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**STRATEGIC ANALYSIS ON THE KEY MINERALS MARKETS IN THE
FRAMEWORK OF THE HYBRIDIZATION OF THE FIGHTING AIRCRAFT,
VEHICLE AND WARSHIP POWERTRAIN**

K.H. Juutilainen, Ugnė Grikinytė

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Executive summary

Hybridization of the fighting vehicle, aircraft and warship powertrain is ongoing trend with simultaneous process in civilian cars, aircraft and vessels. Hybrid powertrains' usage expands more rapidly in ground vehicles and vessels, but process is slower in aircrafts due to weight and energy density challenges. However, hybridization process of aircrafts/UAVs is highly likely inevitable in longer, 10 to 20 years perspective.

Key minerals for hybrid powertrains are metals and non-metals that are considered vital for the economic well-being and military capabilities of NATO nations, yet whose supply may be at risk due to geological scarcity, geopolitical issues, trade policy or other factors. The list of hybrid powertrain key minerals varies depending on country or exact technology, but most critical key minerals are rare earth elements (REE), lithium, cobalt, nickel, natural graphite, aluminum, antimony, titanium, niobium and silicone metal.

Key minerals market and supply chain is currently volatile and uncertain and there is a lack of transparency in complicated, globalized supply chains, but China is a dominating factor in many key minerals, especially in case of REEs, cobalt and graphite. If China does not has key mineral deposits on its own soil, it is actively acquiring mines abroad and/or locating processing and manufacturing parts of supply chain to China. According to open sources, Chinese government is in 2021 actively assessing how key minerals' export restrictions would impact NATO nations' industries.

When NATO nations' dependency on key minerals regarding the hybrid powertrain is reviewed, the situation is dire, especially on short (1-5years) term. The challenge is that when global dependency on China REE-supply chain was acknowledged a decade ago, actions to lessen dependency have been insufficient and during ten years, new dependencies on new critical minerals and supply chains have appeared. In its strategic Made in China 2025 initiative, China has identified a diverse array of industries with emerging strategic and economic significance, including connected, autonomous, shared and electric vehicles and the batteries that power them.

Over 70 per cent of global electrical vehicle battery manufacturing capacity is in China. Over 75 per cent of the lithium-ion battery megafactories under construction worldwide are Chinese. China currently produces more than 60 per cent of the world's cathodes and 80 per cent of anodes for batteries, and the majority of the world's permanent magnets used in EV motors.

When situation is assessed in medium, 5 to 10 years' perspective, the outcome is likely manageable if NATO nations initiate coherent, immediate action lessening key minerals' dependency. There are two, simultaneously taken action tracks. First is long-term research and development funding for recycling and developing substitute materials for current key minerals. At same time, there is the need to develop critical mineral supply chain inside NATO and partner nations and co-operate diversifying process from Chinese and Russian key minerals. However, the problem especially in case of REEs is that it is possible that China would flood markets with REEs when other nations are about starting mining or production. In this case, governmental subsidies are needed to financially support new production.

Long, 10 to 20 years perspective has several possible futures. If NATO nations are satisfied with status quo, future electrical vehicle and hybrid powertrain supply chains will be located in China along knowhow, jobs, and associated military capabilities they enable. If long-term research and development funding for recycling and developing substitute materials is initiated in time along new supply chain (from mining to end-products), future is likely less dystopic. However, technological development does not stand still and it is possible that other new key minerals emerge from new technologies.

Introduction

Definition of key minerals / strategic minerals /critical raw materials varies depending on country, but this Australian government's definition is rather conclusive:

“Critical minerals are metals and non-metals that are considered vital for the economic well-being of the world's major and emerging economies, yet whose supply may be at risk due to geological scarcity, geopolitical issues, trade policy or other factors.”¹

Key minerals are essential to the economic and technological development of nations. These minerals have a range of high-tech applications across a variety of sectors of growing economic and strategic significance, including:

- renewable/green energy
- automotive (particularly electric/hybrid vehicles)
- ships and vessels
- aerospace
- defence technologies
- telecommunications

Technological development has throughout history made previously useless minerals and materials vital for nations and militaries quite suddenly, but challenge has always been the location of these minerals deposits, existing infrastructure on deposit areas, the cost of extracting them and finally the long lead-in time of turning the mineral deposits to a working mine. Historical examples of “sudden” key minerals are e.g. guano (gunpowder, explosives), oil and uranium.

This paper aims to identify the energy dependency of the NATO Nations in short, medium and long term regarding the increase use of batteries in hybrid powertrains of new war materials. Nations naturally have different demands on key minerals depending their or their closest allies' natural resources or demands of their industry and economy and while there are critical mineral lists made for United States and EU, there is no synthesis made from NATO nations' perspective. Additionally there are NATO Enhanced Opportunities Partner nations² like Australia, Finland and Sweden, which are known to have significant potential and proven critical key minerals. This paper review key minerals needed in hybrid powertrains and review those appearing both in US and EU critical minerals list. The main aim to is identify the most

¹ <https://www.ga.gov.au/about/projects/resources/critical-minerals#heading-1>

² https://www.nato.int/cps/en/natohq/news_176327.htm

critical key minerals and the review the strategic geopolitical and market environment affecting those minerals. Definition of individual key minerals needed in hybrid powertrains is based on synthesis from existing US and EU research, but rapid technological breakthrough e.g. in battery technology can make “new” key minerals, since they can provide significant performance leap over old technologies and minerals. There are also several challenges for predicting future demand of minerals. For example, copper is widely available and also widely recycled, but its demand is increasing due to increase of urbanization (e.g. building wirings) and breakthrough of electrical vehicles (EV uses four times as much copper as conventional vehicle). Also cobalt and some other key minerals are often byproducts of copper mining. Exact percentages for global resource, production and consumption share are approximate, since statistics vary depending source and calculation method.

The first part of this paper looks on hybrid powertrains and their current and potential applications on military vehicles, vessels and aircraft. Then characteristics of the key minerals’ supply chain is analyzed. After that strategic market environment along the geopolitics is reviewed. Finally after conclusion there is the detailed list of those most critical key minerals of hybrid powertrains.

The information cut-off date of this paper is 1st March 2021.

Hybrid powertrains

Powered vehicles, aircrafts and warships have a powertrain containing the propulsion energy storage system, the propulsion energy converter and the drivetrain, which provides directly or indirectly the mechanical energy at the wheels or propellers for the purpose of vehicle propulsion. "Propulsion energy storage system" means an energy storage system of the powertrain, whose output energy is used directly or indirectly for the purpose of vehicle propulsion. Energy storage system can be e.g. traditional fuel tank or electric battery or fuel cell etc. "Propulsion energy converter" means an energy converter of the powertrain, whose output energy is used directly or indirectly for the purpose of vehicle propulsion. Energy converter can be conventional combustion or for example an electric engine. "Drivetrain" means the connected elements of the powertrain for transmission of the mechanical energy between the propulsion energy converter(s) and the wheels.³

³ Unece.org ECE/TRANS/WP.29/1121

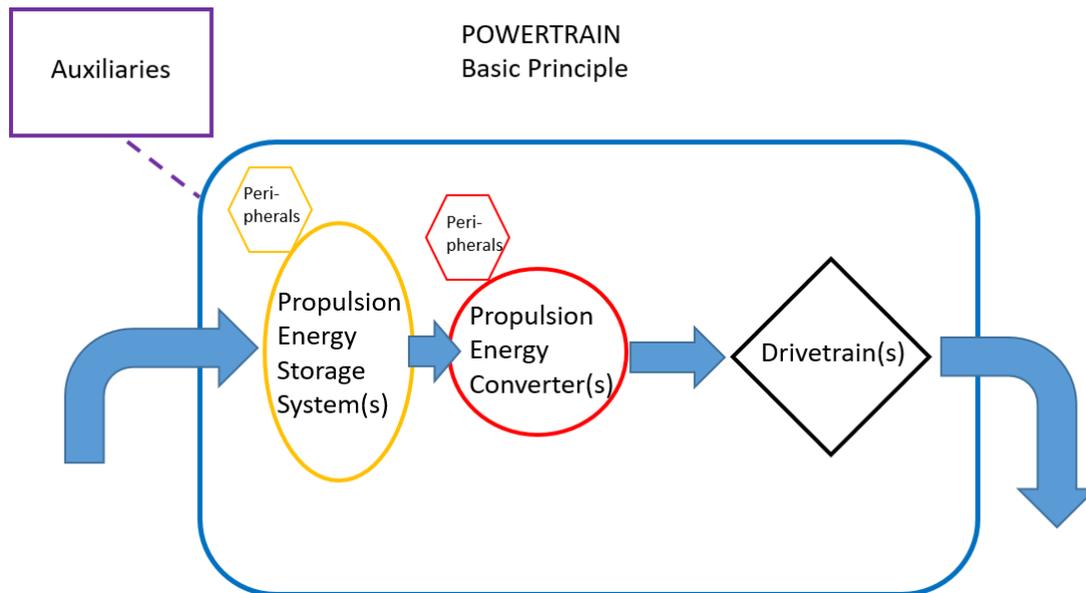


Figure 1: Powertrain basic principle.(Adapted from UN definition)⁴

Generally, hybridization can be defined as the combining of two or more energy sources together to increase efficiency and maximize output. Typically electric engines are better producing torque and combustion engines maintaining speed. These systems can be coupled with energy storage via batteries or super capacitors to help smooth out peak power loads, or even provide peak energy for short-term loads.⁵

Hybridization of powertrains in civilian applications is most common with cars, but usage is increasing in larger vehicles. In addition, ships and other vessels are expanding the use of hybrid powertrains, but hybrid powertrains in aircraft is still under development. The main challenge is aircrafts' greater sensitivity to extra mass and energy density of current batteries. Energy density is usually defined in terms the number of watt-hours (Wh) retrieved per kilogram (kg). A current lithium-ion battery's energy density might reach 250 Wh per kg, while the energy density of jet fuel, or kerosene, is roughly 12,000 Wh per kg⁶. Hybrid powertrains most likely seen first in UAVs and smaller manned airplanes. The ability to use quieter battery-powered electric engines is desirable especially in intelligence and surveillance drones.

⁴ Ibid.

⁵ <https://www.marinelink.com/news/propulsion-tech-hybridization-468308>

⁶ <https://www.bbc.com/future/article/20200617-the-largest-electric-plane-ever-to-fly>

Military applications of hybrid powertrains generally follow civilian development process and markets. Light military ground vehicles with hybrid powertrains are widely developed around world. Advantages of hybrid powertrains in military ground vehicles are e.g. lower sound signature, greater adaptability of powertrain (e.g. different engines for each wheel etc.), on demand torque etc.⁷

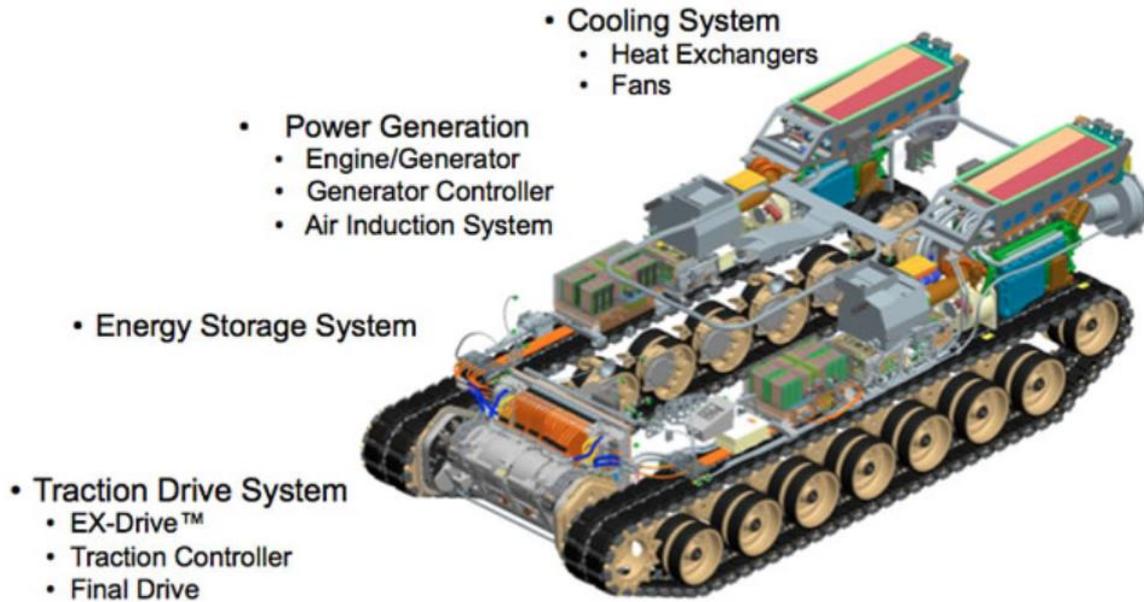


Figure 2: Schematic of powertrain on BAE Systems' cancelled Ground Combat Vehicle plan.(BAE Systems)

Ships have been partly electrified for years: approximately 80 percent of oceangoing ships now use a diesel-electric transmission system. Diesel generators generate the electricity, which then drives the electric engine and ship's propeller. However, this is still not a hybrid drive system, since this kind of vessel cannot run without diesel engines running.⁸ Surface vessels are slowly following the civilian trend of hybrid powertrain, but battery-augmented powertrain are firstly seen on smaller naval vessels. As a weapon system, a diesel-electric submarine has used battery-equipped hybrid powertrain since early 1900s. After Air Independent Propulsion (AIP) technology became prominent in conventional submarines since 1980s, now lithium-ion battery technology provide performance leap in submarines. Compared to the AIP system the overall boat's propulsion system design will be less complex and bulky and lithium-ion

⁷ <https://www.nationaldefensemagazine.org/articles/2019/2/21/army-driving-forward-with-electric-vehicle-plans>

⁸ <https://www.infineon.com/cms/en/discoveries/electrified-ships/>

batteries can provide large output on demand and thus provide faster dash speeds while submerged⁹.



Figure 3: In 2020 Japanese JS OURYU (SS 511) became the first lithium-ion battery powered submarine. (JMSDF)¹⁰



Figure 4: French Navy Multi-Mission Barges "Fourmi", "Scarabée" and "Araignée" (Picture source: DGA)

Military hybrid aircraft have currently the same technical limitations as their civilian counter parts, but hybrid drones will likely be more widely used in the near future.

⁹ <https://www.thedrive.com/the-war-zone/7747/japan-goes-back-to-the-future-with-lithium-ion-battery-powered-submarines>

¹⁰ https://twitter.com/jmsdf_pao_eng/status/1247770200277045248/photo/1



Figure 5: Ampaire’s modified Cessna 337 Skymaster with battery pack slung under fuselage (<https://www.ampaire.com/>)

When key minerals¹¹ market is reviewed in the framework of hybridization of powertrain, the civilian usage of these minerals set the pace of the market environment and supply chain.

Electric Vehicle (EV) demand is globally increasing and the transition is likely to be even faster in the EU due to post-COVID-19 clean transport incentives. For example: in the third quarter of 2020, registrations of electrically chargeable vehicles (including hybrids and all-electric vehicles) in the EU increased 211.6%.¹² According to EU, for e-car batteries and energy storage alone, Europe will for instance need up to 18 times more lithium by 2030 and up to 60 times more by 2050.¹³

Hybridized military powertrain mineral demands are in same time competing with civilian mineral demands on limited resources, but also benefiting from them since military hybrid powertrains use/will use also Commercial-off-the-Shelf(COTS)-components and raw materials. The most critical components of hybrid powertrains that use key minerals are batteries, wiring, electric motors, circuitry and magnets.

¹¹ Other synonyms are “strategic minerals” or “critical minerals”

¹² https://www.ey.com/en_gl/mining-metals/why-mineral-supply-may-be-an-e-mobility-roadblock

¹³ https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1542

The constraining factor on hybrid and electric powertrains in whole is ultimately going to be raw materials since there is simply not enough raw materials for all the vehicle makers to roll out their development plans over the next 10 to 15 years.¹⁴

Supply Chain

The figure 5 shows map with mines, deposits and districts of key minerals of hybrid powertrains. They are globally quite evenly distributed, but the challenge is find mineral deposits that are rich enough concentrations. For example, rare earth elements cerium, yttrium, lanthanum and neodymium have average crustal abundances similar to lead, tin and zinc.¹⁵

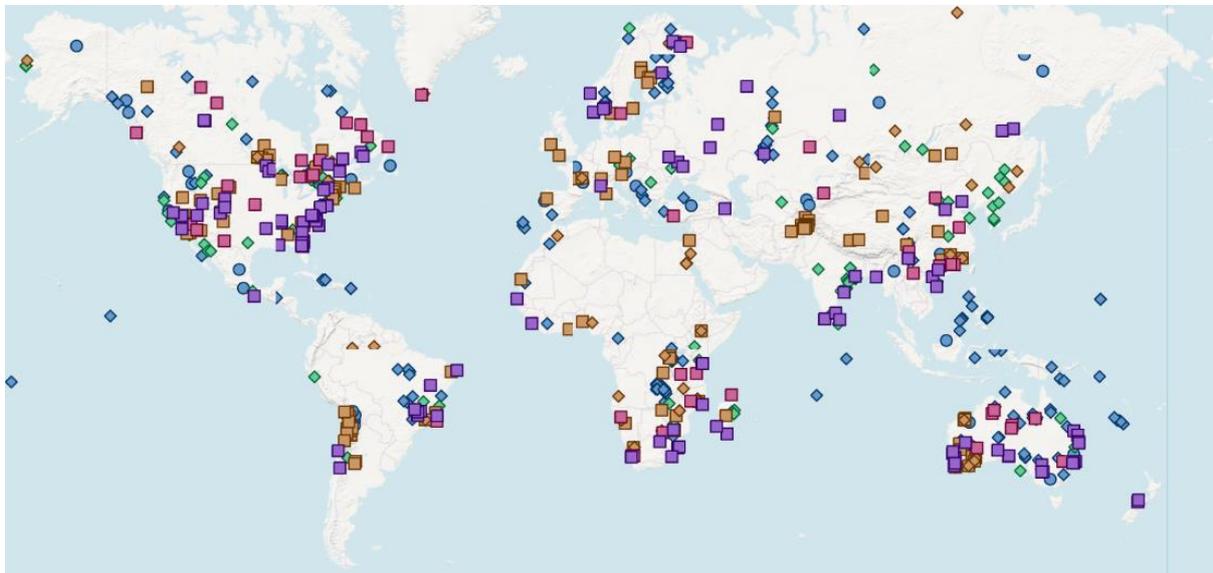


Figure 5: USGS global database show global distribution of selected mines, deposits, and districts of key minerals mentioned in this paper (USGS, Global distribution of selected mines, deposits, and districts of critical minerals)¹⁶

This challenge of mineral concentrations, location and needed infrastructure can be illustrated with example of shale gas and shale oil. China is trying to cut its reliance on oil and gas imports by boosting domestic production, but despite huge proven shale oil and gas reserves of China, the complex geology and lack of infrastructure and water is preventing China to repeat the success of US shale oil and gas.¹⁷¹⁸ Geological challenges and lack of infrastructure are also

¹⁴ <https://www.politico.com/news/2020/12/02/china-cobalt-mining-441967>

¹⁵ <https://geology.com/articles/rare-earth-elements/>

¹⁶ <https://mrdata.usgs.gov/pp1802/>

¹⁷ <https://www.reuters.com/article/us-china-shalegas-idUSKBN29V0ZE>

¹⁸ <https://jpt.spe.org/chinas-unconventional-challenge-spurs-new-thinking-on-shale-and-tight-reservoirs>

common obstacles in front of commercially viable key minerals production too, even when it is known that certain area has proven reserves of needed key minerals.

Mining projects have similarities to oil and gas projects: they need a lot of basic research by geologists, they are capital intensive and delivery times are long. Figure 6 describes generalized Mining Life Cycle. It includes exploration, design, permitting, construction, production and reclamation processes. Even in most optimum cases, where mineral deposit is well known and has infrastructure (roads, water, electricity etc.) already in place, there opening process can take years in democratic societies due to permitting process.

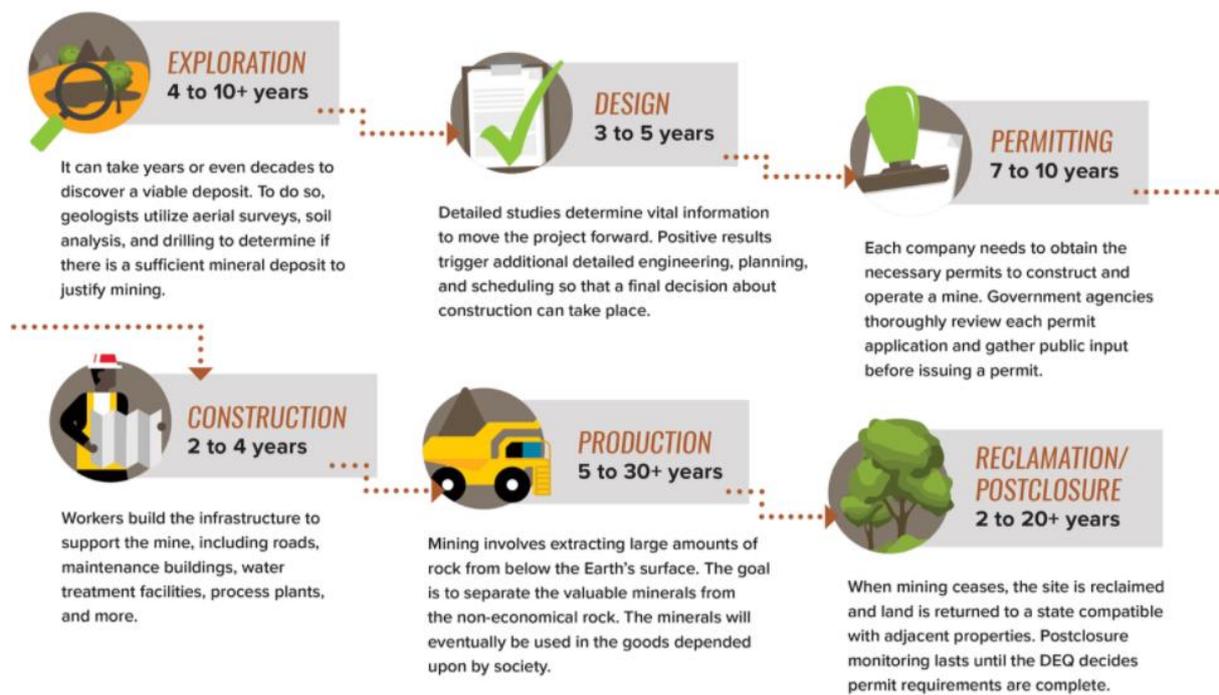


Figure 6: Generalized Mining Life Cycle (www.backfortymine.com).

When the mining has started, it is only the start of the supply chain. Figure 7 illustrates simplified key mineral supply chain after mining has commenced. The mining produces only ore (natural rock or sediment) where desired mineral can be extracted. Concentration or beneficiation is an extractive process that upgrades the value of raw mineral ores by removing low value minerals, resulting in a higher-grade product or concentrate¹⁹. Mining and concentration are so called “upstream” phases or key mineral supply chain. Separation and

¹⁹<https://www.energy.gov/sites/prod/files/2020/04/f73/Critical%20Materials%20Supply%20Chain%20White%20Paper%20April%202020.pdf>

processing are “midstream” phases where desired minerals are further separated and in case of REEs oxides are made to metals and then alloyed with other metals. Manufacturing phase is “downstream” phase and produces e.g. REE-magnets, batteries, wires, electrical engines etc. Some minerals/metals are only produced as a by-product of something else. Example of key minerals (but not a key mineral regarding hybridization of powertrain) produced as a by-product is indium, which is used in semiconductor industry. This means that indium production needs economically viable zinc mines, so that indium can be by-produced from zinc production.

Mining projects and whole supply chain process with manufacturing is increasingly regulated in democratic countries. Regulation includes environmental protection, rights of native people and other citizen, but increasingly also carbon emissions of supply chain. Mining generally has environmental risks, even when the produced ore is seemingly “neutral”. However, erosion of mineralized waste rock into surface drainages may lead to concentrations of metals in stream sediments and acid leakages.²⁰ Environmental risks are highlighted in rare earth elements’ production, where supply chain side product is often radioactive.²¹ Less regulated and thus more cost-effective Chinese REE-production was the main reason why NATO nations lost REE-supply chain to China in first place. Environmental problems and production cost challenges have caused problems to several mining projects, which were started in response to Chinese domination of key mineral markets a²².

In democratic societies, citizen activism is a norm and environmental concerns regarding mining projects are of valid. However, it is good to acknowledge that social media allows foreign governmental actors’ led information operations aimed against mining projects. These information operations can aim to delay or stop key mineral mining projects if they run against foreign governmental actors’ strategic interests.²³

²⁰ <https://www.americangeosciences.org/critical-issues/faq/how-can-metal-mining-impact-environment>

²¹ <https://www.sciencemag.org/news/2019/04/radioactive-waste-standoff-could-slash-high-tech-s-supply-rare-earth-elements>

²² <https://www.ft.com/content/0534d04c-834a-11e9-b592-5fe435b57a3b> “Lynas shares up after Malaysia’s Mahathir clears plant”

²³ <https://www.hsdl.org/?abstract&did=808676> “Russian Attempts to Influence U.S. Domestic Energy Markets by Exploiting Social Media”



Figure 7: Simplified process from finding ore to end product (e.g. battery, wire, magnet etc.).

One way to lessen the dependency on imported key minerals is to improve recycling processes in NATO nations and thus extract part of the needed minerals from waste material. Another new source for some key minerals (mainly cobalt) is to use advanced bioleaching techniques to separate minerals from old mining waste (tailings) where traditional mineral separation would be too challenging and/or expensive.²⁴ Third, faster and less effective way to improve situation is to establish and/or expand government sponsored strategic mineral reserved located at NATO nations' soil.

The final part of key mineral supply chain are components and end products from which hybrid powertrain is made. Some parts are simple like copper wires, but components like batteries need first class R&D to be competitive on global markets. Lithium-ion batteries are the enabling technology of hybrid powertrains and automobile industry and highly likely will be a disruptive technology for energy and utility sectors due to energy storage ability of increasing production of wind and solar power. Lithium-ion battery is at the heart of global lithium-ion economy. Individual battery megafactories (socalled gigafactories), in the pipeline over the next 10 years increased from 118 in 2019 to 181 in 2020. (For context, only four were being planned in 2015). Of the 181, 136 are based in China, 10 in the US, and 16 in continental Europe²⁵

Strategic market environment of key minerals

'Improve the development and application of rare earth, and change the resource advantage into economic superiority.'

—CHINA'S PRESIDENT JIANG ZEMIN, 1999²⁶

The list of hybrid powertrain key minerals varies depending on country or exact technology, but most critical key minerals are rare earth elements (REE), lithium, cobalt, nickel, graphite,

²⁴ <https://h2020-nemo.eu/2020/09/06/bioleaching-of-cobalt-from-low-grade-sulphidic-mining-waste/>

²⁵ Moores, Simon <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2021/02/OEF-126.pdf>

²⁶ <https://oxford.universitypressscholarship.com/view/10.1093/oso/9780190670931.001.0001/oso-9780190670931>

aluminum, antimony, titanium, niobium and silicone metal since all of these are listed critical by both or either the EU or the US and these minerals are used in hybrid powertrains. These minerals, their sources and uses are evaluated at the end of this paper, this chapter review them on strategic market and geopolitical level.

When strategic market environment of key minerals is reviewed, the background of globalization has to be understood. Economic globalization accelerated after Cold War and supply chains globalized especially when China opened up for international trade in late 1980s. Global supply chain utilizes lower raw material and work force costs and produces commodities where it is economically most profitable. This also increases competition and innovation. However, when costs lowered and global supply chain depends complex, “just on time”-global logistical networks with minimal storages, resilience is diminishing. These complex supply chains are usually invisible when everything is going as planned, but dependencies appear when disruptions happen. The example of this is when Eyjafjallajökull volcano erupted in Iceland in 2010 and disrupted global air transports and automakers like BMW and Nissan faced production halts both in Europe and in Asia, when they were not able to receive key components.²⁷ COVID 19 has affected global supply chains, especially regarding microchips and semiconductors.²⁸ When resilience is needed, there is a premium price to pay in form of strategic reserves or subsidized national or allied production.

On strategic level, the main challenge from economic globalization has been the re-location important production facilities of many NATO nations to China. When NATO countries energy dependency on key minerals is reviewed – the challenge is always about China, even when the China does not has certain minerals on its soil, since China has acquired other parts of supply chains. China has had a very-long strategic perspective to increase its national power and key mineral production and processing has been a part of along with the high-tech production facilities and knowledge they enable. These strategies are clearly stated in China’s Communist Party’s Central Committee’s Five-Year Plans.²⁹

²⁷ <https://www.theguardian.com/business/blog/2010/apr/20/nissan-suspends-car-production-volcano-ash-cloud>

²⁸ <https://www.nytimes.com/2021/01/13/business/auto-factories-semiconductor-chips.html>

²⁹ <https://cset.georgetown.edu/publication/proposal-of-the-central-committee-of-the-chinese-communist-party-on-drawing-up-the-14th-five-year-plan-for-national-economic-and-social-development-and-long-range-objectives-for-2030/>

Russia's role in NATO nations' key minerals dependency (related to hybrid powertrains) is insignificant except for potential future use of titanium. However, Russia has USD 1.5 billion investment plan for Russian REE production. The plan includes reduced mining taxes and cheaper loans to investors in a list of 11 projects designed to increase Russia's share of global rare earths output to 10% by 2030. Russia's aim is to become almost self-sufficient in rare earth elements by 2025 and start exports in 2026.³⁰ The USD 1.5 billion investment plan might sound small, but when it is compared with purchasing power parity (PPP), investment plan is significant. It is also important to note that Russian state-owned and private mining companies are increasingly active in Africa.³¹

It is often quoted that former Chinese leader Deng Xiaoping said in 1992 that "the Middle East has oil, China has rare earths."³² Since China has been able to provide most favorable location to many global production facilities to availability and low price of key raw material and work force, China has been able to acquire many key assets of future global power and economic strength. In the framework of the hybridization of the fighting aircraft, vehicle and warship powertrain, this also means that China has key supply chains of minerals, metals and component factories needed in hybrid powertrains.

When the globalization was the "buzz word", geopolitics were thought to be dead and democracy marching to global victory. However, geopolitics and global power competition have come back, but Western attitude and outsourced supply chains are turning slowly. Since the end of the Cold War, Western democracies have accepted "laissez-faire" attitude on strategic materials and supply chains and been satisfied with key mineral markets when there has not been any problems with availability and private companies have been able to provide everything needed. However, now the downside of relaxed attitude starts to appear when China has come more assertive in its global role. As NATO Secretary General has said: "There's no way we can avoid addressing the security consequences for our regional alliance of the rise of China and the shift in the global balance of power."³³ China is more likely to able to weaponize its strategic investments to key minerals supply chains. Global dependency on China's REE supply chain is well-known example and statistics on Figure 7 speaks for themselves.

³⁰ <https://www.reuters.com/article/russia-rareearths-idUSL8N2F73F4>

³¹ <https://www.fdiintelligence.com/article/78348>

³² <https://www.economist.com/china/2019/06/15/rare-earths-give-china-leverage-in-the-trade-war-at-a-cost>

³³ <https://www.dw.com/en/china-is-challenge-and-opportunity-nato-chief-tells-dw/a-56955546>

Economy	Imports from China (metric tons)	Total Imports	% of Imports from China
EU	869.2	882.2	98.5
USA	417.6	438.6	95.2
South Korea	86.1	94.6	90.9
Japan	4,233.4	8,729.2	48.5

Note: Excludes oxides and other compounds

Figure 7: Reliance on Chinese Rare Earth Metals and Alloys (2018) (CSIS China Power Project/UN Comtrade Database)

China has become world biggest car market and world’s lead market for EVs. Additionally to markets, China can offer key components from its supply chains needed in car and hybrid powertrain manufacturing. This lucrative environment has caused that largest European manufacturers have chosen Chinese partners for 41 cooperation projects since January 2018. Since 2018, European carmakers have established nine R&D centers to China, mainly focused on developing EV and AV technology.³⁴

However, China’s role in key minerals market is more multidimensional. When international companies locate their production facilities to China because of the availability of the raw materials and markets, China does not only has physical production plants, but also immaterial knowledge due to cyber-security legislation. China’s cyber-security law from 2017 makes intellectual property protection of global companies located in China very difficult, since among other issues it severely compromise companies secure data, VPN-connections and trade secrets. This is a challenge when a long history of Chinese intelligence supporting Chinese state-owned companies is known. Since the Chinese government is the shareholder in all SOEs and exercising de facto control over China’s major private companies as well, all of this information will then be available to those SOEs and Chinese companies. All this information will be available to the Chinese military and military research institutes.³⁵ It can also be estimated that highly likely Chinese intelligence agencies support Chinese companies in acquiring/bidding processes when these companies are seeking key mineral resources globally.

³⁴ <https://merics.org/en/opinion/european-carmakers-fuel-chinese-innovation>

³⁵ <https://harrisbricken.com/chinalawblog/china-cybersecurity-no-place-to-hide/>

For example, in 2011 it was revealed that in Night Dragon-cyber espionage campaign Chinese cyber actors accessed 2-4 year 5-12 multinational energy companies and focused on financial documents related to oil and gas field exploration and bidding contracts.³⁶

In other hand, China intertwines acquisition of key mineral resources abroad in complex trade and investment deals. Cobalt is an excellent example, since in 2007-2008 China made the approximate USD 9bln³⁷ ‘minerals for infrastructure’ deal between China and the Democratic Republic of the Congo (DRC) In this deal, Chinese state-owned banks provided favorable loans to the DRC government for infrastructure, purportedly in exchange for access to copper and cobalt mineral development rights.³⁸ In total, between 2005 and 2017 China invested 58 billion USD in the sub-Saharan African mining and energy sectors and China continues to be the leading investor in the global mining industry.³⁹

Due to economic growth and technological development, China does not anymore need key minerals just for the production and exporting of various goods – China increasingly needs key minerals for its own usage, which further cause problems on other countries’ dependency. It is just not the threat of malign intentions and weaponization of key minerals, but possibly of honest scarcity of minerals and components.

When strategic and geopolitical dimensions of key mineral market is evaluated, China’s dominance gives it two main lines of action. When new, competing mines or supply chains are coming in production, there is a possibility that China can flood markets of certain minerals and make competing production uneconomical. Other option is to curtail export of minerals and components and thus cause problems in NATO nations’ civilian and military production. According to Financial Times, Chinese government is in 2021 actively assessing how key minerals’ export restrictions would impact NATO nations’ industries.⁴⁰ China is not afraid to its economic power when its interests are threatened. There are numerous examples limiting

³⁶ <https://www.reuters.com/article/us-energy-cyber-china/chinese-hackers-infiltrated-five-energy-firms-mcafee-idUSTRE7190XP20110210?feedType=RSS&feedName=internetNews>

³⁷ <https://www.ft.com/content/f4d34d3a-f6d9-11dd-8a1f-0000779fd2ac>

³⁸ Andrew L. Gulley, Erin A. McCullough, Kim B. Shedd, China's domestic and foreign influence in the global cobalt supply chain, Resources Policy, <https://doi.org/10.1016/j.resourpol.2019.03.015>.

³⁹ Korts, Marju: “The strategic importance of rare earth minerals for NAT, EU and the United States and its implications for the energy and defense sectors” (Energy Security: Operational Highlights no 13, 2020)

⁴⁰ <https://www.ft.com/content/d3ed83f4-19bc-4d16-b510-415749c032c1> China targets rare earth export curbs to hobble US defence industry

both imports and exports in punishing way, but regarding the key minerals the prelude happened in 2010, when China stopped all REE-exports to China. The aim was to persuade Japan to return detained Chinese fishermen.⁴¹ China's new export control law adopted in December 2020 enables the government to control the export of items including dual-use goods as well as military and nuclear products to specific foreign entities. Other goods, technologies and services – and related data such as technical information – will also be subject to controls, unless they were granted by export licenses issued by the State Council and Central Military Commission.⁴²

Global key minerals' market is very complex due to various minerals and different industries using same minerals in very different applications. Due to complexities of markets of these specialized minerals it can be assessed that market price fluctuation will highly likely be very strong in near and medium term. When geopolitical competition is added to commercial competition and technological revolution point that has analogies to transformation, when oil replaced coal as a fuel of navies and enabled motorized ground formations – the competition of resources is likely vicious. Eventually the question is: is there enough key minerals for everyone in time? When price is high enough, commercially unviable mining resources became viable, but problem is before mentioned long lead-times of mining projects.

Rare Earth Elements (REE)

China's dominance on REE supply chain is well researched. It can be summed up, that REEs are critical also in hybrid powertrains of the fighting aircraft, vehicles and warships especially in magnets used in electrical motors. Magnets became globally leading application of rare earths demand in 2015. According to permanent magnet synchronous motors are up to 15% more efficient than induction motors and are the most power-dense type of traction motor commercially available.⁴³ With hindsight it can be also acknowledged that when the Western dependency of China's REE supply chain was firstly highlighted in 2010 China-Japan dispute, but very little have been achieved in decade to lessen the dependency.⁴⁴ China, producing around 70-90% of the world REE production, controls the world market through production controls, export restrictions (e.g. quotas, tariffs), mine closings and company consolidation. All

⁴¹ Allison, Graham: "Destined for War – Can America and China escape Thucydides's Trap?" (Scribe Publications 2017)

⁴² <https://merics.org/en/briefing/chinas-new-export-control-law>

⁴³ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁴⁴ <https://www.fpri.org/article/2020/10/chinas-monopoly-on-rare-earth-elements-and-why-we-should-care/>

these factors contributed to unstable supply, significant price increases and volatility on the world market.⁴⁵

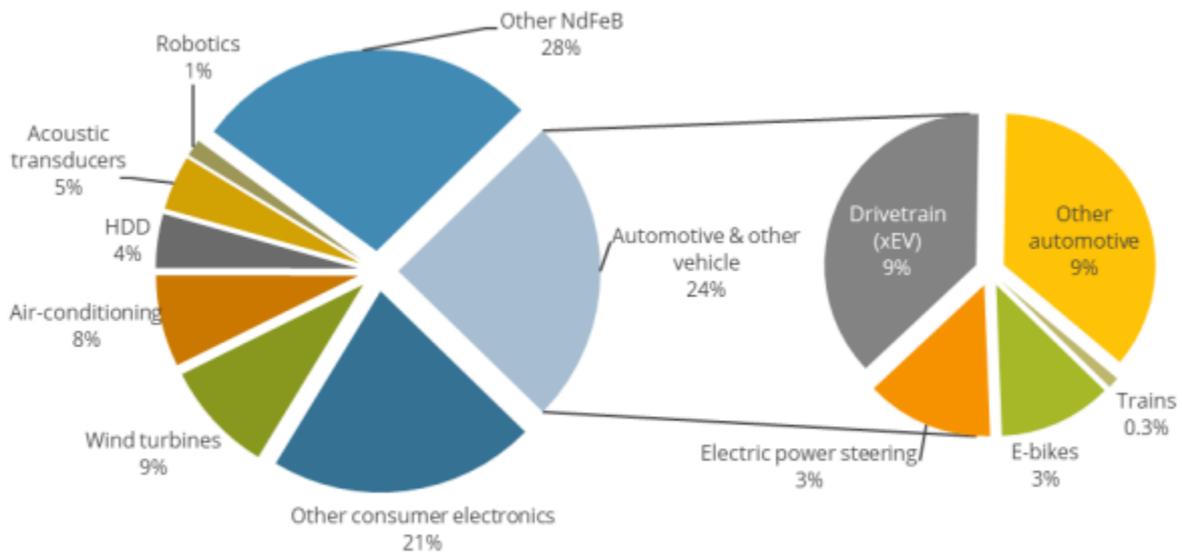


Figure 8: Global applications for NdFeB (REE) permanent magnets in 2019 (Roskill via EU (2020))

Cobalt

Cobalt is needed on lithium-ion batteries and electrical motor components. The cobalt is an excellent example of key mineral resource, that China does not significantly mine on its own soil (only 1 percent of global production⁴⁶), but China has acquired the supply chain. Almost 60 percent of cobalt ore originates from Democratic Republic of Congo (DRC), but China has the 80 percent of cobalt refining capacity. Eight of the 14 largest cobalt miners in the DRC are Chinese-owned, accounting for almost half of the country's output.⁴⁷

Natural Graphite

Graphite comes in two forms: natural graphite, which is mined, and synthetic graphite, which is produced from petroleum coke or coal tar. Synthetic graphite is more expensive and manufacturing process produce more emissions.⁴⁸ Graphite is the largest input raw material into a lithium ion battery. Graphite anode can be manufactured from both natural and synthetic sources, but most battery manufacturers use a natural-synthetic blends. The significance of graphite has not received as much attention as other battery mineral, due to larger market and

⁴⁵ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁴⁶ <https://www.bloomberg.com/graphics/2018-china-cobalt/>

⁴⁷ <https://mneguidelines.oecd.org/Interconnected-supply-chains-a-comprehensive-look-at-due-diligence-challenges-and-opportunities-sourcing-cobalt-and-copper-from-the-DRC.pdf>

⁴⁸ <https://www.greentechmedia.com/articles/read/graphite-the-biggest-threat-to-batteries-green-reputation>

because steelmills are still the main consumers of graphite market.⁴⁹ China is the world's largest producer of natural graphite producing over 70 percent global production. China is also a major graphite exporter and it exports over 59 percent of value of global graphite exports. However, since 2018 China has begun to import large quantities of graphite suitable for processing in battery-grade from Mozambique and Madagascar in order to meet the surging demand in the world's largest lithium-ion battery industry. China's own graphite resources are becoming harder to reach and production costs continue to rise. The graphite market is complex and fragmented because natural graphite is not a homogeneous commodity.⁵⁰

Lithium

Lithium is the key component of Lithium-ion batteries. To understand the NATO countries dependence on Lithium-ion batteries, the picture below is very useful.⁵¹ It shows that the EU and the US supplies 1% each of all raw materials needed for the Li-ion battery production. Then, the EU supplies 8% of processed materials, and 9% of the components, while the US supplies none of those. Furthermore, the US assembles 13% of all Lithium-ion cells, while the EU – a marginal 0.2%. The picture clearly shows the dependence of the EU and the US on Asian countries, and a limited possibility to diversify supplies, since none of the other countries are very rich in Li-ion related raw materials.⁵²

⁴⁹ <https://www.benchmarkminerals.com/china-is-constructing-four-graphite-anode-megafactories-for-the-lithium-ion-battery-surge/>

⁵⁰ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁵¹ European Commission (2020). Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study.

⁵² https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

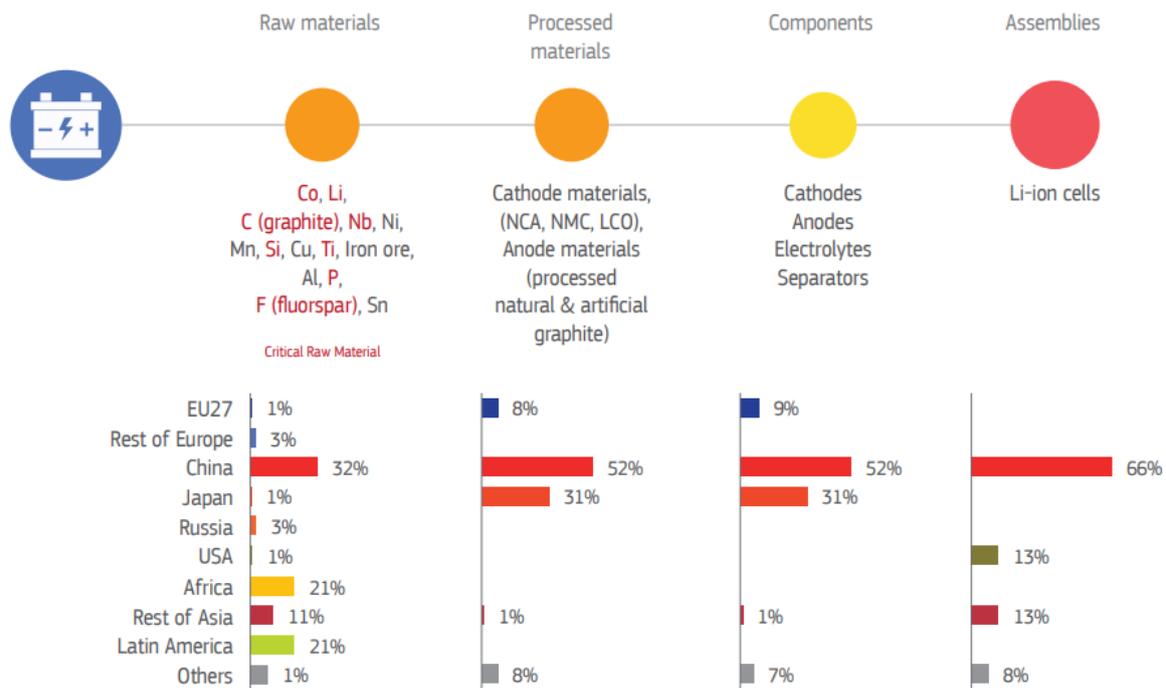


Figure 9: Li-ion batteries: an overview of supply risks, bottlenecks and key players along the supply chain. (European Commission (2020)5354)

Aluminum (Bauxite)

Due to unique properties, aluminum has become the material of choice for clean technology producers in applications like renewable energy, batteries, electricity systems, resource-efficient packaging, energy-efficient buildings, and clean mobility. Despite a projected increase in recycling, primary production will still be needed to meet the increasing demand for our metal. Global demand for primary aluminum alone is expected to increase by 50% in the next thirty years.⁵⁵ Aluminum is produced from bauxite. Most of the rapidly growing global smelting capacity was installed in China (90% of all new capacity during the last decade). Massive government support to the rapidly growing aluminum smelting industry in China is mostly in the form of energy subsidies and concessional finance.⁵⁶

⁵³ <https://ec.europa.eu/docsroom/documents/42881> Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study

⁵⁴ Note: EU include above minerals like fluorspar and phosphorus critical raw materials, mainly due their criticality in aluminium and fertilizer manufacturing.

⁵⁵ <https://aluminiumtoday.com/news/bauxite-recognised-as-critical-raw-material>

⁵⁶ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

Antimony

The important use of antimony, accounting for about 32% of global antimony consumption, is the production of antimonial or hard-lead alloys used in the manufacture of lead-acid batteries. Global consumption of antimony is expected to increase, primarily in the use applications: flame retardants, lead-acid batteries, and plastics. Asia is projected to remain the leading region regarding consumption, accounting for about 60% of global consumption by 2020.⁵⁷

Titanium

Currently titanium is mainly used on paints, polymers and aerospace industry, but in future titanium will highly likely improve Lithium-ion batteries' properties. Prices of titanium ores and concentrates and of titanium final products are strongly linked to their applications demand and prices have been rising since 2008-2009 economic crisis.⁵⁸

Niobium

Niobium is a key mineral, which is mainly used on steel production, but niobium's role in Lithium-ion batteries will grow, since niobium anodes improve battery energy density and shorten charging time. Niobium market is small and applications are relatively new.⁵⁹

Silicone metal

The major uses of metallurgical grade silicon are in metallurgy and for the production of silicones and silanes, representing more than 90% of the total world and EU silicon metal consumption. Polysilicon is used as a semiconductor in photovoltaic applications or in microelectronics. There are no materials that can replace any of the main uses of metallurgical silicon without serious loss of end performance or increase of cost. Lithium-silicone-batteries are subclass of Lithium-Ion batteries. Growth in the silicon metal market is expected to continue in the coming years. Consumption for silicon metal comes primarily from the aluminum and chemical industries.⁶⁰

⁵⁷ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁵⁸ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁵⁹ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁶⁰ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

Nickel

Nickel has been used for a long time nickel cadmium (NiCd) and the nickel metal hydride (NiMH) rechargeable batteries. Nickel usage continues with more advanced batteries used in hybrid vehicles and the proportion of nickel-containing Li-ion batteries in use set to increase. Two of the most commonly used batteries, Nickel Cobalt Aluminum (NCA) and Nickel Cobalt Manganese (NCM) use 80% and 33% nickel respectively.⁶¹The global nickel market is expected to grow in the short and medium term (1-10 years) owing to the rising use of nickel in automotive, electrical and other end-use industries has driven the growth of the nickel market globally. Asia is the major contributor to the global nickel consumption supported by increasing demand for stainless steel and rising use of electric vehicles. China is the fastest-growing market for nickel with increasing industrialization and infrastructure investments.⁶²

Conclusion

When NATO nations' dependency on key minerals regarding the hybridization of vehicle, vessel and aircraft powertrain, the situation is dire, especially on short (1-5years) term. The challenge is that when dependency on China REE-supply chain was globally realized a decade ago, actions to lessen dependency have been insufficient and during ten years new dependencies on new critical minerals and supply chains have appeared. According the Financial Times, the China's Ministry of Industry and Information Technology has in January 2021 proposed draft controls on the production and export of 17 rare earth minerals in China. Chinese government is currently assessing how US and European high-tech companies including defense industry would be affected if China restricted rare earth exports during a bilateral dispute.⁶³ This individual news underlines the urgent challenge NATO nations are currently facing regarding mineral dependency. At the same time, Chinese companies are actively seeking new key mineral deposits outside of China using investments that combine political, economic and military measures.

When situation is assessed in medium, 5 to 10 years' perspective, the outcome is likely manageable if NATO nations initiate coherent, immediate action lessening key minerals'

⁶¹ <https://nickelinstitute.org/about-nickel/nickel-and-transport/>

⁶² <https://www.prnewswire.com/news-releases/world-nickel-market-insights--forecast-2020-2024----growing-use-of-nickel-in-the-healthcare-sector-301201902.html>

⁶³ <https://www.ft.com/content/d3ed83f4-19bc-4d16-b510-415749c032c1> China targets rare earth export curbs to hobble US defence industry

dependency. There are two, simultaneously taken action tracks. First is long-term research and development funding for recycling and developing substitute materials for current key minerals. At same time there is the need to develop critical mineral supply chain inside NATO and partner nations and co-operate diversifying process from Chinese and Russian key minerals. However, the problem especially in case of REEs is that it is possible China would flood markets with REEs to when other nations are about starting mining or production. In this case, governmental subsidies are needed to financially support new production.

Long, 10 to 20 years perspective has several possible futures. If NATO nations are satisfied with status quo, future electrical vehicle and hybrid powertrain supply chains will be located in China along knowhow, jobs, and associated military capabilities they enable. If long-term research and development funding for recycling and developing substitute materials is initiated in time along new supply chain (from mining to end-products), future is likely less dystopic. However, technological development does not stand still and it is possible that other new key minerals emerge from new technologies.

If NATO nations are not able to take drastic, coherent politico-economical joint actions to secure key minerals' supply chain to at least PFP-countries' soil, improve recycling and establish strategic key minerals reserves, North America's, Europe's and Oceania's ability to produce high-tech products, know-how and hybrid-powertrain enabled military abilities highly likely erode in 5-10 years mid-term perspective.

Addendum: Key Minerals for hybrid powertrains

Note: Only the metals/minerals that are deemed as critical by both or either the EU or the US are included in the list. Each of the metal in the list is discussed on several aspects. Firstly, the importance of the mineral is presented, based on the demand for its end-technologies. Then, the geographic concentration and import reliance of the EU and the US aims to show the dependence of NATO countries on external partners. The governance of those regions is also discussed for some of the minerals, if it is problematic. It aims to show the hidden social costs of decarbonizing, that should be taken into account when determining who to partner with. To secure the supply of critical raw materials, the EU and the US must diversify their suppliers by minimizing their reliance on China, recycle, and use alternative materials. Therefore, the

potential suppliers, recyclability and substitutability of each of the critical materials is presented.

Rare earths

Importance

Rare earth minerals are normally used for the production of electric motors, specifically the permanent magnets within the motors. The magnets include many of the rare earths, with the most important being light rare earths (LRE) neodymium, praseodymium, lanthanum, and cerium, and heavy rare earth (HRE) dysprosium. The permanent magnets are necessary for any kind of electric or hybrid vehicle. Also, some of the nickel-types of batteries use rare earths too.

Geographical concentration and governance

Most REEs are mined and processed in China. China produces 70-90% of all global rare earths depending on calculating method. The dispute between China and Japan in 2010, has shown that China is capable of halting supplies for political reasons.

Import reliance

The EU sources 98% and 99% of heavy and light rare earths, respectively, from China. The remaining percentage comes from the UK.⁶⁴ As of 2019, the US has the second biggest mining capabilities of rare earths, in the Mountain Pass in California. Lanthanum, neodymium, and cerium are also extracted there. Nevertheless, the US gets around 80% of rare earths from China.⁶⁵ In sum, the EU and the US are highly dependent on China for the rare earth elements.

Recyclability

The recycling efforts of rare earths are increasing both in the EU and the US. However, at the moment, the EU currently uses 10% of recycled praseodymium, 1% neodymium and cerium, and none of dysprosium or lanthanum. According to the U.S. Geological Survey, only the limited capabilities of rare earths are recycled.⁶⁵

⁶⁴ European Commission (2020). Raw Materials Initiative.

⁶⁵ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Rare Earths

Substitutability

Scholars, such as American Chemical Society in the US, are working towards inventing new permanent magnet alternatives, that would be free from rare earths.⁶⁶ As of now, there are no widely used alternatives.

Potential suppliers

President Trump set a goal to move the entire supply chain of rare earths to the US, to tackle the China's dominance of the industry.⁶⁷ Currently, the only one mining site in California, sends its ores to China for processing. The Pentagon is to designate at least \$125 million to fund various rare earth projects from 2020 onwards⁶⁸. A number of companies in the US has tried to develop sites for rare earths. However, none of them process meaningful amounts of the metals. Experts believe it would take about a decade for the US to be able to reach the goal. Having said that, the USA Rare Earth-company aims to build the first rare earth and critical minerals processing facility outside China, called Round Top mine, near El Paso, expected to be running by 2023.^{67,69} They have already successfully completed the Phase 1: rare earth separation and processing test. Experts believe this project will need time, great amounts of continuous governmental investment and tolerance for pollution.

Just immediate surroundings of Narsaq town in Greenland is estimated to hold around a quarter of world's rare earths⁷⁰. US administration signed IN 2019 a memorandum of understanding with Greenland to map the country's geology and help develop mining sectors, including the ones of REEs.⁷¹ However, China and its mining companies have been very active in Greenland while securing key minerals globally⁷².

⁶⁶ [American Chemical Society \(2019\)](#). New alternatives may ease demand for scarce rare-earth permanent magnets.

⁶⁷ [The New York Times \(2020\)](#). U.S. Companies Vie for Funds in Race to Build Rare Earths Industry.

⁶⁸ <https://www.defensenews.com/congress/2020/05/18/pentagon-legislation-aims-to-end-dependence-on-china-for-rare-earth-minerals/>

⁶⁹ [USA Rare Earth \(2020\)](#). USA Rare Earth Successfully Completes Phase I Rare Earth Separation and Processing Test Work.

⁷⁰ <https://www.npr.org/2019/11/24/781598549/greenland-is-not-for-sale-but-it-has-the-rare-earth-minerals-america-wants>

⁷¹ [U.S. Department of State \(2019\)](#). Joint Statement on U.S.-Greenland MOU and Hyperspectral Survey.

⁷² <https://www.diis.dk/en/research/greenlands-minerals-to-consolidate-chinas-rare-earth-dominance>

Cobalt

Importance

Cobalt is one of the most important materials for the production of Lithium-ion, some of the most common types of nickel batteries, and powder metal components within the electric motors, all of which are used in the hybridization of land, air, and water vehicles. Cobalt is one of those materials that is expected to be needed increasingly in the future, due to the rise of EVs consumption. The demand for cobalt was expected to increase by 60% until 2025, according to the McKinsey & Company report in 2018.⁷³ However, the COVID-19 crisis has indeed dampened the demands and made the future prospects uncertain. Furthermore, the shortage of the material is real. Multiple companies in differing sectors are in competition to secure the supplies of cobalt. Apple was announced to be in talks to purchase cobalt directly from the miners, while BMW and Volkswagen are also looking for multiyear deals.⁷⁴

Geographical concentration and governance

The Democratic Republic of Congo (DRC) is the global supplier of cobalt. Mine production there is associated with unstable political conditions and business difficulties.⁷⁵ The second-largest mining capabilities of cobalt are in Australia. China has the biggest refinery capacity of cobalt, which is mostly imported from Congo (Kinshasa).

Import reliance

The EU sources 68% of cobalt from DRC, and the remaining percentage from Finland (14%) and French Guyana (5%).⁷⁶ The US imports cobalt from a big variety of countries.⁷⁷ The top supplier for the US is Norway (17%), followed by Japan (13%), and China (11%). The remaining 48% comes from other countries. The US also has mining capabilities for cobalt, producing less than 1%.

Recyclability

22% of the EU's demand for Cobalt is met by recycling. For the US, 29% of cobalt consumed, came from purchased scrap.

⁷³ [McKinsey & Company \(2018\)](#). Lithium and Cobalt: A tale of two commodities.

⁷⁴ [Bloomberg \(2018\)](#). Apple in Talks to Buy Cobalt Directly From Miners.

⁷⁵ [The Washington Post \(2019\)](#). Demand for Congo's cobalt is on the rise. So is the scrutiny of mining practices.

⁷⁶ [European Commission \(2019\)](#). Raw Materials in the Battery Value Chain in EU Science Hub: Raw Materials Information System

⁷⁷ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Cobalt

Substitutability

Cobalt is sometimes substituted by manganese, iron, or nickel in the production of Lithium-ion or nickel-types batteries.^{78, 79} Nevertheless, cobalt in lithium-ion batteries is reduced rather than eliminated, as elimination of cobalt could result in loss of performance.⁷⁷ The substitutions for cobalt are crucial, since there is not enough of it for future global consumption. Cobalt-free battery alternatives are perceived as important to pursue, by companies, such as Tesla and CATL.

Potential suppliers

Finland and Sweden have the highest potential for discovering cobalt-containing minerals, of all European countries.⁸⁰ Finland, Poland, and Norway are already producing some of the cobalt. Regardless of the potential mines in Europe, and other democratic countries, such as Canada or Australia, experts believe the reliance on DRC for cobalt will only rise.⁸¹

Natural graphite

Importance

The anode of lithium-ion battery is usually completely made of graphite. Nevertheless, recently, new structures of anode were invented, with increasing use of silicon metal (around 50% of it).⁸² Either way, natural graphite is very important for hybridization of powertrains. Furthermore, natural graphite is important not only for the production of batteries, but also for the steel and automotive industry, meaning there is a great competition among them.

Geographical concentration and governance

The global reserves of natural graphite are concentrated in Turkey (31%), China (25%), and Brazil (24%).⁸³ The mine production is highest China (70%), followed by Mozambique and Brazil. China also refines most of natural graphite. The Chinese mining industry is fragmented, with some of the mines aging. There are many environmental problems around the mining and processing of natural graphite, namely the dust emissions and wastewater disposal.

⁷⁸ T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. vol. 112, n. 20.

⁷⁹ [European Commission \(2018\)](#). Cobalt: demand-supply balances in the transition to electric mobility.

⁸⁰ [Geo Foorumi \(2018\)](#). GTK increases the surveying of battery minerals.

⁸¹ [Green Tech Media \(2018\)](#). Reliance on Congo Cobalt Grows Despite European Discoveries.

⁸² [Chemical and Engineering News \(2019\)](#). In the battery materials world, the anode's time has come.

Import reliance

The EU sources 47% of natural graphite from China, followed by Brazil (12%), Norway (8%), and Romania (2%). The US imports most of it from China (33%), Mexico (24%), Canada (16%), India (9%), and other (18%).⁸³ China is the main supplier of graphite to the EU and the US, which is the major reason why it is deemed as critical.

Recyclability

Approximately 3% of EU demand for natural graphite is recycled.

Substitutability

Natural graphite can be and often is substituted with synthetic graphite for Li-ion production, which is also concentrated in China. As mentioned above, silicon metal is increasingly used in the anode of lithium-ion batteries, substituting natural graphite. However, experts believe graphite will remain a key raw material in battery production for EVs for at least the next decade.⁸⁴

Potential suppliers

Turkey has significant potential graphite resources.⁸⁵ The Geological Survey of Finland (GTK) are conducting studies to evaluate the quality of their graphite supplies.⁸⁶ North America has flake graphite resources: Canada is already a producer, while the US have multiple new projects.⁸⁷ The projects in the US are expected to take decades to develop, as well as it is not likely to meet all of the demand.

Lithium

Importance

Lithium is considered as one of the most important materials for EVs development. Assuming that lithium-ion are the batteries of the future, the demand for lithium is expected to increase threefold between 2017 and 2025.⁷³ Fortunately, the supply of lithium is not expected to be an issue in the short or medium term for lithium-ion production, according to the European Commission (2020).

⁸³ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Graphite (Natural)

⁸⁴ [Investing News \(2019\)](#). 9 Top Graphite-mining Countries.

⁸⁵ <https://eurogeologists.eu/sari-hidden-graphite-resources-in-turkey-a-new-supply-candidate-for-europe/>

⁸⁶ [GTK \(2020\)](#). The survey of Finland's battery mineral potential continues.

⁸⁷ U.S. Geological Survey (2016). Natural graphite demand and supply - Implications for electric vehicle battery requirements.

Geographical concentration and governance

The lithium triangle: Bolivia, Chile, and Argentina, have most of lithium reserves. However, lithium mine production is the highest in Australia (55%), Chile (23%), China (10%), and Argentina (8%).^{88, 89}

Import reliance

The EU imports processed lithium from Chile (78%), followed by the US (8%), and Russia (4%). The US sources most of it from Argentina (53%) followed by Chile (40%), China (3%), and others (4%).⁸⁹

Recyclability

Most components of lithium-ion batteries can be recycled, but the cost of material recovery remains a challenge for the industry. American company has been recycling lithium-ion batteries since 1992 in British Columbia, Canada. In 2015, the first US recycling facility for lithium-ion vehicles batteries began operating in Ohio.⁸⁹

Substitutability

There are various options of lithium substitution in primary batteries, such as calcium, magnesium, mercury, and zinc as anode material.⁸⁹ However, it is not viable for the rechargeable batteries.

Potential suppliers

Australia is currently mining most of the world's lithium. However, neither the US, nor the EU is importing a substantial amount of it from Australia. Furthermore, new mining operations are set to commence in the US, and the UK. The deposits in Cornwell, UK are said to be globally significant and will soon be able to supply almost all of the UK's demand for lithium.⁹⁰ Finland also has significant lithium deposits in the Ostrobothnia region. However, the mining has not yet started.⁸⁰

Aluminum (Bauxite)

Importance

Aluminum is used in Nickel-Metal Hydride (Ni-MH) batteries. Aluminum is also needed for the cathode of lithium-ion batteries, even if the amounts of it are not huge. Aluminum is a metal that is made out bauxite ore. Bauxite is mined, then refined to alumina and finally alumina is

⁸⁸ United Nations (2020). Commodities at a Glance: Special Issue on Strategic Battery Raw Materials.

⁸⁹ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Lithium.

⁹⁰ [Mining.com \(2020\)](#). Cornish Lithium finds "globally significant" grades at UK project.

refined to aluminum. 4kg of bauxite produces 2kg of alumina and 2kg of residue, then 2kg of alumina produces 1kg of aluminum. It should be noted that rare earth element Scandium is mainly sourced more economically from bauxite.

Geographical concentration and governance

Bauxite is mostly extracted in Australia (27%), Guinea (22%), China (20%), Brazil (8%), and India (7%). The majority of alumina is refined in China (56%), followed by Australia (15%).

Import Reliance

The EU imports most of bauxite from Guinea (64%), Greece (12%), Brazil (10%), and France (1%). The US imports alumina from Brazil (39%), Australia (31%), Jamaica (9%) Canada (5%), and other (16%); and bauxite from Jamaica (51%), Brazil (23%), Guinea (10%), Guyana (7%), and other (9%).⁹¹

Recyclability

Both the US and the EU recycle none of the aluminum (bauxite).

Substitutability

Although currently not economically competitive with bauxite, vast resources of clay are technically feasible sources of alumina.

Potential suppliers

According to ENSUREAL Sustainable Aluminium Production, which receives funding for the European Union, Europe has significant resources of bauxite, which are not exploited at the moment due to technological and cost reasons.⁹² Mediterranean countries have known bauxite deposits, including EU-countries Italy and Greece.

Antimony

Importance

Antimony is used for the traditional types of lead-acid batteries. Lead-acid batteries are expected to be technologically overruled by lithium-ion. However, it can be argued that lead-acid batteries will remain to be important, especially for the military transportation, since most of the military hybrid vehicles, that are already in use, utilize lead-acid batteries.^{93, 94}

⁹¹ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Bauxite and Alumina.

⁹² [ENSUREAL \(2020\)](#). Aluminium is an important strategic material for Europe.

⁹³ Australian Government: Department of Defense, Science, and Technology (2017). Review of Battery Technologies for Military Land Vehicles.

⁹⁴ [UPS Battery Center \(2016\)](#). Why There are Lead-Acid Batteries on Submarines.

Geographical concentration and governance

China is the biggest global producer of antimony, with 74% of it coming from there. Tajikistan and Russia are the next largest producers.

Import Reliance

The US sources 67% of it from China, followed by Mexico (15%), Belgium (7%), and others.⁹⁵ However, the EU sources most of it from Turkey (62%), followed by Bolivia (20%) and Guatemala (7%).

Recyclability

The EU recycles 28% of the antimony needed. According to the U.S. Geological Survey, most of the antimony is recycled and consumed by the lead-acid battery industry as antimonial lead.

Substitutability

Combinations of calcium, copper, selenium, sulfur, and tin are substitutes for alloys in lead-acid batteries.

Potential suppliers

There are no potential reserves within the European Union or other Western democracies. The US and Australia mines some of antimony but the amounts are insignificant.

Nickel

Importance

Nickel use globally is approximately: 68% in stainless steel; 10% in nonferrous alloys; 9% in electroplating; 7% in alloy steel; 3% in foundries; and 4% other uses (including batteries). Battery use is critical when considering hybrid powertrains.⁹⁶

Geographical concentration and governance

Indonesia owns the largest nickel reserves of the world (22%) and is also by far the largest producer. Australia's has second largest reserves (21%), then Brazil(12%, Russia(7%) and Cuba (6%).⁹⁷

⁹⁵ [U.S. Geological Survey \(2020\)](#). Antimony. (Chapter C of Critical Mineral Resources of the United States— Economic and Environmental Geology and Prospects for Future Supply)

⁹⁶ https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf

⁹⁷ <https://www.nsenergybusiness.com/features/nickel-reserves-countries/>

Recyclability

No statistics available.

Substitutability

Titanium alloys can substitute for nickel metal or nickel-base alloys in corrosive chemical environments. Lithium-ion batteries may be used instead of nickel metal hydride batteries in certain applications

Potential suppliers

There are potential new nickel resources for example in Canada (British Columbia), US (Nevada) and Finland.⁹⁸⁹⁹

LONGER-TERM

The metals below are going to be increasingly used for the lithium-ion batteries of the future, according to the European Commission. New advanced types of Li-ion batteries are being constantly investigated by the scientists, mostly, in order to improve energy density of the batteries. However, it is not exactly known when those new times will become common in practice. European Commission has included all of the following metals in their critical raw materials list, due to their belief that those technological improvements of batteries are being commercialized soon.

Titanium

Importance

Titanium is increasingly used for lithium-ion batteries, for especially the new compositions of a battery, which aim to carry the specific energy in smaller weight and volume. New anodes and coating materials include titanium, as well as in battery packaging, to make it closer. This element has also been used for nickel-types of batteries. Titanium is also used for the second most common compound of Nickel-Metal Hydride batteries.

Geographical concentration and governance

⁹⁸ <http://verkkolehti.geofoorumi.fi/en/2015/10/significant-metal-resources-are-waiting-to-be-discovered-in-finlands-bedrock/>

⁹⁹ <https://www.bnnbloomberg.ca/why-the-future-is-bright-for-nickel-exploration-1.1562606>

The majority of processed titanium is produced in China (45%), Russia (22%), and Japan (22%).

Import Reliance

EU is 100% reliant on foreign imports for titanium and Norway with 25%, South Africa with 18%, Canada with 16% and Australia with 11% are the major suppliers for the countries of the European Union. . The U.S. Geological Survey distinguish titanium to sponge metal and titanium dioxide pigment.¹⁰⁰ The sponge metal is mostly imported from Japan (86%), followed by Kazakhstan (8%) Ukraine (4%), China (1%), and Russia (1%). Titanium dioxide pigment is imported from Canada (35%), China (25%), and Germany (9%).

Recyclability

The EU recycles 19% of titanium it demands. Titanium recycling in the US makes up a substantial part of domestic consumption too, but the numbers are unknown.

Substitutability

Titanium due to its quite exceptional strength-to-weight ratio and corrosion resistance is going to increasingly be used for Li-ion batteries. Thus, it can be seen as a substitute for other metals used in Li-ion right now.

Potential suppliers

Australia was just restarting mining activities at the Jacinth-Ambrosia Mine in South Australia. In Greenland, the Dundas mining project on the northwestern coast suggest a production capacity of up to 440,000 tons per year. It is planned to start around 2021.

Niobium

Importance

Niobium, just like titanium, is increasingly used for new compositions within the Lithium-ion batteries. The future anode and cathode materials will increasingly use Niobium, to improve stability and energy density.

Geographical concentration and governance

Around 88% of niobium is mined in Brazil, followed by Canada (10%).

¹⁰⁰ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Titanium.

Import Reliance

The US imports ferroniobium and niobium metal from Brazil (70%), Canada (26%), Germany (2%), and other.¹⁰¹ The EU imports most of it from Brazil (85%) and Canada (13%).

Recyclability

In the US, around 20% of apparent consumption of niobium is recycled. The EU does not recycle any of it.

Substitutability

There are possible substitutes of niobium, but likely worse performing and more expensive. Since niobium, like titanium, are planning to be used in Li-ion batteries in the future, they are considered to be substitutes themselves. This part is thus irrelevant.

Potential suppliers

United States (Colorado, Nebraska, Texas).¹⁰²

Silicon Metal

Importance

Silicon metal is not considered to be a critical material for the US; however, it is for the EU. Silicon metal is increasingly used in the anode of the lithium-ion batteries, substituting for some of the natural graphite and improving the anode capacity and energy density of the battery.

Geographical concentration and governance

China exports most of the already processed silicon metal, 66%. However, the EU sources it mostly from Norway and France (30% and 20%, respectively), while Norway and France, have 6% and 4% of the world's supply, respectively.

Recyclability

Not recycled in the EU.

Substitutability

Silicon metal is not a necessary component for lithium-ion batteries; however, it is increasingly used to make the batteries denser.

Potential suppliers

¹⁰¹ [U.S. Geological Survey \(2020\)](#). Mineral Commodity Summaries. Niobium.

¹⁰² https://www.usgs.gov/news/usgs-updates-mineral-database-niobium-deposits-united-states?qt-news_science_products=1#qt-news_science_products

The US, Canada, France, Iceland, Norway, Poland, and Spain has reserves of silicon metal, which are not substantial compared to China, but could be an option for diversification.

Probability assessment definitions

Definitions used in this product:

Almost certain >90%

Highly likely 75-85%

Likely 55-70%

Possible 40-55%

Plausible 25-40%

Unlikely 15-20%

Highly unlikely <10%

Short term 1-5 years

Medium term 5-10 years

Long term 10-20+ years

Acronyms Used:

BMW	Bayerische Motoren Werke
CATL	Contemporary Amperex Technology Co., Limited
COTS	Commercial off-the-shelf
COVID	Coronavirus disease
DGA	la Direction générale de l'armement
DRC	Democratic Republic of Congo
ENSUREAL	Ensuring Zero Waste Production Alumina in Europe
EU	European Union
EV	Electric Vehicle
GTK	Geologian Tutkimuskeskus / Geological Survey of Finland
HRE	Heavy Rare Earths
JMSDF	Japan Maritime Self-Defense Force
Li-ion	Lithium ion
LRE	Light Rare Earths
NATO	North Atlantic Treaty Organization
NdFeB	Neodymium-Iron-Boron
Ni-MH	Nickel-Metal Hybride
PPP	Purchasing Power Parity
REE	Rare Earth Elements
R&D	Research & Development
SOE	State-owned enterprise
UAV	Unmanned Aerial Vehicle
USGS	Unites States Geological Survey
VPN	Virtual Private Network
Wh	Watt-hour