, machine guns, and turrets.

Certain materials (terbium, borates, tungsten, gallium, hafnium, molybdenum, manganese, chromium, silver, nickel, zinc, and thorium) are less prevalent in the land domain's weapon systems than the aforementioned ones. They are included in Appendix I, which illustrates the materials used in each land domain application at the component level.

Figure 12 shows the categorization of materials according to Probability X Impact for the land domain while the detailed breakdown in components can be found in Figure 13. Figure 14 displays an example of the application of the materials in an infantry fighter vehicle.

65 Information about the application of materials across air domain application is taken from Pavel and Tzimas, "Raw Materials in the European Defence Industry," unless differently indicated.

Figure 12. Risk assessment matrix for the land domain

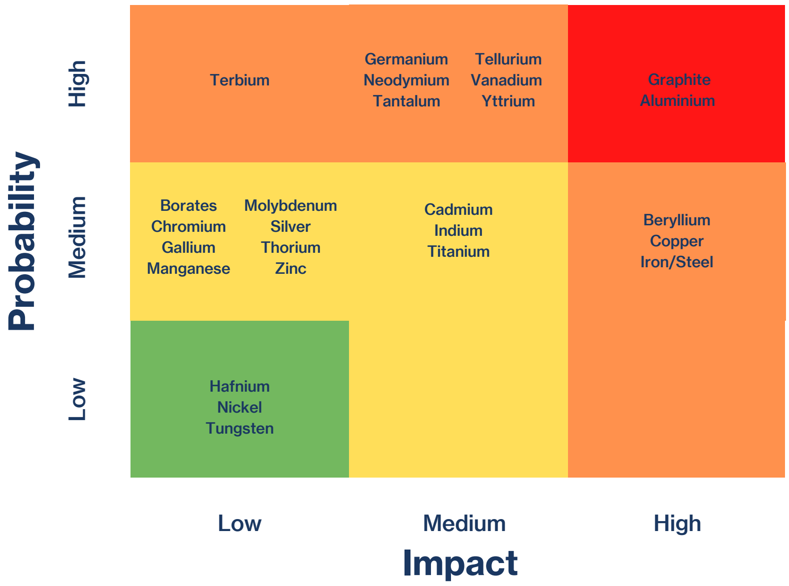


Figure 13. Use of selected materials across land domain applications

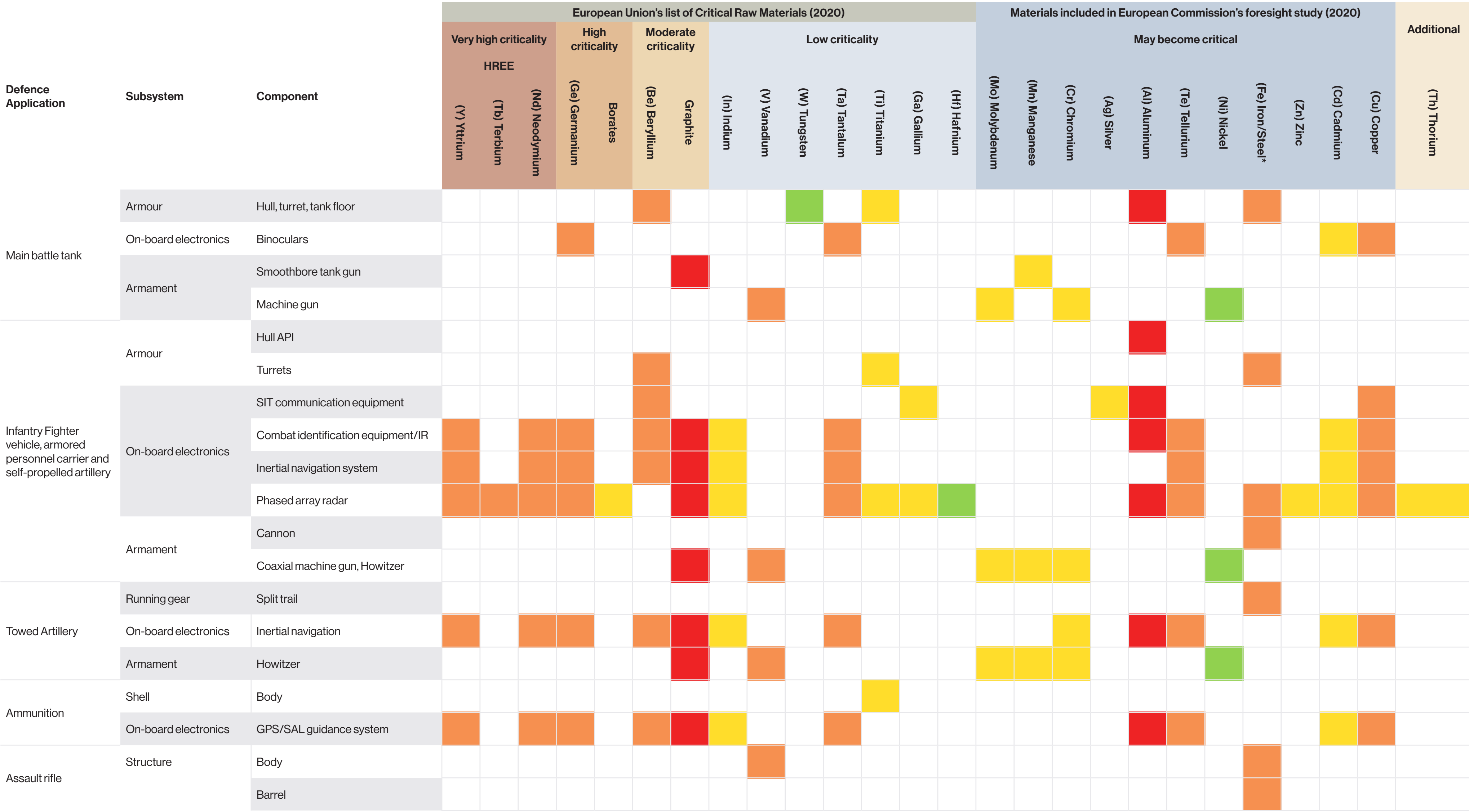


Figure 14. Use of materials in an infantry fighter vehicle

4. Observations

Countries worldwide are embarking on a similar trajectory of energy transition, digitalisation, and green defence. This will sharply increase the global demand for CRM across sectors. For example, if governments manage to limit global temperature increase by 2 degree Celsius the global demand for graphite is expected to increase 25-fold by 2040 relative to 2020 as a result of the energy transition alone.[66] Yet graphite is also one of the materials perceived to have the highest supply risk for European defence. The increase in CRM demand across different sectors will lead to competition for their supply.

Scarcity is not just caused by insufficient mining. A holistic view of mineral supply chains that includes refining and processing of minerals and the manufacturing of semi-finished products is necessary to assess supply risks.

The increase in demand for raw materials could furthermore lead to supply scarcity for materials that are not yet on the EU's critical raw materials list. Even though materials like aluminium or titanium are not 'critical' as of 2022, their production is concentrated in a few countries, outside of the EU, enhancing supply security risks. Moreover, products like gunpowder and ammunition can come under pressure if global demand suddenly increases, even if their supply was not deemed problematic until then. Supply security is largely determined by geopolitics, trend which is only becoming more prominent as of 2022. The European dependence on Russian oil and natural gas came at the forefront during the war in Ukraine. For the first months of the war, EU countries were financing Putin's war efforts by purchasing Russian oil and gas at record prices.[67] The freedom of action in EU foreign policy was severely constrained by this undesirable dependency as Europe's credibility as a geopolitical actor suffered.

The same approach of developing dependency relations based on cheap and abundant supplies from unreliable actors has dominated Europe's critical raw materials sector. For decades, the Chinese government has purposefully expanded the country's stronghold over mining operations, refining facilities and production of semi-finished products in strategic sectors.[68] Export restrictions, vertical integration of state-owned companies, decreasing quotas for domestic production are strategies that unfriendly governments can employ to deprive European governments of critical and 'soon-to-be' critical raw materials.

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[66] Numbers according to the Sustainable Development Scenario of the IEA. See IEA, "The Role of Critical Minerals in Clean Energy Transitions," 2020, 47, https://iea.blob.core.windows.net/assets/24d5dfbb-a77a-4647-abcc-667867207f74/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf.

[67] CREA, "Financing Putin's War: Fossil Fuel Exports from Russia in the First Six Months of the Invasion of Ukraine," *Centre for Research on Energy and Clean Air* (blog), 2022, https://energyandcleanair.org/publication/financing-putins-war-fossil-fuel-exports-from-russia-in-the-first-six-months-of-the-invasion-of-ukraine/.

[68] Patrahau et al., "Securing Critical Materials for Critical Sectors: Policy Options for the Netherlands and the European Union."

5. Recommendations

Securing supplies of CRM for defence requires national, European and transatlantic cooperation.

In the Netherlands, the national raw materials strategy should be operationalised into targeted research of CRM in the defence sector. Pairing this research with the Defence Industry Strategy[69] (DIS) of 2018 would ensure coherence across national security interests. The DIS describes the Netherlands' priorities in terms of knowledge, technology and industrial capabilities that can support national security. As such, CRM should be integrated in broader national security and strategic considerations. This would offer concrete points of action for CRM in defence to the Netherlands government.

European coordination is furthermore required to secure supplies of CRM for defence. Especially since the Russian invasion of Ukraine in 2022, pledges of increased European defence spending are swiftly multiplying. CRM supply vulnerabilities should be considered when investing in developing defence capabilities.

For a long time, the EU has primarily been investing in circularity and research as strategies to become less dependent on foreign supplies of CRM. Recycling is essential in reducing the demand of primary materials and will contribute to supply security after 2035. The EU's Circular Economy Action Plan[70] and the Netherlands' National Programme on Circular Economy[71], among others, will ensure this. Until then, insufficient products will reach their end-of-life stage to account for a massive increase in secondary supply.

The civil and military sectors can work together to reduce CRM supply risks, given that minerals are needed across sectors: energy, defence, transport, digital technologies. The competition to secure raw materials for strategic sectors will likely intensify over the next decades and securing minerals will require consistent policies across sectors.

Through financing programmes and incentives, European governments can de-risk investments and encourage companies to innovate and start up the production of CRM. The Untied Loan Guarantees, for instance, can provide (political) credit default risk to projects considered crucial for the supply of CRM and hence support European companies sourcing materials abroad.[72]

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69 "Defence Industry Strategy" (Government of the Netherlands, 2018), https://www.government.nl/documents/reports/2018/11/30/defence-industry-strategy.

70 "Circular Economy Action Plan" (European Commission, 2020), https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf.

71 "Rijksbrede programma Circulaire Economie," 2016, https://www.tweedekamer.nl/kamerstukken/brieven_regering/detail.

72 Jeff Amrish Ritoe, "Tying Critical Materials through the Untied Loan Guarantee | A Proven and Effective Way to Secure Materials Needed for Europe's Energy Transition," HCSS, 2022, https://hcss.nl/report/critical-materials-untied-loan-guarantee/.

Strong responsible sourcing and due diligence regulations can minimise the climate footprint of strategic goods' supply chains. The EU Conflict Minerals Regulation[73] and Corporate Sustainability Due Diligence[74] are beneficial regulations in this sense, as well as Netherlands' OESO guidelines for multinational corporations[75] and recent initiatives focused on human rights as part of the foreign policy[76].

The list of CRM officially recognised by the EU is furthermore likely to expand over the next decade. There is a set of materials, including aluminium, copper and nickel, that are not as of 2022 facing massive supply risk disruptions but that are needed in a wide range of applications. Whereas the risk of disruption is not imminent, it is likely to aggravate over the next 10-15 years due to the rapid increase in global demand, lack of supply diversification and/or unreliable supplier countries.

Finally, transatlantic cooperation is essential when it comes to European defence. While Europe's own capabilities should be strengthened, transatlantic relations remain at the centre of EU defence procurement. American companies supply high-performance alloys and aerospace materials for Europe, among others.[77] The International Traffic in Arms Regulations (ITAR) of the United States is central to the trade of defence and military related technologies. This includes "items and information inherently military in design, purpose of use".[78] Given that the EU is highly dependent on the US for military procurement, ITAR remains at the basis of much of EU defence action, even in the field of raw materials. Open dialogue on CRM supply chains and the procurement of military technology between transatlantic partners is necessary to reduce supply risks in a concerted manner.

73 European Commission, "Conflict Minerals Regulation," 2017, https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation_en.

74 European Commission, "Proposal for a Directive on Corporate Sustainability Due Diligence and Amending Directive (EU) 2019/1937," 2022, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX-%3A52022PC0071.

75 Ministerie van Buitenlandse Zaken, "OESO-richtlijnen" (Ministerie van Buitenlandse Zaken, December 8, 2014), https://www.oesorichtlijnen.nl/documenten/brochure/201/12/8/volledige-tekst-oeso-richtlijnen.

76 "Brief van de Minister voor Buitenlandse Handel en Ontwikkelingsamenwerking: Mensenrechten in het buitenlands beleid," 2022, https://www.eerstekamer.nl/nonav/behandeling/20220401/brief_regering_reactie_op_de_2/document3/f=/vlskg63ro4yp.pdf.

77 Pavel and Tzimas, "Raw Materials in the European Defence Industry," 2016, 69–72.

78 "International Traffic in Arms Regulations - ITAR," MIT Office of the Vice President for Research, accessed December 12, 2022, https://research.mit.edu/integrity-and-compliance/export-control/information-documents/export-control-regulations.

Appendix I

List of materials considered in the analysis

1. Aluminum
2. Barium
3. Beryllium
4. Borates
5. Cadmium
6. Chromium
7. Cobalt
8. Copper
9. Dysprosium Gallium
10. Germanium
11. Gold
12. Hafnium
13. Indium
14. Iron/Steel
15. Lanthanum
16. Lead
17. Lithium
18. Manganese
19. Molybdenum
20. Graphite
21. Neodymium
22. Nickel
23. Niobium
24. Platinum
25. Praseodymium
26. Samarium
27. Selenium
28. Silicon Metal
29. Silver
30. Tantalum
31. Tellurium
32. Terbium
33. Thorium
34. Tin
35. Titanium
36. Tungsten
37. Vanadium
38. Yttrium
39. Zinc
40. Zirconia

List of defence applications considered in the report

1. Aircraft (fighter, transport, maritime patrol and unmanned)
2. Helicopter (combat and multi-role)
3. Aircraft and helicopter carrier
4. Amphibious assault ship
5. Corvettes
6. Offshore patrol vessels
7. Frigates
8. Submarine
9. Torpedoes
10. Main battle tank
11. Infantry Fighter vehicle
12. Armoured personnel carrier
13. Self-propelled artillery
14. Towed Artillery
15. Ammunition
16. Assault rifle
17. Missiles

Appendix II
Security of Supply risks

Main global suppliers of CRM

For materials Dysprosium -> Hafnium, the source is the EU.[79] For materials Molybdenum -> Lead, the sources are USGS Mineral Commodity Summaries 2022 for each material.[80] Unit of measurement for the latter is thousand ton unless otherwise specified.

Table 4. Largest global producers of the critical materials used in low-carbon energy technologies

	Supply chain stage	Top 3 global producers					
Dysprosium	Processing	China	86%	Australia	6%	USA	2%
Yttrium	Processing						
Terbium	Processing						
Lanthanum	Processing						
Praseodymium	Processing						
Neodymium	Processing						
Niobium	Processing	Brazil	92.38%	Canada	6.16%		
Germanium	Processing	China	76.07%	Finland	14.53%	Russia	4.27%
Borates	Mine production	Turkey	39.67%	USA	23.13%	Chile	13.05%
Beryllium	Mine production	USA	90.22%	China	7.63%		
Platinum	Mine production	South Africa	71.86%	Russia	12.95%	Zimbabwe	7.17%
Cobalt	Mine production	DRC	53.55%	China	7.29%	Canada	6.30%
Graphite	Mine production	China	69%	India	12%	Brazil	8%
Indium	Processing	China	56.79%	S. Korea	13.85%	Japan	9.70%
Vanadium	Processing	China	52.30%	South Africa	26.79%	Russia	18.37%
Lithium	Processing	Chile	37.46%	Australia	32.60%	China	13.35%
Tungsten	Processing	China	82.78%	Russia	3.60%	Canada	3.50%

79 European Commission, "Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability."

80 U.S. Department of Interior, "Mineral Commodity Summaries 2022" (Reston VA: U.S. Geological Survey, January 2022), https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf.

Table 4. Largest global producers of the critical materials used in low-carbon energy technologies (continued)

	Supply chain stage	Top 3 global producers					
Tantalum	Mine production	Rwanda	46.14%	DRC	19.85%	Brazil	15.05%
Titanium	Processing	Australia	15.87%	South Africa	14.88%	China	14.62%
Gallium	Processing	China	63.29%	Ukraine	13.92%	Japan	10.13%
Silicon Metal	Mine production	China	70.58%	Russia	6.82%	Brazil	4.59%
Hafnium	Mine production	France	46.88%	USA	46.88%	Ukraine	3.13%
Molybdenum	Mine production	China	38.73%	USA	23.28%	Chile	14.85%
Manganese	Mine production	South Africa	24.07%	China	20.67%	Australia	17.85%
Tin	Mine production	China	43.64%	Indonesia	27.82%	Peru	6.93%
Chromium	Mine production	South Africa	45.16%	Kazakhstan	15.11%	Turkey	14.04%
Zirconium	Mine production	Australia	46.95%	South Africa	15.53%	China	10.83%
Silver	Mine production	Mexico	22.39%	Peru	14.12%	China	14.11%
Aluminium	Smelter production	China	46.13%	Russia	6.85%	Canada	6.21%
Tellurium	Mine production	China	58.62%	Japan	12.93%	Russia	12.06%
Nickel	Mine production	Indonesia	32.73%	Philippines	12.38%	Australia	9.19%
Iron/steel	Mine production	China	30.51%	Australia	12.68%	Brazil	14.72%
Selenium	Mine production	Germany	31.06%	Japan	9.76%	Belgium	8.87%
Zinc	Mine production	China	37.72%	Australia	11.27%	Peru	9.99%
Cadmium	Refinery production	China	32.13%	South Korea	17.92%	Japan	8.36%
Gold		China	15.04%	Australia	9.42%	USA	8.08%
Copper	Refinery production	Chile	31.96%	China	8.85%	Peru	7.61%
Lead	Mine production	China	53.48%	Australia	12,68%	USA	6.06%
Barium	Mine production	China	42.15%	India	11.98%	Morocco	9.70%
Samarium	Mine production	China	86%	Australia	6%	USA	2%
Thorium	Mine production	India	81.57%	Malaysia	9.06%	Vietnam	5.57%

Materials' analysis for probability indicator

Table 5. Analysis of probability indicator

Materials		Dysprosium	Yttrium	Terbium	Lanthanum	Praseodymium	Neodymium
Application Domain		**Air**	**Air, Land**	**Air, Land**	**Air**	**Air**	**Air, Land**
Short-term supply security	Supplier diversity	China 86%, Australia 6%, USA 2% The deposit and mining of REE elements take place primarily in China in the Bayan Obo deposit in Inner Mongolia, which accounts for 70% of REE production in China. Outside of China, the Mount Weld Central Lanthanide Deposit in Australia is the largest in the world.[81]					
	Supply chain bottlenecks	Government crackdown on illegal mining of REEs has decreased China's production from 98% to 86%.[82] Further regulation could cause disruption.	China produces Yttrium as a by-product of Iron. The profitability of mines depends on the price of Iron, making the supply of the REE, subjected to demand of Iron	Applications of terbium in EVs, drones, and appliances, will create a bottleneck for terbium due to the scarcity of the REE.[83]	An overproduction of cerium and lanthanum could occur by 2030, due to increased mining of Nd, Pr, Dy, and Tb.[84]	Low-level mine production in the EU makes it vulnerable to supply disruptions and bottlenecks.[85]	The EU is 100% import reliant for Nd due to no mining.[86] Demand is expected to overtake supply by 2050.[87]
		China's monopoly allows it to impose price and supply control mechanisms, such as quotas on domestic production and export reduction.[88]					

81 Jason Mitchell, "Can the West Break China's Stranglehold on Rare Earth Supply Chains? - Dysprosium and Terbium Supply Bottlenecks," Investment Monitor, 2021, https://www.investmentmonitor.ai/sectors/extractive-industries/china-rare-earths-supply-chain-west.

82 Ryan Castilloux, "Spotlight on Dysprosium: Revving up for Rising Demand" (Toronto: Adamas Intelligence, 2018), http://www.adamasintel.com/wp-content/uploads/2018/04/Adamas-Intelligence-Spotlight-on-Dysprosium-April_2018.pdf.

83 Jason Mitchell, "Can the West Break China's Stranglehold on Rare Earths Supply Chains?," *Investment Monitor* (blog), July 30, 2021, https://www.investmentmonitor.ai/sectors/extractive-industries/china-rare-earths-supply-chain-west.

84 Mitchell, "Can the West Break China's Stranglehold on Rare Earth Supply Chains? - Dysprosium and Terbium Supply Bottlenecks."

85 Darina Blagoeva et al., "Assessment of Potential Bottlenecks along the Materials Supply Chain for the Future Deployment of Low-Carbon Energy and Transport Technologies in the EU," JRC Science for Policy Report (Luxembourg: Publications Office of the European Union, 2016), 78, https://publications.jrc.ec.europa.eu/repository/handle/JRC103778.

86 Luca Ciacci et al., "Recovering the 'New Twin': Analysis of Secondary Neodymium Sources and Recycling Potentials in Europe," *Resources, Conservation and Recycling* 142 (March 2019): 143–52, https://doi.org/10.1016/j.resconrec.2018.11.024.

87 Chen and Zheng, "What Happens after the Rare Earth Crisis."

88 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

Materials		Dysprosium	Yttrium	Terbium	Lanthanum	Praseodymium	Neodymium
Long-term supply security	Worldwide reserves (thousand tonnes)	120,000					
	Future global supply	China's dominance in REE mining is expected to continue. Projects are developing in Australia, Greenland, Canada, and Namibia and are in an advanced stage.[89]	Technology to recycle Yttrium from electronic waste is still in the early stages.[90] Nonetheless, there are opportunities in Canada, Greenland, Australia, Brazil, and South Africa to diversify supply.[91]	Projects in Greenland and Sweden are being developed for REE mining. The Balnkans and Finland could also have potential for REE mining.[92]	Recycle mining of end-of-life products is possible but inefficient, as few REEs are recovered, the process is expensive, complex, and polluting.[93]		Reuse and recycling technologies of Neodymium are still in their early conceptual stages.[94]
Geopolitical challenges	Stability	China: 66.9/120 Australia: 22.7/120 USA: 46.6/120					
	Reliability	China: low Australia: high US: high					
	Geopolitical problems between Europe and suppliers	China's reliance on trade protectionism has allowed them to develop the capacity to manipulate the supply chain of REE. This generates a volatile and uncertain market where Chinese companies stand to benefit and where tensions with countries are exploited due to their reliance on Beijing for these REEs.[95]					

89 Castilloux, "Spotlight on Dysprosium: Revving up for Rising Demand."

90 Mordor Intelligence LLP, "Global Yttrium Market - China's Quasi-Monopoly Is Being Disrupted" (Hyderabad, India: Mordor Intelligence LLP, 2016).

91 Kuangyuan Zhang, Andrew N. Kleit, and Antonio Nieto, "An Economics Strategy for Criticality – Application to Rare Earth Element Yttrium in New Lighting Technology and Its Sustainable Availability," *Renewable and Sustainable Energy Reviews* 77 (September 2017): 902, https://doi.org/10.1016/j.rser.2016.12.127.

92 Patricia Alves Dias et al., *The Role of Rare Earth Elements in Wind Energy and Electric Mobility: An Analysis of Future Supply/Demand Balances* (LU: Publications Office of the European Union, 2020), https://data.europa.eu/doi/10.2760/303258.

93 Linda Omodara et al., "Recycling and Substitution of Light Rare Earth Elements, Cerium, Lanthanum, Neodymium, and Praseodymium from End-of-Life Applications - A Review," *Journal of Cleaner Production* 236 (November 2019): 117573, https://doi.org/10.1016/j.jclepro.2019.07.048.

94 Ciacci et al., "Recovering the 'New Twin.'"

95 Chen and Zheng, "What Happens after the Rare Earth Crisis," 21.

Materials		Niobium	Germanium	Borates	Beryllium	Platinum	Cobalt
Application Domain		**Air, Sea**	**Air, Land**	**Air, Land**	**Air, Land**	**Air, Sea, Land**	**Air, Land, Space**
Short-term supply security	Supplier diversity	Brazil 92.38% Canada 6.16% Other countries 1.46%	China 76.07% Finland 14.53% Russia 4.27%	Turkey 39.67% USA 23.13% Chile 13.05%	USA 90.22% China 7.63% Other Countries 2.15%	South Africa 71.86% Russia 12.95% Zimbabwe 7.17%	D.R. Congo 53.55% China 7.29% Canada 6.30%
	Supply chain bottlenecks	Due to the high geographical concentration of production in Brazil, risks exist in relation to security of supply.[96]	The Russian invasion of Ukraine has affected the supply chain and caused disruptions.[97]	Turkey and USA control the market for borates, which could create complications in the supply chain.[98]	Due to China's unwillingness to report its beryl production, the share of US world production is unknown. This lack of transparency could mean that other players strongly influence the supply chain of beryllium, which could create disruptions.[99]	Degrading ore grades, a phenomenon which has afflicted South African mines throughout their lifetime, can cause supply chain bottlenecks. 18% of mined platinum is mined as co-production, as co-products of nickel in Russia.[100]	The instability of the leading supplier increases the risk of supply chain disruption. Reliance on DRC for mining and on China for refining means a disruption would impact the global market for cobalt.[101]
Long-term supply security	Worldwide reserves (thousand tonnes)	> 4300	N.A.	210,000	N.A.	66 (all PGM)	7200
	Future global supply	Extraction of Nb from electronic waste is considered effective through the use of Urban mining.[102]	N.A.	New production centres are being built in Latin America, more specifically in Argentina, Bolivia, Chile, and Peru.[103]	Scientists are trying to discover how and where beryllium is located on the Earth's crust to address future demand. Recycling of this material is also being investigated for the same reason.[104] Russia is also planning to resume mining and construction of a processing plant for beryllium[105]	Improving the end of life collection and recycling processes for platinum can address future supply risks.[106]	Investment and time is required to diversify the current list of suppliers. There is potential for a cobalt vein in Chile.[107]

96 Duncan A. R. Mackay and George J. Simandl, "Geology, Market and Supply Chain of Niobium and Tantalum—a Review," *Mineralium Deposita* 49, no. 8 (December 2014): 1028, https://doi.org/10.1007/s00126-014-0551-2.

97 Sharon E. Burke, "Russia Is a Mineral Powerhouse — and Its War with Ukraine Could Affect Global Supplies - The Boston Globe," BostonGlobe.com, September 3, 2022, https://www.bostonglobe.com/2022/03/09/opinion/russia-is-mineral-powerhouse-its-war-with-ukraine-could-affect-global-supplies/.

98 Birol Elevli, Irem Yaman, and Bertrand Laratte, "Estimation of the Turkish Boron Exportation to Europe," *Mining*, no. 2 (2022): 156, https://doi.org/10.3390/mining2020009.

99 Graham W. Lederer et al., "Beryllium—A Critical Mineral Commodity—Resources, Production, and Supply Chain," Fact Sheet, Fact Sheet (U.S. Geological Survey, 2016).

100 Kasper Dalgas Rasmussen et al., "Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis," *Environmental Science & Technology* 53, no. 19 (October 1, 2019): 11541–51, https://doi.org/10.1021/acs.est.9b01912.

101 Susan van den Brink et al., "Identifying Supply Risks by Mapping the Cobalt Supply Chain," *Resources, Conservation and Recycling* 156 (May 2020): 6, https://doi.org/10.1016/j.resconrec.2020.104743.

102 Witold Kurylak, "Innovation Potential in the Recovery of Refractory Metals from Urban Mines" (MSP-REFRAM, 2016).

103 Steven B Carpenter and Robert B Kistler, "Boron and Borates," in *Industrial Minerals & Rocks: Commodities, Markets, and Uses*, 7th ed. (Littleton, CO: Society for Mining, Metallurgy, and Exploration, 206AD), 276.

104 Lederer et al., "Beryllium—A Critical Mineral Commodity—Resources, Production, and Supply Chain."

105 Lederer et al.

106 Rasmussen et al., "Platinum Demand and Potential Bottlenecks in the Global Green Transition."

107 Brian Townley, Alejandro Diaz, and Rodrigo Luca, "Exploration and Mining Potential for Cobalt Mineral Resources in Chile" (Comite CORFO, 2017), https://www.corfo.cl/sites/Satellite?blobcol=urldata&blobkey=id&blobtable=MungoBlobs&blobwhere=1475166637554&ssbinary=true.

Materials		**Niobium**	**Germanium**	**Borates**	**Beryllium**	**Platinum**	**Cobalt**
Application Domain		**Air, Sea**	**Air, Land**	**Air, Land**	**Air, Land**	**Air, Sea, Land**	**Air, Land, Space**
Geopolitical challenges	Stability	Brazil 73.9/120 Canada 20.1/120	China 66.9/120 Finland 15.1/120 Russia 72.6/120	Turkey 78.1/120 USA 46.6/120 Chile 43.2/120	USA 46.6/120 China 66.9/120	South Africa 72.0/120 Russia 72.6/120 Zimbabwe 97.8/120	D.R. Congo 107.3/120 China 66.9/120 Canada 20.1/120
	Reliability	Brazil: middle Canada: high	China: low Finland: high Russia: low	Turkey: middle USA: high Chile: high	USA: high China: low	South Africa: middle Russia: low Zimbabwe: low	D.R. Congo: low China: low Canada: high
	Geopolitical problems between Europe and suppliers	Due to Brazil's dominant production share of Nb, they have price-setting power. Canada is a crucial supplier of the US for commercial and defence purposes, which impacts the relations between Canada and the US/EU.[108]	Germanium is an essential component of electronic circuits and microchips used in consumer products and also in military technology. China dominates the supply of germanium which makes critical infrastructure subject to potential import restrictions.[109]	The positive trend between Turkish and EU relations has halted.[110]	The EU imports Beryllium from stable countries, which lowers the geopolitical risk. Nonetheless, they heavily rely on a single country for the supply of beryllium, making them subject to supply shocks.[111]	The largest platinum reserves are in Southern Africa, where instability and resource nationalism is growing. Union militancy and upheaval due to inequalities can generate geopolitical challenges.[112]	The market stability of Cobalt is dependent on copper and nickel mines, which are mostly owned by China, which increases the geopolitical risk.[113]

108 Talal Omar and Marcello M. Veiga, "Is Niobium Critical for Canada?," *The Extractive Industries and Society* 8, no. 2 (June 2021): 100898, https://doi.org/10.1016/j.exis.2021.100898.

109 David Criekemans, *The Geopolitics of Renewable Energy: Different or Similar to the Geopolitics of Conventional Energy?* (Antwerpen: Garant, 2006).

110 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

111 Eskinder D. Gemechu et al., "Import-Based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments," *Journal of Industrial Ecology* 20, no. 1 (2016): 154–65, https://doi.org/10.1111/jiec.12279.

112 Stoddard, "Analysis."

113 Gavin D Harper, "The Geopolitics of Cobalt," *American Affairs* 5, no. 4 (2021), https://americanaffairsjournal.org/2021/11/the-geopolitics-of-cobalt/.

Materials		**Graphite**	**Indium**	**Vanadium**	**Lithium**	**Tungsten**	**Tantalum**
Application Domain		**Air, Sea**	**Air, Sea, Land, Space**	**Air, Land**	**Air, Sea, Space**	**Air, Sea, Land**	**Air, Land**
Short-term supply security	Supplier diversity	China (69%) India (12%) Brazil (8%)[114]	China 56.79% Republic of Korea 13.85% Japan 9.70%	China 52.30% South Africa 26.79% Russia 18.37%	Chile 37.46% Australia 32.60% China 13.35%	China 82.78% Russia 3.60% Canada 3.50%	Rwanda 46.14% D.R. Congo 19.85% Brazil 15.05%
	Supply chain bottlenecks	High energy prices can limit the production of graphite. Graphite production is unfriendly to the environment and not all graphite can be used for industry.[115]	The high-cost of Indium mining discourages governments and companies to exploit the abundance of the material on the Earth's crust.[116]	The supply chain of vanadium is subject to high price volatility. Also, vanadium is mined as a by-product of steel, making supply driven by demand for steel rather than vanadium. The supply stream is also prone to disruptions, as 10 mills which make up 75% of the global production are located in China and Russia, causing price volatility.[117]	There is diverse stock and, therefore low risk in the provision of lithium.	Along with, tin, tantalum, and gold, tungsten is associated with human rights abuses.[118]	The tantalum supply chain has been prone to incidents such as theft, missing containers, logistical issues, and conflict minerals entering the market. Despite these disruptions, supply of tantalum is regarded as resilient.[119]
Long-term supply security	Worldwide reserves (thousand tonnes)	320,000	N.A.	15,000	13,500	3,300	>100
	Future global supply	By exploring graphite reserves in Europe, Latin America, and Africa, supply could be diversified.[120] Finance, know-how, and sustainable production processes are all obstacles to this.	Sites in Canada and Australia represent opportunities for diversification of supply.[121]	The demand of vanadium is highly linked to steel as it is utilized as an additive.[122]	Continued development of recycling technology will be crucial for the supply security of lithium in the future.[123]	New mines are operating in Spain, Portugal, and South Korea, with other ones being present in the DRC and Rwanda which have issues with ESG.[124]	Tantalum projects are being explored in Canada, Colombia, Egypt, Madagascar, Namibia, Saudi Arabia, Sierra Leone, South Africa, Tanzania, Venezuela, and Zimbabwe. Reserves are expected to meet future demand.[125]

114 Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

115 Amrish Ritoe, Irina Patrahau, and Michel Rademaker, "Graphite: Supply Chain Challenges & Recommendations for a Critical Mineral" (The Hague: The Hague Centre for Strategic Studies, 2022), 19, https://hcss.nl/wp-content/uploads/2022/03/Graphite-Challenges-and-Recommendations-HCSS-2022.pdf.

116 T Werner, G. M. Mudd, and S. M. Jowitt, "Indium: Key Issues in Assessment Mineral Resources and Long-Term Supply from Recycling," *Transactions of the Institutions of Mining and Metallurgy, Section B: Applied Earth Science*, 2015, 5.

117 Kara Rodby et al., "Materials Availability and Supply Chain Considerations for Vanadium in Grid-Scale Redox Flow Batteries," preprint (Chemistry, June 14, 2022), https://doi.org/10.26434/chemrxiv-2022-tnpsv.

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119 Nabeel A. Mancheri et al., "Resilience in the Tantalum Supply Chain," *Resources, Conservation and Recycling* 129 (February 2018): 56–69, https://doi.org/10.1016/j.resconrec.2017.10.018.

120 Ritoe, Patrahau, and Rademaker, "Graphite: Supply Chain Challenges & Recommendations for a Critical Mineral," 2022.

121 Werner, Mudd, and Jowitt, "Indium: Key Issues in Assessment Mineral Resources and Long-Term Supply from Recycling."

122 Rorie Gilligan and Aleksandar N. Nikoloski, "The Extraction of Vanadium from Titanomagnetites and Other Sources," *Minerals Engineering* 146 (January 2020): 106106, https://doi.org/10.1016/j.mineng.2019.106106.

123 Patrahau et al., "Securing Critical Materials for Critical Sectors: Policy Options for the Netherlands and the European Union."

124 Amanda Stutt, "Diversifying the Tungsten Supply Chain," Mining, 2020, https://www.mining.com/diversifying-the-tungsten-supply-chain/.

125 Mancheri et al., "Resilience in the Tantalum Supply Chain."

Materials		**Graphite**	**Indium**	**Vanadium**	**Lithium**	**Tungsten**	**Tantalum**
Application Domain		**Air, Sea**	**Air, Sea, Land, Space**	**Air, Land**	**Air, Sea, Space**	**Air, Sea, Land**	**Air, Land**
Geopolitical challenges	Stability	China 66.9/120 India: 75.3/120 Brazil: 73.9/120	China 66.9/120 Republic of Korea 32.7/120 Japan 31.0/120	China 66.9/120 South Africa 72.0/120 Russia 72.6/120	Chile 43.2/120 Australia 22.7/120 China 66.9/120	China 66.9/120 Russia 72.6/120 Canada 20.1/120	Rwanda 83.7/120 D.R. Congo 107.3/120 Brazil 73.9/120
	Reliability	China: low India: middle Brazil: middle	China: low Republic of Korea: high Japan: high	China: low South Africa: middle Russia: low	Chile: high Australia: high China: low	China: low Russia: low Canada: high	Rwanda: low D.R. Congo: low Brazil: middle
	Geopolitical problems between Europe and suppliers	Europe's minimal market share of graphite makes it highly dependent on Chinese mines. Moreover, graphite mining sites are located in unreliable countries affected by internal issues such as corruption.[126]	Dependency on China is inevitable as recycling indium is not enough to meet demand.[127]	Uncertainty in the supply chain exists because of concentrated production and reliance on co-production. The EU has adopted a reusing and recycling system to mitigate geopolitical risk and reduce waste.[128]	Due to increasing demand, there is competition to secure supply and monopolise production.[129]	Legal frameworks adopted by the US and the EU have targeted funds flowing into militia groups in the DRC. Private companies play a major role in the transparency of Tungsten mining.[130]	Tantalum is produced in countries with relatively high political instability, threatening the risk of disruptions in the supply chain.[131]

[126] Clare Church and Alec Crawford, "Minerals and the Metals for the Energy Transition: Exploring the Conflict Implications for Mineral-Rich, Fragile States," in *The Geopolitics of the Global Energy Transition*, vol. 73 (Springer Open, n.d.), 288.

[127] Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

[128] Andrea Ashley-Oyewole, "Endangered Element Vanadium: Can the Texas Oil and Gas Sector Provide It a Sustainable Future?," *International Journal of Applied Science and Technology* 11, no. 1 (2021): 1–8, https://doi.org/doi:10.30845/ijast.v11n1p1.

[129] Rademaker, Patrahau, and van Geuns, "Scenariostudie Kernenergie."

[130] Elif Härkönen, "Conflict Minerals in the Corporate Supply Chain: Is Transparency the Solution to Human Rights Violations in the Tantalum, Tin, Tungsten and Gold Supply Chains?," *European Business Law Review* 29, no. 5 (2018): 691–727.

[131] Anitha Sivaramakrishnan, "Risk Assessment of the Availability of Tantalum and Niobium," n.d., 29.

Materials		**Titanium**	**Gallium**	**Silicon Metal**	**Hafnium**	**Molybdenum**	**Manganese**
Application Domain		**Air, Sea, Land, Space**	**Air, Land, Space**	**Air**	**Air, Land**	**Air, Sea, Land**	**Air, Sea, Land**
Short-term supply security	Supplier diversity	Australia 15.87% South Africa 14.88% China 14.62%	China 63.29% Ukraine 13.92% Japan 10.13%	China 70.58%[132] Russia 6.82% Brazil 4.59%[133]	France 46.88% USA 46.88% Ukraine 3.13%	China 38.73% USA 23.28% Chile 14.85%	South Africa 24.07% China 20.67% Australia 17.85%
	Supply chain bottlenecks	The War in Ukraine has caused prices of Titanium to skyrocket, also due to the dependency on Russia and China.[134]	The War in Ukraine has had a tremendous impact on the supply of gallium. Ukraine is an actor in the export of the material, and the decrease in supply has led to price increases and shortages.[135]	Industry competition over silicon remains a risk in the supply chain.[136]	One potential issue in the supply chain is that hafnium is a by-product of zirconium, and the demand for the former is driven by the demand for the latter. Hafnium is also highly concentrated in France and the US.[137]	China and the US dominate the supply chain for molybdenum. Nonetheless, the rest of the supply chain is diversified across different countries.[138]	Producers are quite widespread despite the dominance of certain countries in the market for manganese. Nonetheless, short-term supply disruptions are not expected.[139]
Long-term supply security	Worldwide reserves (thousand tonnes)	Ilmenite (720,000) Rutile (47,000)	N.A.	N.A.	N.A.	11,000	570,000,000
	Future global supply	Potential reserves located in Kazakhstan, Mozambique, and Vietnam.	Gallium is a vital element for the production of semiconductors. The market for gallium is expected to grow as a result of advanced technologies and also due to its use in the renewable energy industry.[140]	High dependency on China. Nonetheless, vast inventory and distribution worldwide which make the risk in the future supply chain relatively low.[141]	The demand for hafnium is expected to grow due to its properties and their use in advanced technologies. Projects in Australia are currently under development.[142]	Demand for molybdenum is expected to grow steadily due to the growing use of high-performance steels.[143]	Along with nickel and graphite, manganese is a vital element for the production of batteries. Supply is expected to keep up with demand despite the increase in demand for batteries.[144]

132 Emily K. Schnebele, “Silicon” (U.S. Geological Survey, January 2022).

133 Rademaker, Patrahau, and van Geuns, “Scenariostudie Kernenergie.”

134 Jennifer Creery, Eri Sugiura, and Hudson Lockett, “Japan’s Titanium Makers Expected to Gain More US Business from Ukraine War,” *Financial Times*, April 10, 2022, https://www.ft.com/content/c8a3d527-0348-498f-b31c-9a12d978e03c.

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137 Raymond Moss et al., “Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies” (LU: Publications Office of the European Union, 2011).

138 Moss et al.

139 Elsa A. Olivetti et al., “Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals,” *Joule* 1, no. 2 (October 11, 2017): 229–43, https://doi.org/10.1016/j.joule.2017.08.019.

140 Shane Lesley, “A Little Gallium Makes High-Tech Techier,” North of 60 Mining News, December 23, 2020, https://www.miningnewsnorth.com/story/2020/12/31/critical-minerals-alaska-2020/a-little-gallium-makes-high-tech-techier/6491.html.

141 Elsa A. Olivetti et al., “Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals,” *Joule* 1, no. 2 (October 2017): 229–43, https://doi.org/10.1016/j.joule.2017.08.019.

142 Tim Highley, “Hafnium: You’ve Never Seen It, but Your Future Depends on It,” *Alkane Resources Ltd* (blog), September 29, 2017, https://www.alkane.com.au/hafnium-youve-never-seen-future-depends/.

143 Moss et al., “Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies.”

144 Olivetti et al., “Lithium-Ion Battery Supply Chain Considerations,” October 11, 2017.

Materials		**Titanium**	**Gallium**	**Silicon Metal**	**Hafnium**	**Molybdenum**	**Manganese**
Application Domain		**Air, Sea, Land, Space**	**Air, Land, Space**	**Air**	**Air, Land**	**Air, Sea, Land**	**Air, Sea, Land**
Geopolitical challenges	Stability	Australia 22.7/120 South Africa 72.0/120 China 66.9/120	China 66.9/120 Ukraine 68.6/120 Japan 31.0/120	China 66.9/120 Russia 72.6/120 Brazil 73.9/120	France 30.9/120 USA 46.6/120 Ukraine 68.6/120	China 66.9/120 USA 46.6/120 Chile 43.2/120	South Africa 72.0/120 China 66.9/120 Australia 22.7/120
	Reliability	Australia: high South Africa: middle China: low	China: low Ukraine: middle Japan: high	China: low Russia: low Brazil: middle	France: high USA: high Ukraine: middle	China: low USA: high Chile: high	South Africa: middle China: low Australia: high
	Geopolitical problems between Europe and suppliers	Russia's role in the titanium supply chain has generated fear and increased prices of the material, which is important for the manufacturing of jet engines. Reluctancy to support Russia's economy and avoiding further escalation has shrunk the market for titanium.[145]	The poor substitutability and low recycling rate of molybdenum increase the level of import dependency and susceptibility to supply risks.[146]	Supply disruptions could cause tensions between producers and end-product manufacturers due to China's monopoly on extraction.[147] The high concentration of the value chain in China increases vulnerability to geopolitical risk.	The EU is a net exporter of Hafnium and thus does not face major geopolitical risks. Hafnium.[148] Therefore, there are minimal geopolitical risks associated with the material.	The poor substitutability and low recycling rate of molybdenum increase the level of import dependency and susceptibility to supply risks.[149]	The unequal distribution of manganese reserves between countries and the high levels of EU reliance on imports to sustain supply threatens the security of the material.[150]

145 Thompson, "Supply Chains"; "Titanium Supply Threatened by Ukraine Conflict."

146 Shiwei Yu, Haoran Duan, and Jinhua Cheng, "An Evaluation of the Supply Risk for China's Strategic Metallic Mineral Resources," *Resources Policy* 70 (March 1, 2021): 101891, https://doi.org/10.1016/j.resourpol.2020.101891.

147 M. D. Udayakumar et al., "The Impact of Advanced Technological Developments on Solar Pv Value Chain," *Materials Today: Proceedings* 45 (2021): 2053–58.

148 Oliver Wright, David E. Bond, and Matt Solomon, "Quest to Bolster Critical Mineral Supply Will Persist through Economic Downturn | White & Case LLP," September 22, 2022, https://www.whitecase.com/insight-our-thinking/mining-metals-2022-quest-bolster-critical-mineral-supply.

149 Yu, Duan, and Cheng, "An Evaluation of the Supply Risk for China's Strategic Metallic Mineral Resources."

150 "A New World: The Geopolitics of the Energy Transformation" (International Renewable Energy Agency, 2019); "Manganese," Professional Paper, Professional Paper (U.S. Geological Survey, 2017).

Materials		**Tin**	**Chromium**	**Zirconium**	**Silver**	**Aluminium**	**Tellurium**
Application		**Air**	**Air, Sea, Land**	**Air, Sea**	**Air, Sea, Land, Space**	**Air, Sea, Land**	**Air, Land**
Short-term supply security	Supplier diversity	China 43.64% Indonesia 27.82% Peru 6.93%	South Africa 45.16% Kazakhstan 15.11% Turkey 14.04%	Australia 46.95% South Africa 15.53% China 10.83%	Mexico 22.39% Peru 14.12% China 14.11%	China 46.13% Russia 6.85% Canada 6.21%	China 58.62%[151] Japan 12.93% Russia 12.06% (excl. US production)
	Supply chain bottlenecks	High supply concentration in the hands of countries that have adopted restrictive trade policies in the past can cause tin supply disruptions. [152]	Russia's large market share of chromium is subject to disruptions due to the invasion of Ukraine.[153]	China controls 95% of the global production for Zirconium Oxychloride, which is the material used for downstream manufacturing for commercial products and also naval vessels.[154]	The majority of silver is produced as a by-product of copper, lead, and zinc. Therefore, most of the supply is dependent on the production of other metals, which increases the potential for disruptions. Furthermore, the primary three producers have internal issues which can also impact the flow of supply. [155]	Concerns over environmental standards in the industry could affect supply.[156] Also, Indonesia's export embargo, expected to be fully in action by 2022, and Malaysia's policy to also ban exports of aluminium will cause disruptions.[157]	The growing application of Tellurium and the high costs of expanding production makes the supply chain prone to bottlenecks due to risks in the market. [158]

151 Schuyler C. Anderson, "TELLURIUM" (U.S. Geological Survey, January 2022).

152 Moss et al., "Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies."

153 Greg Brown, "The Mother of All Supply Chain Shocks," *Kenaninstitute.Unc.Edu* (blog), accessed November 2, 2022, https://kenaninstitute.unc.edu/commentary/the-mother-of-all-supply-chain-shocks/.

154 Tom Wilson, "Zirconium and Establishing a Domestic Rare Earths Supply Chain," InvestorIntel, August 26, 2020, https://investorintel.com/markets/technology-metals/technology-metals-intel/zirconiums-role-in-establishing-a-rare-earths-supply-chain/.

155 Moss et al., "Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies."

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158 Moss et al., "Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies."

Materials		**Tin**	**Chromium**	**Zirconium**	**Silver**	**Aluminium**	**Tellurium**
Application		**Air**	**Air, Sea, Land**	**Air, Sea**	**Air, Sea, Land, Space**	**Air, Sea, Land**	**Air, Land**
Long-term supply security	Worldwide reserves (thousand tonnes)	4800	>480,000	78,000 (Zirconium Dioxide equivalent(	530	28,000,000	31,000 (tonnes)[159]
	Future global supply	Despite supply being concentrated in the largest three producers, Australia has immense potential for tin mining, with 90 deposits across the country.[160]	Projects in South Africa, Nigeria, and Oman are underway to develop new mines that produce chromium.[161]	High demand for zirconium and the limited supply is expected to drive prices up in the short term.[162]	New projects for silver mining are underway in Canada and in the United States.[163]	As many countries are phasing out bauxite production, the availability of the resource could be threatened.	There are concerns regarding the supply of tellurium and whether its production (mined as a by-product of copper) can sustain the growing demand for tellurium. Higher efficiency in tellurium extraction is necessary for the future market.[164]

159 Anderson, "TELLURIUM."

160 Matthew Hall, "What Does the Future Look like for Australian Tin?," *Mining Technology* (blog), September 2, 2020, https://www.mining-technology.com/analysis/what-does-the-future-look-like-for-australian-tin/.

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164 Richard Goldfarb, "Tellurium —The Bright Future of Solar Energy," Fact Sheet, Fact Sheet (U.S. Geological Survey, 2015).

Materials		Tin	Chromium	Zirconium	Silver	Aluminium	Tellurium
Application		**Air**	**Air, Sea, Land**	**Air, Sea**	**Air, Sea, Land, Space**	**Air, Sea, Land**	**Air, Land**
Geopolitical challenges	Stability	China 66.9/120 Indonesia 66.6/120 Peru 69.8/120	South Africa 72.0/120 Kazakhstan 59.5/120 Turkey 78.1/120	Australia 22.7/120 South Africa 72.0/120 China 66.9/120	Mexico 70.3/120 Peru 69.8/120 China 66.9/120	China 66.9/120 Russia 72.6/120 Canada 20.1/120	China 66.9/120 Japan 31.0/120 Russia 72.6/120
	Reliability	China: low Indonesia: middle Peru: middle	South Africa: middle Kazakhstan: low Turkey: middle	Australia: high South Africa: middle China: low	Mexico: middle Peru: middle China: low	China: low Russia: low Canada: high	China: low Japan: high Russia: low
	Geopolitical problems between Europe and suppliers	Most tin deposits are found in countries with sub-standard human rights records. European countries must comply with legislation to ensure that the tin used in their industries is sourced ethically.[165]	The supply risk of lead is considered to be minimal by the EU defence industry.[166]	China controls 95% of Zirconium Oxychloride production, which is the starting material required for manufacturing naval vessels, including nuclear-powered ones.[167] Reliance on Chinese production for this critical materialhighlights key vulnerabilities in the defence industry.	Due to the environmental risks associated with silver mining, government crackdowns on sites that do not respect guidelines could affect the supply chain.[168]	Chinese production of aluminium threatens American production capacity.[169] The US also views import dependency from China as a matter of national security, due to the applications of the material, which range from technology to military.	Tellurium is indirectly mined and is a by-product of copper and iron. The main risk associated with the element is whether demand can be addressed considering that copper mining occurs in relatively unstable countries.[170]

165 Geopolitical Monitor, "Conflict Minerals and Global Supply Chains."

166 Silvia Bobba et al., *Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study*, 2020, https://doi.org/10.2873/58081.

167 Wilson, "Zirconium and Establishing a Domestic Rare Earths Supply Chain."

168 Haddaway et al., "Evidence of the Impacts of Metal Mining and the Effectiveness of Mining Mitigation Measures on Social–Ecological Systems in Arctic and Boreal Regions."

169 "The Effects of Imports of Aluminum on the National Security."

170 "Tellurium - The Bright Future of Solar Energy," Fact Sheet, Fact Sheet (U.S. Geological Survey, 2015).

Materials		Nickel	Iron/Steel	Selenium	Zinc	Cadmium	Gold
Application Domain		**Air, Sea, Land**	**Air, Sea, Land**	**Air**	**Air, Land**	**Air, Land**	**Air, Sea**
Short-term supply security	Supplier diversity	Indonesia 32.73% Philippines 12.38% Australia 9.19%	China 30.51% Australia 12.68% Brazil 14.72%	Germany 31.06% Japan 9.76% Belgium 8.87%	China 37.72% Australia 11.27% Peru 9.99%	China 32.13% Republic of Korea 17.92% Japan 8.36%	China 15.04% Australia 9.42% USA 8.08 %
	Supply chain bottlenecks	The high concentration of nickel supply in Indonesia is a potential for disruptions in the supply chain due to the restrictive policies adopted by the government to protect domestic production. [171]	High concentration of the supply chain in China exposes import countries to potential disruptions in the case of trade barriers. Also, environmental concerns over the production of iron could spur government legislation to impose restrictions on unsustainable methods.[172]	Despite Germany and Japan dominating the production, the high concentration in these two countries could still give rise to potential bottlenecks and disruptions in the supply chain. [173]	The invasion of Ukraine has impacted the zinc market due to high energy prices, leading to market shocks in the near future. As a result, zinc production has slowed down in Europe.[174]	Cadmium has been subject to Chinese tariffs, resulting in supply shortages for industries that use the element. While efforts to circumvent these restrictions were made by certain countries, the supply chain is still subject to shortages.[175]	The supply chain for gold has some production that comes from illicit mining.[176]
Long-term supply security	Worldwide reserves (thousand tonnes)	81,000	87,000,000	120	230,000	660	55
	Future global supply	Demand for nickel is expected to overtake supply in the coming years, giving rise to new opportunities for investors to establish new sources for nickel. Increased adoption of EV will require nickel to produce batteries.[177]	The future market for iron is expected to grow due to its application in green energy sources such as solar panels.[178]	Selenium is considered a "technology metal", an essential material for electronic applications. An increase in the demand for selenium is expected in the future.[179]	The future outlook of the zinc market could experience scarcity as a result of increased metal prices.[180]	Cadmium has grown in importance for the production of solar panels. With growing investments in green energy sources, demand for cadmium is expected to grow.[181]	Mining operations have become more diverse and less geographically concentrated in South Africa. New mine discoveries, however are increasingly rare.[182]

171 Moss et al., "Critical Metals in Strategic Energy Technologies - Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies."

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Materials		**Nickel**	**Iron/Steel**	**Selenium**	**Zinc**	**Cadmium**	**Gold**
Application Domain		**Air, Sea, Land**	**Air, Sea, Land**	**Air**	**Air, Land**	**Air, Land**	**Air, Sea**
Geopolitical challenges	Stability	Indonesia 66.6/120 Philippines 80.5/120 Australia 22.7/120	China 66.9/120 Australia 22.7/120 Brazil 73.9/120	Germany 23.6/120 Japan 31.0/120 Belgium 31.9/120	China 66.9/120 Australia 22.7/120 Peru 69.8/120	China 66.9/120 Republic of Korea 32.7/120 Japan 31.0/120	China 66.9/120 Australia 22.7/120 USA 46.6/120
	Reliability	Indonesia: middle Philippines: middle Australia: high	China: low Australia: high Brazil: middle	Germany: high Japan: high Belgium: high	China: low Australia: high Peru: middle	China: low Republic of Korea: high Japan: high	China: low Australia: high USA: high
	Geopolitical problems between Europe and suppliers	Indonesia is the largest nickel producer and has imposed various policies in the early 2010s to restrict exports causing the sudden interruption of resources.[183]	The steel industry has been subject to tariffs by the US government and the EU to protect domestic producers.[184] Tariffs can escalate and drive the costs of production higher.	The supply of selenium is affected by the supply of copper and (to a lesser extent) nickel, as it is a by-product.[185] Copper mining takes place in unstable countries.	The Russian invasion of Ukraine has slowed down zinc production as the region is responsible for 1/5 of refined zinc.[186]	The supply risk of lead is considered to be low by the EU defence industry.[187]	The supply of gold is considered to be minimal by the EU defence industry.[188]

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188 Bobba et al.

Materials		**Copper**	**Lead**	**Barium**	**Samarium**	**Thorium**
Application Domain		**Air, Sea, Land**	**Air, Sea**	**Air, Sea**	**Air, Sea**	**Air, Land**
Short-term supply security	Supplier diversity	Chile 31.96% China 8.85% Peru 7.61 %	China 53.48% Australia 12.68% USA 6.06%	China 42.15% India 11.98% Morocco 9.70%	China 86% Australia 6% USA 2%	India 81.57% Malaysia 9.06% Vietnam 5.57%
	Supply chain bottlenecks	Water shortages in South America and Sub-Saharan Africa, where the largest reserves of copper are located are reducing extraction.[189] Environmental concerns over the damage of mining to locals is also a concern in Peru.[190]	There are minimal supply chain disruptions associated with lead.[191]	Lead is being replaced by substitutes in the electronics industry.[192] Nonetheless, it remains an important component in the production of EV batteries.[193]	Samarium is a REE, and as such, China is the dominant world producer. This exposes countries to supply chain vulnerabilities as a result of potential trade restrictions.[194]	The high concentration of thorium production in India creates potential bottlenecks in the supply chain.
Long-term supply security	Worldwide reserves (thousand tonnes)	700,000	87,000	350,000	2,498 tonnes	N.A.
	Future global supply	Despite new copper resources discovered in the DRC and in Indonesia, shortages in supply are still a possibility in the coming future.[195]	Lead is being replaced by substitutes in the electronics industry.[196] Nonetheless, it remains an important component in the production of EV batteries.[197]	The market for barium was heavily impacted by COVID-19 but is expected to grow and recover in the coming years.[198]	Demand for samarium is expected to increase due to their importance for the production of magnets and the lack of substitutes.[199]	Thorium could be used in next-generation nuclear reactors, which would increase the size of the market and compete with uranium as fuel.[200]

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Materials		**Copper**	**Lead**	**Barium**	**Samarium**	**Thorium**
Application Domain		**Air, Sea, Land**	**Air, Sea**	**Air, Sea**	**Air, Sea**	**Air, Land**
Geopolitical challenges	Stability	Chile 43.2/120 China 66.9/120 Peru 69.8/120	China 66.9/120 Australia 22.7/120 USA 46.6/120	China 66.9/120 India 75.3/120 Morocco 70.1/120	China: 68.9/120 Australia: 22.7/120 USA: 46.6/120	India 75.3/120 Malaysia 56.4/120 Vietnam 60.9/120
	Reliability	Chile: high China: low Peru: middle	China: low Australia: high USA: high	China: low India: middle Morocco: middle	China: low Australia: high USA: high	India: middle Malaysia: middle Vietnam: middle
	Geopolitical problems between Europe and suppliers	The supply of copper is abundant however it is affected by political instability in mining countries. China has also been purchasing mines in Latin American countries to strengthen its position in the supply chain.[201]	Despite high production of Lead by China, the supply risk of lead is considered to be minimal by the EU defence industry.[202]	Naturally occurring barytes are subject to EU REACH regulations.[203] However, barium levels in water, food, and soil have not been enough to warrant a health concern. Risks to the supply chain are minimal, according to the EU.[204]	Dependency on China for the supply of Samarium makes it subject to disruption and vulnerabilities.[205]	

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