Critical Raw Materials and European Defence

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Contents

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A general view of a pit in Tenke Fungurume Mine, one of the largest copper and cobalt mines in the world, owned by Chinese company CMOC, Democratic Republic of the Congo, 17 June 2023. (Photo by Emmet Livingstone/AFP via Getty Images)

Executive Summary

Security of supply issues are of growing concern for defence policymakers. This relates to components, platforms and munitions, but also to the raw materials that are used in manufacturing processes. In recent years, NATO and the European Union have released lists of the raw materials they deem critical, both for defence purposes as well as for broader industrial and technological resilience, as have several European nations.

NATO has stated that the availability and secure supply of these critical materials is important for 'NATO's technological edge and operational readiness'. These concerns are not new, but they have been exacerbated by geopolitics, technology-modernisation imperatives and initiatives across Europe to pursue energy-transition plans.

Western states' potential adversaries have, in some cases, a near-monopoly on the supply of vital materials that either are used in current defence platforms or are necessary to power European digital and industrial development and energy-transition ambitions. This is a result of economic and political choices taken by Western states. Mines and processing facilities, for instance, were closed as cheaper alternatives were sourced abroad and as environmental concerns strengthened at home.

The COVID-19 pandemic served as a reminder of the effects of supply-chain disruptions on key industries, but changes in the geopolitical environment are sharpening these concerns, raising the prospect that raw-materials supplies could be restricted or cut off. Indeed, studies conducted by Western governments, international organisations and think tanks in recent years have highlighted Western countries' level of dependence on external suppliers for some defence-critical materials, such as gallium, tungsten and titanium. China's use of export controls on critical materials has served to heighten concerns further.

Responses to these issues have taken different forms. Governments concerned by supply-chain risk are examining strategies such as diversifying sources of supply, stockpiling, recycling and strengthening domestic production capabilities to reduce overdependence and mitigate demand and pricing shocks. One task is to define what materials are critical, and why, and to assess where points of vulnerability exist. Publishing lists helps place materials security on the political agenda and can be useful in setting targets for industry and politicians. Legislation can also be beneficial. The EU's Critical Raw Materials Act pushes governments and industry to identify strategic-raw-materials dependencies and assess vulnerability to supply disruptions. Likewise, other agreements and legislation across Europe increasingly contain provisions relating to critical-materials security of supply.

Other 'defensive' measures now being pursued include investing in extraction and processing facilities. However, this may lead to some difficult choices, including over environmental, social and governance rules and ways of financially supporting business and industry. Another strategy is to build new overseas partnerships and diversify existing partnerships. While such 'raw materials diplomacy', and friend-shoring more broadly, may help mitigate risk, they bring with them additional trust concerns.

Stockpiling critical materials and components is also being considered. While it would require careful management, in a crisis stockpiling could not only allow support to be provided relatively quickly but also give industry the time to spool-up or restart production. Governments and industry can also pursue materials substitution and recycling measures to reduce supply-chain risk, though substitution can be difficult because of the unique properties of materials and the cost of investing in alternatives. Recycling equipment to harvest components and materials is still an evolving field, not only because of the complexity of extracting materials but also due to cost. However, there are a number of European firms now active in the 'circular economy'.

As concern mounts in Europe over the deteriorating security environment, it seems likely that there will be greater impulse to improve the security of supply of defence-relevant critical materials. Notably, this process as well as European states' energy-transition initiatives and funding could generate useful spinoffs for defence purposes, and vice versa; after all, many critical raw materials are common to both sectors.

Introduction

On 11 December 2024, NATO released a list of 12 raw materials that it determined were 'integral to the manufacture of advanced defence systems and equipment'.[1] In doing so, the Alliance joined the European Union and individual EU and NATO members that have drawn attention to the importance of raw materials in the production and operation of modern defence equipment, and have expressed concerns over supply due to the origin of these materials.

The geopolitical environment is sharpening these concerns. European states are looking to rebuild their defence capabilities, driven by worries over Russia's military aggression in Ukraine and Moscow's future military posture and, most recently, by uncertainties over the trajectory of transatlantic relations. They have placed significant orders for defence equipment, fuelled by defence-spending increases since 2014 and particularly after February 2022. Many of these equipment platforms, and the sensors, systems and weapons they contain, incorporate in their construction and components a range of raw, processed and semi-finished materials that may enable high performance but also embed security-of-supply risks.

As NATO said in its December announcement, 'the availability and secure supply of these materials are vital to maintaining NATO's technological edge and operational readiness'.[2] These concerns are not new, but they are exacerbated by geopolitics, technology modernisation and initiatives across Europe to pursue energy-transformation plans. While investments stemming from industrial development or energy-transition plans could have beneficial spin-offs for defence, growing demand means there is also greater chance of competition for the same raw materials. In launching its 2024 Critical Raw Materials Act, the EU said that the union's 'demand for rare earth metals is expected to increase six-fold by 2030 and seven-fold by 2050, for lithium, EU demand is expected to increase twelve-fold by 2030 and twenty-one-fold by 2050'.[3]

Significantly, many materials commonly used in defence applications presently do not originate from the European continent, or even from the territories of European allies and partners. Western states' potential adversaries have, in some cases, a near-monopoly on the supply of vital materials that either are used in current defence platforms or are necessary to power European digital and industrial development and energy-transition ambitions. This is a result of economic and political choices taken by Western states. Mines, refineries and processing facilities, for instance, were closed as cheaper alternatives were sourced abroad and as environmental concerns strengthened at home.

China and Russia are important sources of critical raw materials and China has, in recent decades, also invested heavily abroad in mines in third countries. As such, China holds an important place in the global supply not only of upstream raw materials but also of processed product that is mined elsewhere. For some materials, it holds a virtual monopoly. For instance, in 2021, the United States government noted that gallium and iridium – used in defence applications such as radars and sensors – were primarily sourced from China, and in 2023, the US Aerospace Industries Association said the country had 'a 100% net reliance' on gallium, with China noted as the primary source and producer. The latter report continued by observing that 'no domestic primary (low-purity, unrefined) gallium has been recovered since 1987'.[4]

Tungsten serves as another example of Western dependency on China. It is used in multiple defence applications, with properties including its hardness, strength and heat resistance making it important in the production of engine components and warheads, among other uses.[5] The high-quality, high-performance tungsten needed in defence applications is mainly produced in China, which has the largest share of global production, at around 83% in 2020.[6] There are some initiatives underway to redress this imbalance in Europe. One project for tungsten extraction in Spain is projecting initial production in 2027 with the eventual aspiration to meet up to 20% of the EU's tungsten demand, while in the United Kingdom, there are hopes to restart tungsten extraction at a site in Devon.[7] Cobalt, meanwhile, is another mineral in focus due to China's significant role in its production. It is used as a superalloy base in applications including combat-aircraft-propulsion systems, and in electric motors and batteries. It is primarily extracted in the Democratic Republic of the Congo (DRC), with reports indicating that a number of large mines producing cobalt are Chinese-owned.[8] Concerns have likewise been raised about Chinese firms' pursuit of lithium resources, with these minerals deemed important due to electric-battery expansion plans worldwide as well as, for China, the country's own electrification plans.[9]

Western governments have expressed similar worries regarding reliance on China for rare-earth elements (REEs). In 2020, the EU estimated that China provided 62% of the world's primary production of REEs and noted in 2024 that China 'provides 100% of the EU's supply of heavy rare earth elements'.[10] Some of these materials present a credible risk of supply-chain disruption, which could restrict the pace of civil and military technology development and production.[11] Furthermore, demand for these materials is rising rapidly. In 2023, the EU estimated that its requirement for REEs would grow by 2,666% by 2050.[12] As a measure of the importance of these materials to defence applications, the US Department of Defense has noted their use in several platforms, including the F-35 *Lightning* II combat aircraft, which it says requires the equivalent of more than 400 kilograms of REEs.[13] One use is in permanent magnets, such as neodymium–iron–boron and samarium–cobalt magnets, which are used in military components exposed to high temperatures and pressure differentials.[14] However, it is debatable whether REEs are actually that rare. There are known deposits in Western states and others are now being identified, but as China has in recent decades built a position of dominance in REE supply, building up alternate sources will take time and significant investment.[15]

Europe's high dependence on external supplies, and particularly on critical raw materials that are highly concentrated, often in one location, represents a significant and growing risk for European defence manufacturing. Disruption can stem from several factors. The COVID-19 pandemic saw interruptions to upstream production and downstream distribution, while attacks by Ansarullah (Houthis) on shipping in the Red Sea are a more recent cause of disruption.

Geopolitics also has an impact, with the use of export controls recently gaining attention. China has used its near monopoly on some raw materials for political and economic purposes.[16] In July 2023, it imposed export controls on gallium and germanium in response to Washington's export restrictions on segments of the semiconductor supply chain.[17] In December 2023, China restricted the export of graphite.[18] Then, in December 2024, Beijing tightened its approach further, halting exports to the US of gallium, germanium and antimony, and also requiring greater scrutiny of the end-usage of graphite items.[19] China had earlier, in August 2024, restricted the export of antimony, used in military applications including armour-piercing ammunition. While these restrictions largely target the US, they could affect European states that operate or have contracted US-origin defence supplies and components utilising such materials. These restrictions followed the announcement of changes to China's export-control regime, which introduced greater monitoring of dual-use materials.

Titanium is another potential target for similar measures, and another area of raw-materials dependence for Europe, with Russia remaining a key source of aerospace-relevant titanium. Its properties make it difficult to source substitutes, especially when it comes to durable, strong and light-weight components needed for many military applications, such as structural components for aircraft and missile systems.[20] In late 2024, Russian President Vladimir Putin threatened to limit Russia's export of strategic materials, referencing uranium, nickel and titanium.[21]

With continuing tension between Russia and European states, and the strained relationship between China and the US, there is potential for Europe's technology and energy transformation and defence-industrial plans to be further affected by restrictions and shortages of materials.[22] Growing pressures in the transatlantic relationship add another complication. To gauge the effect of these factors on Europe's defence sector, researchers from the International Institute for Strategic Studies (IISS) have studied the use of these materials in modern defence equipment in service in European inventories, using as examples the equipment illustrated below. Although some materials are specific to the equipment shown, many of the listed components and materials can be found in a variety of other defence equipment.

Table 1: Critical raw materials

NATO defence-critical raw-materials list	EU critical-raw-materials list	Largest global producer, average 2016–20 share of global production	EU import reliance
	Antimony	China, 52%*	47%*
	Arsenic	China, 44%***	39%***
	Baryte	China, 32%***	74%***
Aluminium	**Bauxite (alumina/aluminium)**	China, 56% (aluminium)*	58% (aluminium)*
Beryllium	Beryllium	US, 50%*	100%*
	Bismuth	China, 69%***	71%***
	Boron – metallurgy grade	Turkiye, 45% (borates)*	72%*
Cobalt	**Cobalt**	DRC, 63%***	81%**
	Coking coal	China, 69%*	0%*
	Copper	China, 38%*	17%*
	Feldspar	Turkiye, 32%***	54%***
	Fluorspar	China, 56%***	60%***
Gallium	**Gallium**	China, 94%***	98%***
Germanium	**Germanium**	China, 83%*	42%*
Graphite	**Graphite – battery grade**	China, 67% (natural graphite)**	99%**
	Hafnium	France, 49%***	0%***
	Helium	US, 56%***	100%***
Lithium	**Lithium – battery grade**	China, 56%*	100%*
	Magnesium	China, 91%***	100%***
Manganese	**Manganese – battery grade**	China, 58%*	66%*
	Nickel – battery grade	China, 33%*	75%*
	Niobium	Brazil, 89%*	100%*
	Phosphorus	China, 78%***	100%***
Platinum	**Platinum-group metals**	South Africa, 94% (iridium/ruthenium/osmium)***	100% (iridium, from primary sources)*** 100% (ruthenium, from primary sources)*** n.k. (osmium)
		Russia, 40% (palladium)***	8% (palladium)*
		South Africa, 71% (platinum)***	30% (platinum)*
		South Africa, 81% (rhodium)***	n.k. (rhodium)
REEs	**REEs for permanent magnets (Ce, Dy, Gd, Nd, Pr, Sm and Tb);** heavy and light REEs	China, 68% (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Y and Yb)***	100% (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Y and Yb)***
	Scandium	China, 67%***	100%***
	Silicon metal	China, 77%***	64%***
	Strontium	Iran, 37%***	0%***
	Tantalum	DRC, 35%**	99%**
Titanium	**Titanium metal**	China, 43% (titanium metal)***	100% (titanium metal)***
Tungsten	**Tungsten**	China, 86%*	80%*
	Vanadium	China, 62%*	100%*

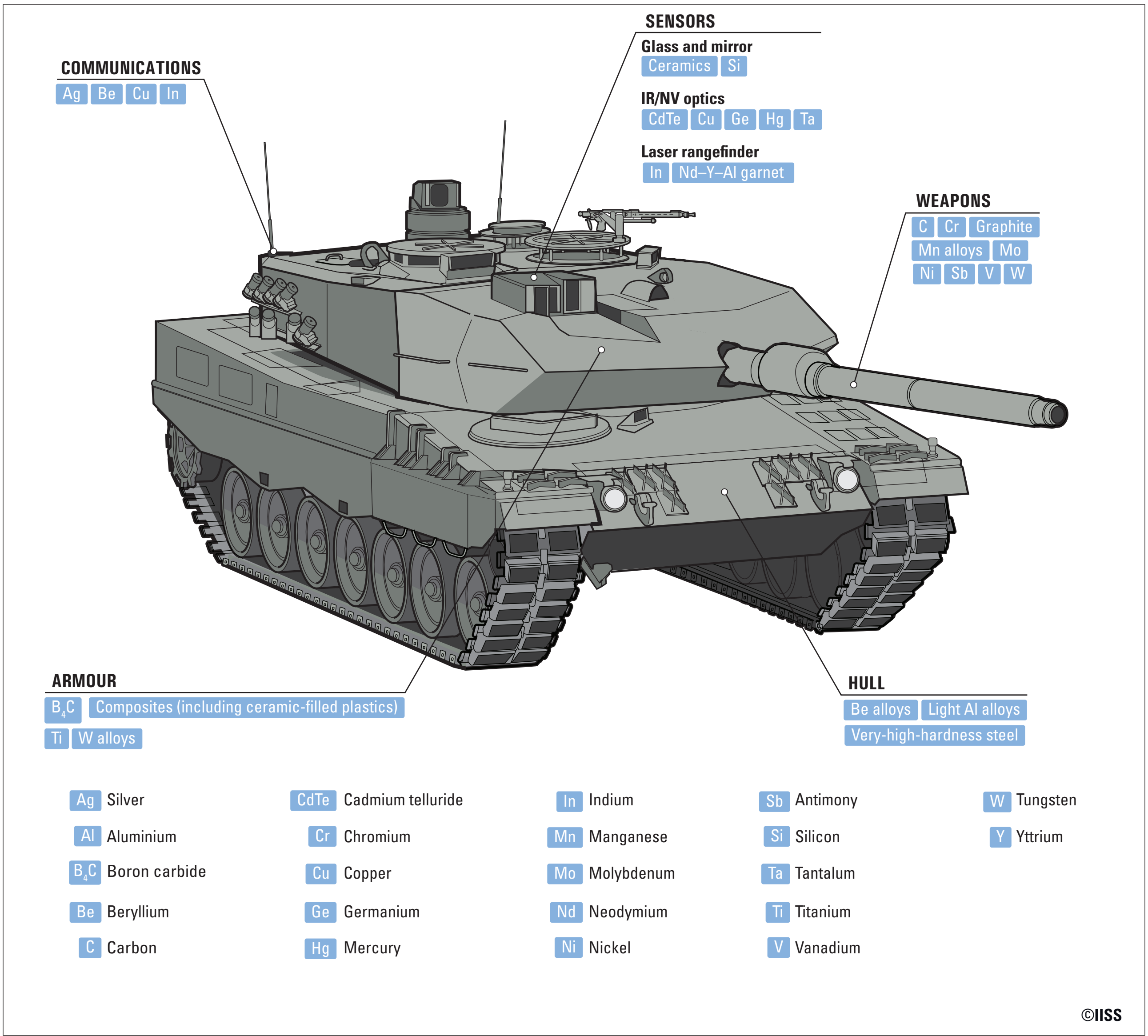
Ce	Cerium	Eu	Europium	La	Lanthanum	Pr	Praseodymium	Tm	Thulium
Dy	Dysprosium	Gd	Gadolinium	Lu	Lutetium	Sm	Samarium	Y	Yttrium
Er	Erbium	Ho	Holmium	Nd	Neodymium	Tb	Terbium	Yb	Ytterbium

*Processing stage. **Extraction stage. ***Unspecified whether processing or extraction stage. **Bold** = EU strategic raw materials
Sources: NATO, https://www.NATO.int; European Commission, https://commission.europa.eu/index_en; SCREEN, https://scrreen.eu/

1. Land Sector

The capability of a modern main battle tank (MBT) is now judged by both the sophistication of its sensors and optronics as well as traditional metrics such as firepower, protection and mobility. In this regard, better sensors offer improved battlefield awareness, which means the crew has the potential to extend target detection, recognition and identification ranges. Sensors are increasingly complex and rely on a range of critical materials. The basic glass and mirrors utilise silicon and ceramics, while infrared (IR) and night-vision (NV) sights – which are key enablers in low-visibility environments – can contain mercury, cadmium telluride, germanium, copper and tantalum. Laser rangefinders and muzzle reference sensors are common features of modern tanks, serving to accelerate the generation of firing solutions once a target is visually identified. These

Figure 1: **Components and raw materials used in an MBT or infantry fighting vehicle**



Note: The application of materials shown is illustrative and not exhaustive. Some materials will be used in multiple places on armoured vehicles, including carbon, copper and very-high-hardness steel.
Source: IISS analysis

can utilise neodymium–yttrium–aluminium garnet and indium and erbium.[23] Neodymium and yttrium are REEs, with yttrium 94% sourced from China, according to the US Geological Survey.[24]

Communications systems are seen as a key discriminator in modern battlefield conditions, especially as some NATO members look to move towards implementing multi-domain operational concepts, making efforts to deliver more rapid and secure communications more important. Moreover, being able to share accurate information between different units is vital for efficient command and control and tactical success. Radios and battlefield-management systems are vital components of an MBT's communication capabilities, and these high-technology systems utilise copper and other critical materials such as gallium arsenide, gallium nitride, beryllium, silicon, silver and indium.

The main gun armament of Western MBTs is typically a large-calibre smoothbore or rifled cannon, utilising a range of munitions including armour-piercing and high-explosive rounds. The relative balance of these munitions is dependent, in part, on the role intended for the tank. The barrel's key properties include high-tensile strength to resist deformation under the high pressure of repeated firing. Special materials are also used to mitigate uneven heating and in damping vibrations from repeated firing, although the effect of this on sighting is also corrected by muzzle reference sensors. The barrel's design often incorporates a liner, made from a wear-resistant material, to further extend its lifespan and maintain accuracy.[25] Important critical materials utilised in tank armament include antimony, carbon, manganese alloys, chromium, nickel, molybdenum and vanadium.

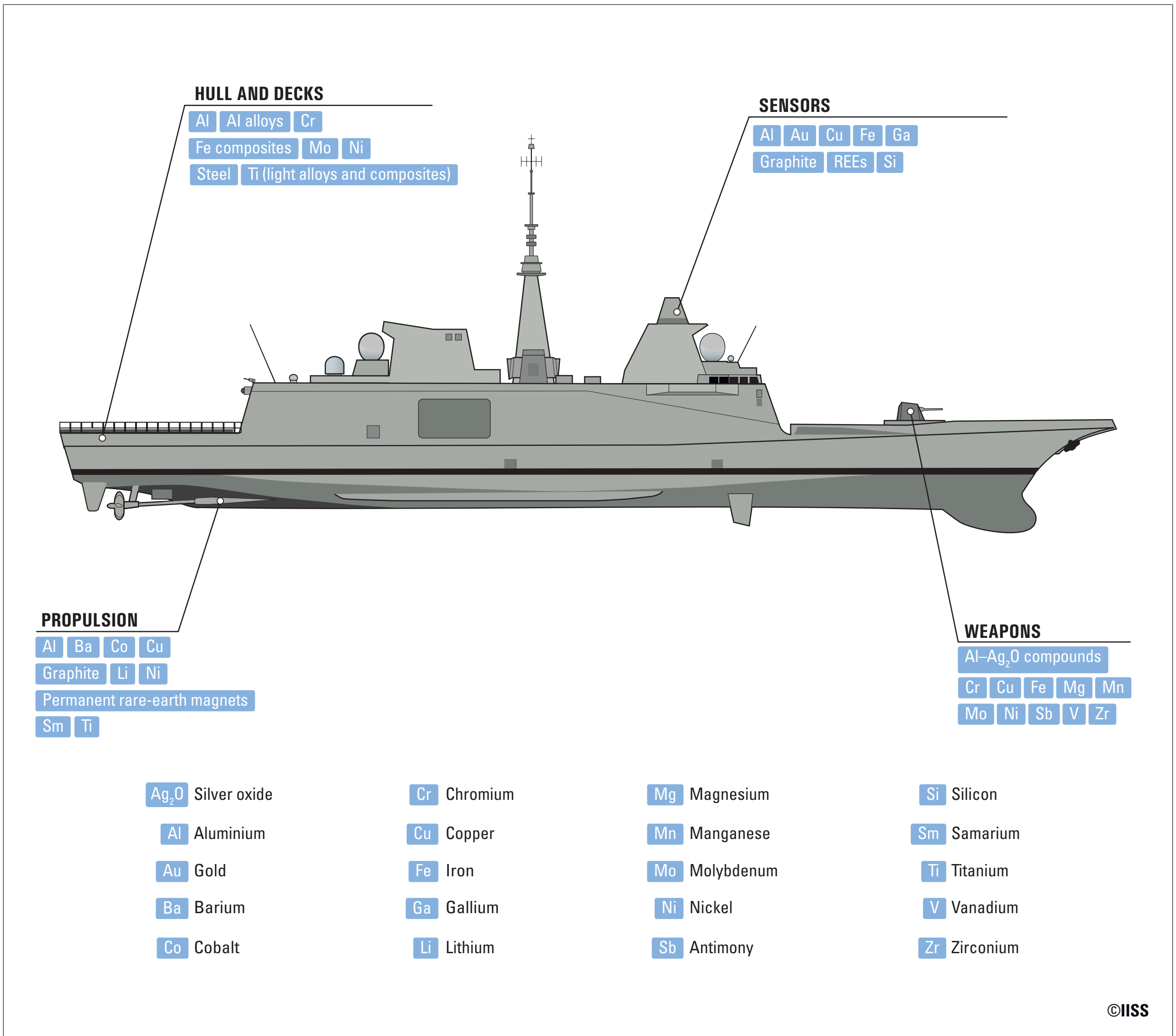
The hull is the backbone of the vehicle, designed to support and protect critical systems under battlefield conditions. Crafted from high-strength steel and advanced alloys, tank hulls are built to absorb and distribute the forces generated during combat, intended to ensure stability and survivability. Beryllium alloys, light aluminium alloys and very-high-hardness steel are employed in hull construction. Tank armour, meanwhile, is increasing in sophistication as a passive protection system, even as parallel advances take place in the development and integration of active protection systems. Comprised of a high strength-to-weight ratio combination of tungsten alloys, composite materials and other elements, MBT armour is designed to absorb and dissipate the energy from incoming projectiles, including explosive projectiles and kinetic-energy penetrators. It often features layers of spaced or sloped plating to increase its effectiveness and utilises not only high-strength steels but also composites (including ceramic-filled plastics), tungsten alloys, titanium and boron carbide.[26]

2. Naval Sector

Modern warships utilise a variety of critical materials in their composition, although the maritime domain uses fewer than the aerospace, land or guided weapons sectors. Nonetheless, there is still a high requirement for many materials deemed to have a moderate supply-chain risk, such as aluminium, iron (and steel), graphite, titanium and copper. Given the naval sector's demand for their high-end principal surface combatants (such as the European Multi-purpose Frigate (FREMM)) to have all-round capabilities geared towards anti-submarine, anti-surface and anti-air warfare tasks, a range of critical materials are needed to support modern warship and system design. The same holds for other naval vessels with similar roles and equipment, and perhaps even more so when it comes to submarine design and construction.

Aluminium is heavily used in shipbuilding, including for decks and elements of the superstructure and

Figure 2: **Components and raw materials used in a principal surface combatant**



Note: The application of materials shown is illustrative and not exhaustive. Some materials will be used in multiple places on maritime platforms.
Source: IISS analysis

in internal compartment components such as piping. It is seen as a replacement in some cases for steel, with its relatively light weight being an important factor. The metal is also used in many of a ship's systems, including radar components, elements of the propulsion system, and naval armaments and housings, such as main guns, torpedoes and missile bodies.[27]

Graphite is utilised in battery technologies as well as in radars and sonars. These system applications, as well as other high-frequency components and optoelectronic devices, also use gallium and gold.[28] Other materials including chromium, cobalt, copper, iron (and steel), nickel and titanium are employed directly or as additives in steels and alloys for use throughout a ship's hull and its decks, including parts of the superstructure and internal compartments, as well as for wiring and fittings.[29]

Titanium, titanium alloys, nickel, chromium, manganese, molybdenum, vanadium and steel are used in equipment such as guns and torpedo tubes and smaller mechanical components such as valves and heat exchangers.[30] Together with cobalt, copper, titanium and nickel, REEs such as samarium can be found in naval propulsion systems, including in diesel engines, gas turbines, thrusters, gearboxes, shafts and propellers.[31] Electric motors that support these propulsion systems, in addition to current and future battery technologies within submarines, are additionally dependent on materials such as lead and lithium. Advanced batteries require copper, graphite, silicon, aluminium, cobalt, manganese and nickel for electrodes, wires and other conductive parts, as well as coatings and packaging.[32]

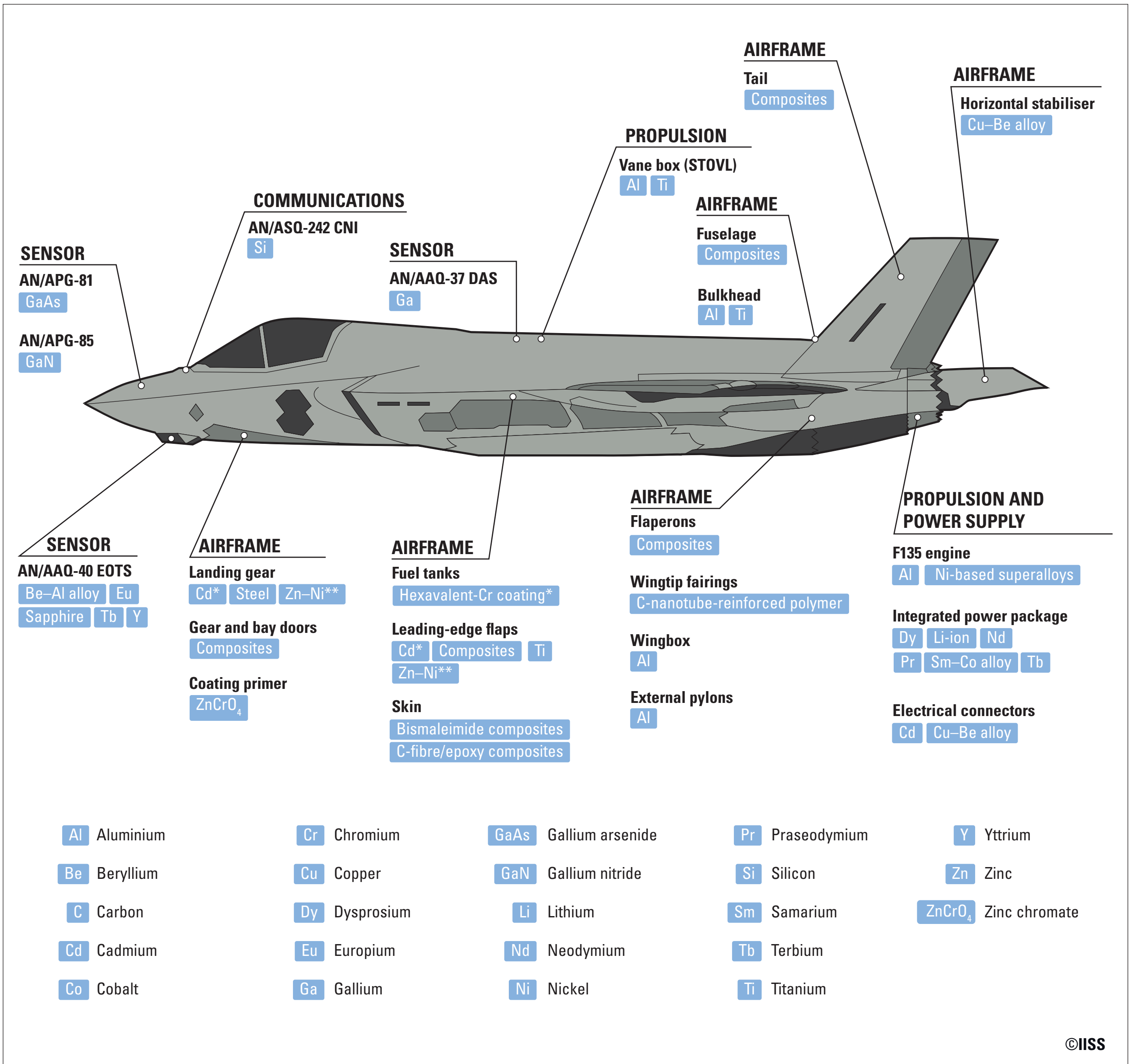
Radars, sonar transducers, jamming devices and targeting systems are among other naval systems that also include critical materials, while IT, communications and combat systems can (as for other domains) additionally contain REEs, including in components such as microchips, data-storage devices, fibre-optic cables, display screens, magnets, optical lenses and lasers. As noted above, US defence authorities have attempted to make these naval dependencies more easily understood by quantifying them, including by stating that an *Arleigh Burke*-class destroyer requires the equivalent of 2.3 tonnes of REEs and a *Virginia*-class submarine the equivalent of some 4 tonnes.[33]

3. Aerospace Sector

As aircraft become more sophisticated and incorporate more low-observable technologies, and sensors and electronics become more advanced, the amount of critical raw materials in aircraft components will likely increase. This is already true for the aircraft often described as the most advanced in active service, the F-35.

The US Congress first raised concerns regarding the large amount of REEs found in a single F-35 aircraft in 2013 (likely referring to the total weight of components with some traces of REEs), and commissioned a report listing all components containing these elements.[34] Since then, the supply of REEs and other critical raw materials for the F-35 has continued to cause concern.

Figure 3: **Components and raw materials used in an advanced combat aircraft**



*Being replaced. **Being introduced.
Note: The application of materials shown is illustrative and not exhaustive. Some materials will be used in multiple places on aerial platforms.
Source: IISS analysis

The F-35's F135 engine contains structures and disks made of titanium and blades and vanes made of single-crystal nickel-based superalloys.[35] The F-35B variant's lift-system vane box, intended to direct air flow and enable short take-off and vertical landing (STOVL), contains aluminium and titanium.[36]

The combined power supply and thermal management system of the F-35 is called the 'integrated power package'. Its key component, the turbomachine, uses magnets that include a cobalt–samarium alloy. In 2022, it was discovered that the materials used in the magnets came from China and further deliveries of the F-35 were temporarily halted. Following an investigation, the Pentagon eventually determined that the materials did not represent a security or flying hazard and deliveries resumed.[37] The integrated power package also incorporates lithium-ion batteries, providing the system with a reserve of emergency power for the aircraft's control surfaces and electrical systems while in-flight.[38] More broadly, magnets for electric motors that have been associated with the F-35 also contain dysprosium, neodymium, praseodymium and terbium.[39]

The centrepiece of the F-35's sensors, the AN/APG-81 active electronically scanned array (AESA) radar, relies on gallium-arsenide components.[40] However, in the future, Block 4 F-35 aircraft are to be equipped with a new AESA radar, the AN/APG-85, which will likely rely instead on gallium-nitride components.[41] The AN/AAQ-37 Distributed Aperture System (DAS), the F-35's situational awareness and missile/aircraft detection/tracking system, may also contain gallium components, owing to the similar manufacturing technique used by Raytheon to manufacture gallium-nitride radars.[42] Like the US, the EU currently relies on China to supply the majority of its gallium.[43] The AN/AAQ-40 Electro-Optical Targeting System (EOTS), a forward-looking IR and long-range IR search and track system, has components including an azimuth gimbal housing unit made of beryllium–aluminium alloy.[44] Materials such as europium, terbium and yttrium have also been linked with the production of laser designators.[45] The entire AN/AAQ-40 system is housed in a sapphire window.[46] The US supplies 60% of the EU's beryllium, while europium, terbium and yttrium are solely supplied by China.[47] The AN/ASQ-242 Communications, Navigation and Identification (CNI) system, meanwhile, combines radio-frequency hardware with computer processors, and likely includes silicon as a key material.[48]

The F-35 airframe is mostly constructed from composites, aluminium and titanium. The fuselage and tail are made from composites, as are the gear and bay doors, flaperons and leading-edge flaps, though the leading-edge flaps also have titanium components.[49] The skin of the airframe is made specifically from bismaleimide and carbon fibre/epoxy composites, while carbon nanotubes are used on the wingtip fairings.[50] The aircraft's bulkheads are made of aluminium and titanium, while its wingbox and external pylons are made of aluminium.[51]

In late 2023, Howmet Aerospace, a major manufacturer of F-35 components, was sued by Lockheed Martin for halting the delivery of titanium components due to pricing issues resulting from a tightening of global titanium supplies after Russia's full-scale invasion of Ukraine.[52] The case was eventually settled out of court but highlighted the importance of pricing in materials supply.[53] In this case, the lack of substitutes exacerbates the risk from fluctuations in demand and pricing.[54]

Electrical connectors, fasteners and structural components contain copper–beryllium alloys, as do horizontal stabiliser assemblies.[55] Until 2024, electrical connectors were also plated with cadmium. The landing gear, made of steel, and the leading-edge flaps are also plated with cadmium, which is being replaced with zinc–nickel plating.[56] Similarly, the F-35 fuel tank was coated with hexavalent chromium until 2024, when it was replaced with a non-chrome coating.[57] However, zinc-chromate primer is still used on the F-35.[58]

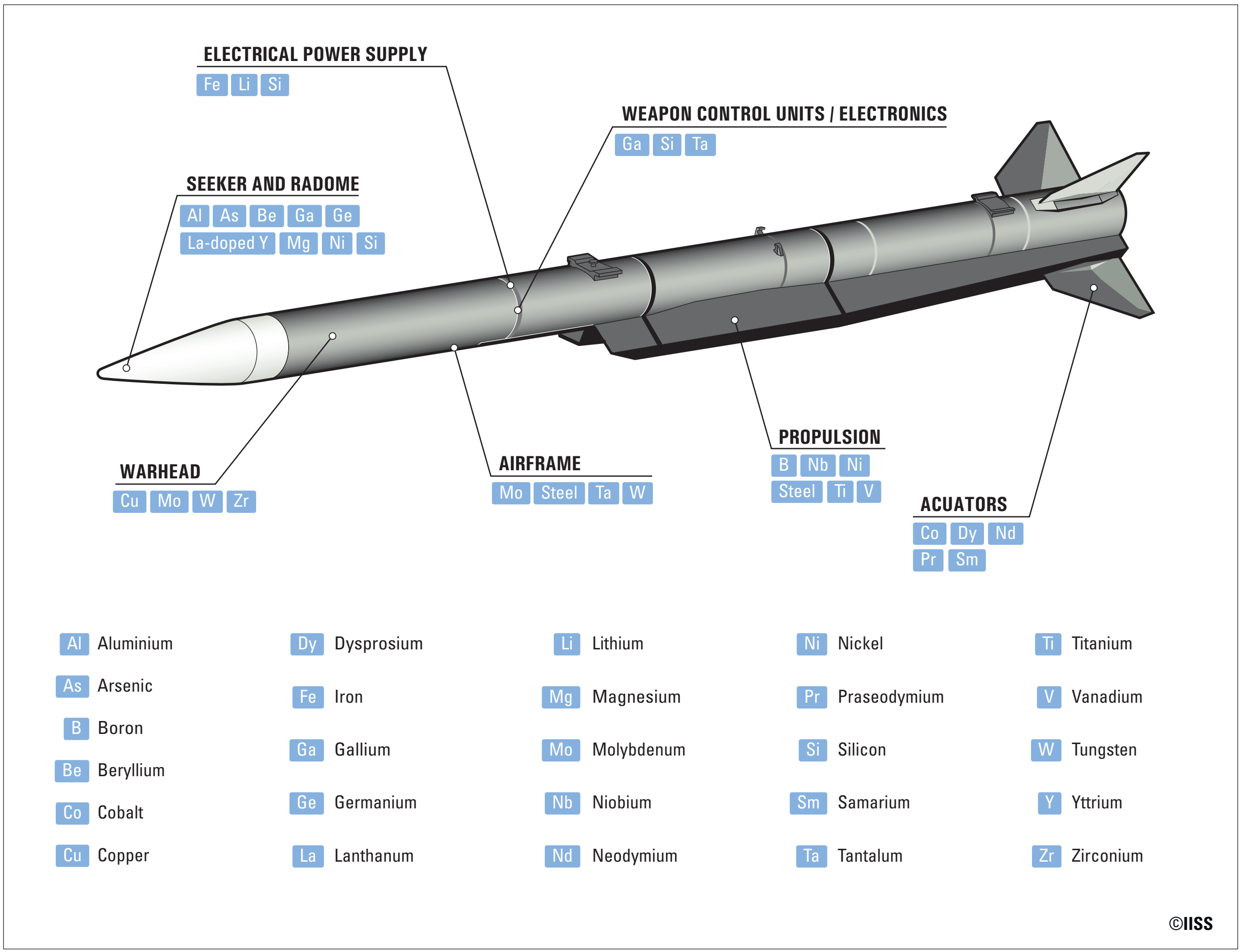
4. Guided-weapons Sector

Modern guided weapons also utilise significant amounts of critical materials. One example is the *Meteor* beyond-visual-range air-to-air missile, developed as part of a joint European project between six partner nations: France, Germany, Italy, Spain, Sweden and the UK.

The *Meteor* uses a derivative of the AD4A (active anti-air) radio-frequency (RF) seeker, jointly developed by Thales and MBDA, during the terminal phase of flight.[59] Missile seekers tend to rely on monolithic microwave integrated circuits to achieve improved performance in comparison to traditional silicon-based electronics.[60] Gallium-arsenide products have been readily used within RF systems since the 1980s. Recently however, gallium-nitride components have replaced these, because of their much-enhanced power density.[61]

The radome behind which the seeker sits utilises ceramic material patented by MBDA Italia and internally known as NIMAS.[62] Expected to be suitable for supersonic and hypersonic operations, the radome consists of between 80–95% silicone nitride and 5–15% magnesium aluminosilicates.[63] Another ceramic material used in anti-air missiles is Corning's Pyroceram 9606.[64] It is predominantly made from magnesium-aluminosilicate glass with titania

Figure 4: **Components and raw materials used in a modern guided weapon**



Note: The application of materials shown is illustrative and not exhaustive. Some materials could be used in multiple places.
Source: IISS analysis

as the nucleating agent.[65] Other missile systems use IR seekers which often contain nickel-plated beryllium mirrors.[66] A variety of materials are used for the windows through which IR seekers receive signals, notably germanium, magnesium, yttria and lanthanum-doped yttria.[67]

Guided weapons tend to use one of three propulsion systems: either an air-breathing ramjet, an air-breathing turbojet or a solid-fuel rocket motor. Many of the structural components that form the airframe of a ramjet are made from high-strength steel.[68] While steel is predominantly made of iron, small quantities of critical minerals such as nickel, niobium, vanadium and titanium are used as alloying elements to enhance structural properties. Titanium is also used to form the intakes through which air enters a ramjet.[69] The *Meteor's* ramjet utilises a gas-generator sub-assembly to produce fuel-rich products. To maximise the available thrust, boron is added to the oxygen-deficient composite propellant used within the gas generator.[70] The fuel-rich products are then mixed with the ducted air within the ramjet combustion chamber. Owing to the high temperatures within a combustion chamber, ramjets often use ceramic thermal barrier coatings (TBCs) to protect metallic elements. Zirconia is a commonly used TBC.[71] Ramjets do not have any rotating components, therefore electrical components must source power from elsewhere within the missile. Lithium-silicon/iron disulfide thermal batteries are often used due to their high energy capacity per unit volume.[72]

Unlike a ramjet, a turbojet possesses both a compressor and turbine and can generate electrical power through the rotation of the engine shaft. For instance, the Safran TR40 turbojet makes use of Inconel 718, a nickel-based superalloy. Small quantities of titanium, silicon, cobalt and other elements are used as alloying elements.[73] Aluminium alloys are common throughout the aerospace and defence sector and are used to make the stator blades of the turbojet compressor.[74] Electrical power is generated by a permanent-magnet-based 270V DC generator. Samarium and cobalt are the most common elements in permanent magnets, however other REEs such as neodymium, dysprosium and terbium are also used.[75]

Along with impact and RF proximity fuses, blast-fragmentation warheads are utilised to increase the chance of target destruction. Typically blast-fragmentation warheads contain a high-energy explosive encased within a high-strength metal fragmentation sleeve, which includes materials such as tungsten and molybdenum.[76] Shaped-charge warheads are used to penetrate armoured targets. Tantalum is often used in the liner of the warhead, though other high-density metals including copper and tungsten have also been used.[77]

5. Possible Policy Responses

The international supply chain for critical materials, as it has developed in recent decades, contains inherent vulnerabilities. One of the first steps in addressing this problem is defining what materials are critical, and why, and assessing where these points of vulnerability are. To this end, several European governments have, in recent years, published critical- or raw-materials strategies, and it is no surprise that the EU and NATO critical-materials lists overlap. European governments will be considering 'defensive' measures, such as investing in extraction and processing facilities, as well as building and diversifying partnerships, in order to mitigate risk.

The generation of official critical-materials lists places materials security on the political agenda and is useful in setting targets for industry as well as politicians. For instance, the EU's 2024 Critical Raw Materials Act:

> sets benchmarks for domestic capacities along the strategic raw material supply chain to be reached by 2030: 10% of the EU's annual needs for extraction; 40% for processing and 25% for recycling. No more than 65% of EU's annual needs of each strategic raw material at any relevant stage of processing should come from a single third country.[78]

The act pushes governments and industry to help identify strategic-raw-materials dependencies and, for industry, to assess its vulnerability to supply disruptions.[79] More broadly, there is also a focus on expanding domestic production in Europe and friendshoring, though the latter still raises important considerations over trust. In the first quarter of 2025, the EU is expected to select and support the first list of strategic projects on raw materials, which also can involve third countries.[80] The September 2024 Draghi report on EU competitiveness proposed a number of initiatives, including the creation of a financial instrument to strengthen supply security and the creation of strategic stockpiles of critical materials.[81] The October 2024 Niinistö report also called for the establishment of an ad hoc EU Stockpiling Strategy.[82] However, the European-level legislation so far lacks the focus on defence seen elsewhere, such as in the 2024 US National Defense Industrial Strategy and the US National Defense Authorization Act for Fiscal Year 2024, as well as in earlier announcements.[83] It also contains little detail similar to that seen in the '100-day' review of US supply chains generated under the administration of former president Joe Biden.[84]

Governments concerned by supply-chain risk are examining strategies such as diversifying sources of supply, stockpiling, recycling and strengthening domestic production capabilities to reduce overdependence and mitigate demand and pricing shocks. New strategic partnerships are being sought abroad and existing ties strengthened as part of what has been termed 'raw materials diplomacy'.[85] European supply risks associated with titanium, for instance, have the potential to be mitigated somewhat through the EU's strategic partnership with Kazakhstan and the memorandum of understanding on a strategic partnership with Greenland.[86] Critical minerals have also featured in UK discussions regarding potential partnerships in Africa, India and elsewhere, within the context of technology-investment and energy-transition initiatives.[87] Within Europe, a number of bilateral agreements have also been reached on defence-production cooperation, including under the EU's Act in Support of Ammunition Production to increase production capacity.[88] Meanwhile, in a different approach, in 2023 the US included Australia under the US Defense Production Act's definition of a domestic source, allowing the US to 'provide grants for critical minerals producers and projects'.[89]

Defence stockpiles are also being scrutinised. The US example is salutary. While there may have been some concern in the US that the volume of defence supplies sent to Ukraine was depleting the United States' overall munitions stockpile, these actions demonstrated the utility of stockpiles in enabling the US to provide support relatively quickly as well as giving industry the time to spool-up or restart production. The US National Defense Stockpile allows the US not only to build up stocks of weapons but also materials unique to military applications.[90]

In Europe, a similar approach was introduced by France's 2024–30 military programming law, which enabled the defence ministry to request by decree the creation of industrial stockpiles of materials, components and semifinished products that might be needed by the armed forces.[91] The Spanish Defence Industrial Strategy 2023 also included references and recommendations to improve and strengthen both the supply chain and the provision of raw materials.[92] Similarly, Germany's 2024 National Security and Defence Industry Strategy paves the way for the use of a national raw-materials fund to strengthen supply security in the security and defence sector, and states that there should be improved monitoring of supply chains for critical raw materials required by the defence sector.[93] Other countries in Europe, such as Italy, Poland and the UK, also have strategies relating to raw materials and the potential exploitation of national resources, though there are not yet defence-specific government documents available.[94]

The European Commission has proposed an EU security-of-supply regime under the European Defence Industry Programme (EDIP) which, if adopted as proposed, would have the mandate to identify and monitor critical products and potentially fund strategic stockpiling of components used for military products.[95] Regardless of the outcome of the EDIP negotiations, however, EU defence commissioner Andrius Kubilius has identified exploring possible stockpiles as a priority of his mandate, which could be included in the White Paper on defence that is scheduled to be published in March 2025.[96] NATO's Defence-critical Supply Chain Security Roadmap, meanwhile, lists the identification of recommendations for strategic stockpiling among its 'lines of effort'.[97]

Governments and industry can also pursue materials substitution and recycling measures to reduce supply-chain risk. Recycling equipment to harvest components and materials is an evolving field, not only because of the complexity of extracting materials but also due to the cost of doing so, though it is receiving closer attention at the European institutional level (through 'circular economy' initiatives) and also among groups of European states and industry associations.[98]

Substitution can be complex because of the unique properties of materials, and the cost of investing in alternatives. As such, despite international sanctions on Russia, the country is still able to export titanium, which remains outside some international sanctions regimes due to supply-chain concerns (though Russian President Vladimir Putin raised the possibility of an export ban in 2024).[99] Notably, Europe currently possess 'no domestic titanium sponge production, limited ingot capacity and virtually no recycling facilities'.[100] In the US, re-shoring plans include investments related to titanium production.[101] Other factors beyond geopolitics can also fuel materials substitution. Cadmium is being replaced in F-35 applications as it is a recognised carcinogen, and there have been health concerns raised regarding the industrial use of beryllium.[102]

Substitution will also require greater production effort and, like re-shoring, greater scrutiny of environmental, social and governance policies. So too will recovering raw materials from domestic sources more broadly, such as through mining or from mining tailings. Mining has reduced in the West, due to factors including higher labour costs and environmental requirements. According to the US Government Accountability Office, more rigorous environmental standards in the US 'allows China to mine and process rare earths and certain other critical materials at a lower cost'.[103] As such, as European states consider re-shoring the extraction and processing of critical materials, expediting progress may require not only funding support but also greater scrutiny of the regulatory and permitting process for existing and new facilities, though healthcare considerations will almost certainly remain.[104] Test cases will emerge once permits begin to be issued for the mineral-extraction projects associated with the EU's Critical Raw Materials Act.[105] Substitution will likely also require an acceptance that increased costs are likely. However, the restrictions on critical materials and technology imposed by the US and China have provided another reason for governments and industry to refocus on their supply chains. Western initiatives to restrict technology exports to China were judged significant in China's decision to restrict critical materials exports. Overall, this application of export controls could give further impetus to some Western states' plans to improve their critical-raw-materials security of supply and reduce their level of dependence on Chinese sources. It remains to be seen whether, in Europe, a similar impulse could now come from new-found uncertainty over the trajectory of transatlantic relations.

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