András Edl

Supply Chains and Space Capabilities in the New Space Age

Introduction

The globalisation of value chains has had a significant impact on the U.S. and EU economies and, as a consequence, on their defence and space capabilities. From the point of view of supply chains and production capacities, the military and civil space sectors are tightly interconnected and will become even more so in the future. Recent years have witnessed increasing instances of supply chain disturbances which have directly or indirectly affected the space sector, highlighting its vulnerability. This chapter will examine the interconnectedness between geopolitics, supply chains, raw materials and space activity. Limiting the analysis to the space supply chain would only provide a limited understanding of the challenges the sector faces today or might face in the future which could hold it back from reaching its full potential.

The Growth of the Space Sector

One of the most well-known and often repeated facts about New Space is that the sector is growing rapidly and opening many new opportunities to participants. A key measurement of this growth is the increasing revenue generated by the market and its future prospects seem to be very promising, which is a strong incentive to invest in the sector. However, the amount of actual revenue generated by the industry is not easy to identify, and the sources of it vary greatly. The numbers for 2023 are not available yet, but there are considerable

DOI: https://doi.org/10.36250/01208_20

deviations even in the 2022 figures. The Space Foundation reported a revenue of USD 546 billion,[1] while Euroconsult gave a figure of USD 464 billion[2] and the Satellite Industry Association (SIA) estimated it at USD 384 billion.[3]

The differences can be often attributed to different calculating methods, simply due to the fact that it is not always easy to decide what constitutes revenue generated by space. How much of a delivery company's profit can be attributed to the GPS they use? What about a company providing data about agriculture which uses Earth observation satellites among many other sources of information? There is no consensus about what should be included and to what degree when calculating the value of the industry. The OECD is aware that there is a wide disparity between the numbers and suggests a range rather than attempting to name a single figure, stating that space revenue excluding government spending is between USD 200–350 billion.[4] At the same time,

Table 1
Change in the value of the space economy in billion USD from 2019 to 2022 based on SIA data

	2019	2022	Difference	Growth in %
Global Space Economy	366.0	384.0	18.0	4.91%
Government Spending	95.0	103.0	8.0	8.42%
Satellite Industry	271.0	281.0	10.0	3.69%
Satellite Service	123.0	113.0	**−10.0**	**−8.13%**
Ground Equipment	130.3	145.0	14.7	11.28%
Satellite Manufacturing	12.5	15.8	3.3	26.40%
Share of the U.S.	*7.8*	*10.2*	*2.4*	*30.76%*
Launch Industry	4.9	7.0	2.1	42.85%
Share of the U.S.	*1.7*	*3.9*	*2.2*	*129.41%*

Source: Compiled by the author.

1 Space Foundation 2023.
2 Euroconsult 2023a.
3 Satellite Industry Association 2023.
4 OECD 2023.

the OECD also encourages discussion about the proper methodology for estimating these amounts and has published material about the topic.[5]

Even if we take the most conservative estimates, the growth figures are impressive.

Based on the SIA's dataset the sector's total revenue in 2019 was around USD 366 billion. Of this, USD 271 billion was from the satellite market. In that subsector, USD 123 billion is derived from services provided by satellites, telecommunications, satellite detection, etc. USD 130.3 billion is the value of the terrestrial infrastructure and the launch industry reported a profit of USD 5 billion.[6] In comparison, by 2022, so after only three years, there had been substantial growth in nearly all aspects.[7] The value of ground equipment, satellite manufacturing and the launch industry as a percentage grew by double digits. The performance of the U.S. exceeded the world average, especially in the launch industry sector, while non-U.S. commercial launches even decreased by USD 0.1 billion. This growth is largely due to SpaceX. In 2019 the company only performed 13 launches, while the world total was 102. 78 of these were commercially procured launches. In 2022 the company carried out 61 launches from a total of 186 global launches, of which 161 were commercially procured. The company shows no signs of slowing down, and in 2023 they completed 96 launches.[8]

Government spending is estimated by the three sources in a range between USD 103 and 119 billion. While the SIA does not provide data on it, the U.S. governmental space budget is between USD 69.5 and 73.2 billion according to the Space Foundation and Euroconsult. There are even fewer sources for Russian and Chinese spending due to a lack of data and the rather opaque relations between civil and military entities. Euroconsult estimated the Chinese budget at USD 14.15 billion while the Russian budget was at USD 3.4 billion. Euroconsult

5 OECD 2022.
6 Satellite Industry Association 2019.
7 Satellite Industry Association 2023.
8 SpaceX 2024.

also highlighted a significant change compared to previous years, as for the first time space defence spending surpassed the budget for civil programmes, at USD 59 billion.[9]

Not surprisingly, the predictions about how much the industry will grow also vary. Jules Varma of the ESA compared a few predictions. For entities which did not give such estimates, he extrapolated their figures and used their calculating methods to illustrate how they would evaluate the space sector's performance in 2040. The Union Bank of Switzerland estimates this 2040 value at USD 926 billion, Morgan Stanley puts it at USD 1.1 trillion, the U.S. Chamber of Commerce gave a figure of USD 1.5 billion, Goldman Sachs goes for the multi-trillion range, while the SIA's projected value calculated by Varma would be USD 580 billion.[10] The origin of most of these predictions can be traced back to a 2017 study by Morgan Stanley. Nevertheless, estimates all agree that there will be considerable growth and suggest that the value of the sector could double by 2040. Calculating the often mentioned high economic multiplier effect also poses various challenges. This number is supposed to show how much the total economic output increased after every dollar invested in the space sector. There is agreement among experts that even for less advanced economies, space investment can be beneficial and have a positive multiplier effect. However, the actual figure depends on the calculation methods employed (e.g. based on income, expenditure and production method), which will have different effects in various sectors, and it is dependent on the development level of a given economy. The analysis of calculating methods and their results is not the subject of this paper but the most frequent numbers are from 5 to 9 for countries with highly developed space sectors. For countries in the early stages of space development, the multiplier could be from 1.5 to 5 in this field.[11]

Another indicator that is widely used to demonstrate the rapid expansion of the space economy is the number of satellites in space. Back in 2020, more conservative assessments assumed that the number of satellites would reach

[9] Euroconsult 2023b.

[10] Varma 2023.

[11] Barjak et al. 2015.

10,000 by 2029, with the most optimistic estimate being close to 100,000.[12] The Union of Concerned Scientists (UCS) maintains a database about the number of satellites and usually updates its figures three times a year. On 1 April 2020, there were 2,666 satellites in space. On 31 July 2020, the UCS reported 2,787 satellites orbiting the Earth, of which 1,425 are owned by the United States or U.S. companies.[13] The majority of these satellites, around 2,032, were in Low Earth Orbit (LEO). The same database gave a figure of 7,560 satellites by 1 May 2023, among which 5,184 were U.S. satellites.[14] By 11 February 2024, this number had reached 9,359. This rise in numbers is undoubtedly impressive. However, the context is important. The building of megaconstellations has had a significant impact on these statistics. 5,236 of the satellites were active Starlink satellites. OneWeb had an additional 632 active assets in LEO.[15] Based on this, unless there are significant developments, we can assume that the number of active satellites will exceed 10,000 in 2024. The amount of space debris is just as significant. According to the ESA's calculations, in December 2023 there were 36,500 pieces of space debris larger than 10 cm, 1,000,000 debris objects between 1 cm and 10 cm and approximately 130 million pieces from 1 mm to 1 cm.[16]

MINERALS FOR THE SPACE SECTOR

In order to realise the full potential of the industry and to accomplish the goals of crucial scientific and defence projects, the space sector needs an industrial base. The supply chains of the space industry have many sector-specific attributes. The uses of rare earth elements show how much the space industry can be affected. As Bleddyn E. Bowen puts it, the value chains for the space

12 Satellite Industry Association 2020.
13 Datta 2020.
14 Union of Concerned Scientists 2023.
15 Orbiting Now 2024.
16 European Space Agency 2023.

industry extend across nations, continents and oceans. Maintaining a space industry supply chain (or rather a network) consisting only of companies in one specific country would be very costly or often impossible. The solution is to rely on foreign countries and companies, but if external actors are used, there is a risk that they will not provide capacities according to the needs of the country concerned.[17]

Moreover, the sector requires numerous high-technology and high-quality components which are able to withstand the harsh environment of space or another celestial body. For example, Intelsat's Galaxy 30 (G-30) communication satellite is made up of several hundreds of units which are themselves made of several hundreds of components in total having more than a hundred thousand components.[18] The satellite weighs 3,298 kg and uses a GEOStar-2 Bus as the basis for its specific configuration. This design was originally built by Orbital ATK and the fact sheet provided states that the 800–1,500 kg dry mass bus, with a payload capacity of 500 kg usually takes 2 years to manufacture.[19] The company was acquired by Northrop Grumman in 2018 and renamed Northrop Grumman Innovation Systems. This firm also delivers the more advanced GEOStar-3 design with a 1,000 kg payload mass capacity, which is also supposed to be delivered 24 months after the order was placed.[20]

To manufacture all the necessary components at the first level of the supply chain, raw materials are needed, and without these no production is possible. To model the concept of the supply chain and the role of each step depending on the approach some classifications have divided the chain into upstream, midstream and downstream levels. Other models only distinguish between upstream and downstream. The mining of raw materials is usually at the beginning of each supply chain or it is among the first levels of the upstream category. The following diagram presents a more detailed model of the mineral value chain.

17 Bowen 2020: 139–148.
18 Intelsat 2021.
19 Orbital ATK 2017.
20 Northrop Grumman 2024.

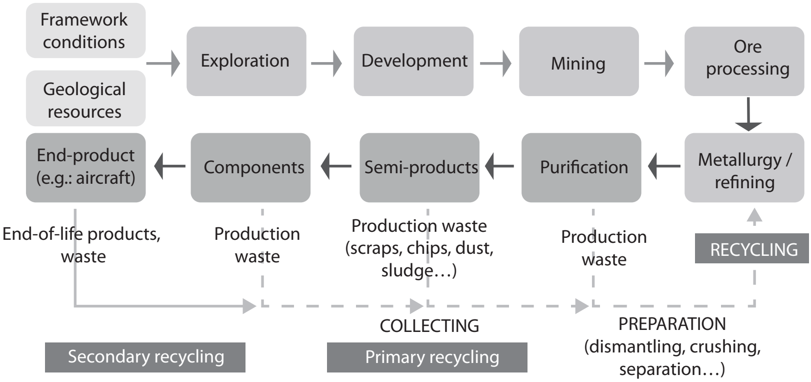

Figure 1
Schematic representation of a minerals or metal-dependent value chain
Source: Ayuk et al. 2020

Depending on the supply chain model, ore processing, metallurgy/refining or purification could be the highest level of the upstream category, although these are sometimes put in the mid-stream category.

A 2023 report by the EU Joint Research Centre on supply chains and material demand forecast dedicates a whole section to space. The report combines launchers and satellites into a category called space systems. According to the report, the European space sector itself is somewhat concentrated in terms of both geography and the corporations involved. Four industrial groups (Airbus, Thales, Safran, Leonardo) dominate the sector, along with smaller players such as OHB, RUAG or GMV and these corporations are mostly located in France, Germany, Italy, Spain, Belgium and the U.K., which is still a member of ESA. The report also provides a list of elements that are crucial for the space industry. Critical raw materials as per the EU's definition are important for the European economy and have a high risk of supply disruption. Strategic raw materials are a subgroup of critical raw materials, and they are the most important for strategic technologies used in green, digital, defence and space applications. Table 2 lists the critical raw materials for the space sector and a few of their usages:

Table 2
Critical raw minerals for the space sector

CRM	Usage
Aluminium (Al)	component for metal alloys
Antimony (Sb)	glasses and ceramics in optical devices
Arsenide (As)	semiconductors
Beryllium (Be)	component for metal alloys
Chromium (Cr)	coating for alloys
Hafnium (Hf)	component for metal alloys
Helium (He)	for pressurisation tanks, inert purge and cooling agent
Niobium (Nb)	mostly in nozzle and thrusters as metal alloy components
Phosphorus (P)	semiconductors for photovoltaic panels, treatment of lenses and optical filters
Vanadium (V)	in metal alloys for structural and propellent tank parts

Source: Compiled by the author.

Strategic raw materials are a subgroup of critical raw materials, and they are the most important for the strategic technologies used in green, digital, defence and space applications.

The list also contained xenon and krypton as propellants for Hall effect power systems, but they were not considered to be critical or of strategic importance by the EU, similar to other elements of which the EU has an abundant supply.[21] China, Australia, Japan and Canada also maintain lists of raw materials whose supply is of crucial importance to their economies. In 2022 Japan was the only one of these countries which had lead (Pb) on its list, while China was the sole country to include oil and iron on its list.[22]

[21] Carrara et al. 2023: 128.
[22] Su–Hu 2022.

Table 3
Strategic raw minerals for the space sector

SRM	Usage
Bismuth (Bi)	propellant for electric propulsion (Hall thruster)
Boron (B)	special glass ingredient for optical instruments
Carbon (C)	space-grade composite materials, like graphite, space-grade ceramics and silicon carbide, coating combined with other elements
Cerium (Ce)	increasing radiation resistance
Cobalt (Co)	alloys especially for injectors and thrusters, cathode materials, semi-permanent magnets
Copper (Cu)	electronics and wiring
Gallium (Ga)	semiconductors and chips used for satellite communications, lasers, solar panels, spacecraft power management
Germanium (Ge)	solar cells and semiconductors, infra-red filters
Lithium (Li)	alloys, batteries, glasses and ceramics for optics
Magnesium (Mg)	light alloys
Nickel (Ni)	alloys especially for injectors and thrusters, 3D printing powder
Phosphorus (P)	semiconductors for photovoltaic panels, treatment of lenses and optical filters
Platinum group minerals[23]	nozzles and combustion chambers (specific usage for different elements, e.g. iridium (Ir) container for plutonium fuel, coating on X-ray mirrors)
Rare earth elements[24]	Semi-permanent magnets, crystal laser sources, glass for optical devices (specific usage for different elements, e.g. samarium [Sm] in magnets for three-axis attitude control system, or in magnets exposed to huge temperature variations)
Titanium (Ti)	metal alloys, electro-optical systems and robotic devices
Tungsten (W)	alloys for nozzle and thrusters

Source: Compiled by the author.

[23] Platinum group metals (platinoids): ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), platinum (Pt).

[24] Rare earth elements: a group of 17 elements, the lanthanides group: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu). In addition, yttrium (Y) and scandium (Sc) are also included in the group.

Different countries have different critical or strategic mineral lists, depending on their production, circle of allies and industrial needs. Examining only the materials relevant to the space industry listed above, significant differences between them are evident:

Table 4
Critical and strategic metal lists comparison in relation to the space industry

Material	U.S.	EU	PRC
Aluminium (Al)	x	x	x
Antimony (Sb)	x	x	x
Arsenic (As)	x	x	
Beryllium (Be)	x	x	
Bismuth (Bi)	x	x	
Boron (B)		x	
Carbon (graphite) (C)	x	x	x
Cerium (Ce)	x	x	
Chromium (Cr)	x		x
Cobalt (Co)	x	x	x
Copper (Cu)	x	x	x
Gallium (Ga)	x	x	
Germanium (Ge)	x	x	
Gold (Au)			x
Hafnium (Hf)	x	x	
Helium (He)		x	
Lithium (Li)	x	x	x
Magnesium (Mg)	x	x	
Nickel (Ni)	x	x	x
Niobium (Nb)	x	x	
Phosphorus (P)	x	x	x
Platinum Group Minerals	x	x	
Rare Earth Elements	x	x	x
Titanium (Ti)	x	x	
Tungsten (W)	x	x	x
Vanadium (Va)	x	x	

Source: EU critical mineral list; U.S. critical mineral list; Su–Hu 2022; Carrara et al. 2023

The obvious conclusion is that China is much less in need of minerals compared to the U.S. and Europe. The simple reason for this is that China is a mining powerhouse which cannot only cover its own needs but is also able to export various minerals. Indeed, many countries are heavily reliant on Chinese capacities, not only in raw material mining but also in refining and smelting. Anomalies like the presence of gold on China's list can be attributed to Beijing's decision to buy a large quantity of gold for financial reasons.

To give just a few examples of sensitive minerals for the space industry, in January 2023 the U.S. was heavily dependent on China for arsenic (100% dependency), gallium (100%), graphite (100%), tantalum (100%), yttrium (100%), bismuth (96%), antimony (83%), germanium (50%) and tungsten (50%). Many other elements were imported from other countries but the supply risk is more limited in the case of Mexico, Brazil or Canada.[25]

RARE EARTH ELEMENTS

The security risk posed by the disruption or loss of supply of raw materials and products imported from abroad has been a major concern for the United States and Europe since the early 2010s. This is especially true when China is involved. The space industry was also affected when China imposed restrictions on the volume of rare earth elements (REE) exports in 2009. China had gained an REE market share of 90% by the 2000s, which has affected the vulnerability of several countries and companies. This position in the world market was not a spontaneous development but the result of a deliberate long-term strategy by China intended to make the country dominant in the sector. Beijing was aware of the possible future influence it could wield due to REEs. As early as 1992, Deng Xiaoping compared REEs to oil in the Middle East.[26]

The reason for this is that the 17 metals in this group are essential raw materials for high-tech applications. They cannot be substituted or are very

25 U.S. Geological Survey 2023.

26 Pitron 2023: 92–94.

difficult to substitute, mostly with a loss of performance or only at the cost of increased weight, which is a crucial factor for all space equipment.

The 2012 U.S. National Strategy for Global Supply Chain Security highlighted this dependency problem. It stressed the need to make the supply system more secure while ensuring that any shortages can be quickly compensated for in the event of an incident.[27] The U.S. also established a research team in 2013 to find solutions to replace rare earth elements. However, the results of this effort were modest for several years.[28] New developments have emerged recently but industrial scale production and incorporation into designs remain elusive. One example of such progress is a 2022 announcement from Cambridge, where researchers managed to synthesise tetrataenite, an iron-nickel alloy only found in meteorites until their breakthrough. The lab-produced version has magnetic properties that are similar to REE magnets.[29]

Similarly to the EU, the U.S. has made efforts to increase domestic production. Decree 13817, issued on 20 December 2017, aims to help secure supplies of critical raw materials, mainly by developing the domestic private sector.[30] U.S. domestic production of certain REEs in 2019 was 26,000 tonnes (a 44% increase compared to 2018), but even for these elements imports still amounted to 14,000 tonnes. 80% of the country's REE imports between 2015 and 2018 came from China.[31] Washington therefore pushed for the previously loss-making mining at the Mountain Pass deposit in California to be re-started.[32] The operating company, MT Materials, has rapidly increased production, although the ore still had to be shipped to China for processing. However, the company planned to have the ore processed on site by 2022 and to produce magnets, which are also essential for the space industry. In November 2020, the Pentagon provided $9.6 million to achieve this goal.[33] The objective of on-site processing was met

27 The White House 2012.
28 Kalantzakos 2018: 77.
29 Zaleski 2023.
30 The White House 2017.
31 U.S. Geological Survey 2020.
32 Kalantzakos 2018: 16–28.
33 Magnuson 2020.

but the goal of magnet production was not achieved and in 2022 they had only started to build their factory in Fort Worth, Texas. The first phase production capacity will be around 1,000 tonnes of magnets which will be 1% of the current world production. Three other known sites in the U.S. and the EU are set to start production, hopefully in the near future. At the same time, China is still responsible for 90% of world production.[34] The Biden Administration continued to tackle the problem and has also implemented different policies. Executive Order 14017 and Executive Order 14051 are examples of these. The emphasis is on building up U.S. capabilities and developing supply chains while also managing stockpiles to serve as a buffer against potential problems.[35] Not surprisingly, the 2023 National Defense Industrial Strategy highlights the need for stockpiling as only a short-term tool. The document treats minerals as being equally important to chemicals, medical supplies, parts or technologies.[36]

Another option could be to source the metals from friendly foreign states. Australia, Myanmar, India, Vietnam and Japan seem to be suitable candidates. The latter discovered rich deposits on the seabed near Minami-Torishima Island in 2013. In 2021 a feasibility study was carried out which concluded that with new methods and considering the current needs, extraction is financially feasible.[37] Japan intends to test the technology in 2024 and this might be a crucial step towards achieving the goals set in the 2020 international research strategy. A key organisation in this regard will be the Japan Oil Gas and Metals National Corporation (JOGMEC).[38] A 2023 analysis evaluated 146 individual rare earth projects. Among these, many have not reached maturity yet but as soon as they are completed, they can form additional supply chains outside of China. Because of their military applications, heavy rare earth projects might have a greater impact on strategic positions, especially the ones promoted by the U.S. and Canada (Round Top, Zeus, Strange Lake, Bokan Mountain,

34 Okun–Cefai 2024.
35 The White House 2022.
36 U.S. Department of Defense 2023.
37 Yamazaki et al. 2021.
38 Pereira 2023.

Foxtrot sites). Projects in Europe, Greenland and Africa might have the greatest economic value but a significant number of projects have been delayed due to environmental issues and the protests of the local population.[39]

GALLIUM AND GERMANIUM

Of course, apart from the supply of REEs, there are other threats to space supply chain security. In July 2023, China announced limitations on its exports of gallium (Ga) and germanium (Ge), then in August the country did not export any of these elements at all. As noted above, both of these elements are important for the space sector. Gallium (Ga) is used for semiconductors and chips for satellite communications, lasers, solar panels and spacecraft power management. Germanium (Ge) is applied in solar cells, semiconductors and infrared filters. China gained a dominant position in the supply chain of these materials, especially in the case of gallium. By July 2023 China had gained a 98% share of the global market of the element. It is worth considering that the Western powers knew about the risk of such a monopoly situation arising. The U.S. Geological Survey has had gallium on its critical minerals list since 2018. According to a CSIS analysis, there was a bias towards a few minerals needed for green technologies and it simply did not pay attention to lesser-known minerals like gallium.[40] The U.S. and Europe reacted immediately, by launching recycling initiatives. One example is a joint project launched in 2022 between the U.S. Department of Defense and the Defense Logistics Agency. Instead of dumping old military optical equipment scrap into a landfill or selling it as scrap metal to China, they intend to recycle it and produce 2,200 to 3,000 kg of germanium. This could cover about 10% of the U.S. yearly consumption of germanium. The purity grade obtained is also reasonably good 99.999%.[41]

39 Liu et al. 2023.
40 Funaiole et al. 2023.
41 Reece 2022.

However, for high-end applications, this might need additional purification. Besides projects like this, governments have also approached private companies to start or re-start germanium and gallium production, but these projects still require time and cannot replenish the missing Chinese supplies, at least not within the near future.

A segment of the market compared the restriction of the two elements to the 2010 Chinese export control on rare earth elements. Like today, the materials were available in abundance, but only in China. Using the metals inside China and then taking the end product outside China was also legal. Worstall argues that the gallium and germanium supply problem can be solved just like the rare earth problem and that the West will find alternative sources although it might take a few years. Raw gallium can be obtained by refitting already existing bauxite processing plants and extracting the small quantities of gallium present in the ore. Raw germanium can also be secured when extracting zinc from sphalerite or fly ash from coal power plants. The output of this could be thousands of tonnes, while the world only uses 200 tonnes per year.[42] This is rational, as normally bauxite ore contains 30–80 ppm[43] gallium, and above 100 ppm is considered good quality. Black coal can contain up to 500 ppm and the ash remaining after burning the coal could even reach levels above 10,000 ppm, and thus above 1%.[44] Again, the Chinese dominance in the market was the result of a long-term strategy, because Beijing required its aluminium producers to have the capacity to extract gallium, effectively forcing companies in Germany, Kazakhstan, the U.K. and Hungary out of business. In time this production could be started again.

However, there is a shortage of processing plants that can refine the raw mineral up to the required purity for semiconductor production, although the technology is known and old plants can be reopened. The purity required

42 Worstall 2023.

43 ppm = parts per million. The amount of unit, usually a chemical, in relation to the substance that contains it.

44 Földessy 2020.

for semiconductor production is ultra high quality (usually 8N),[45] which is suitable for use in vacuum chambers part of an MBE[46] system. One facility that is able to produce gallium of such purity is the Vital Pure Metal Solutions plant in Langelsheim, Germany. The company is a fully owned subsidiary of Vital Materials Group. The plant restarted production in 2021 and its main customers include producers of compound semiconductors and optics or infrared advanced sensor manufacturers.[47] Another company active in the field is CMK, s.r.o. in Slovakia, which recycles and refines low quality (3N or 4N) gallium or even gallium arsenide scraps.[48]

Research projects are also working on ways to improve the existing technology. One example of such efforts is the Selective Vanadium recovery by the Alumina Refinery (VALORE) supported by the EU. The project should be ready by the end of 2024 and bring an already validated technology in a relevant environment (TRL5)[49] to a system prototype demonstration at an operational environment (TRL7) level. The technology will provide the tools to extract gallium and the often neglected vanadium during aluminium production. This technique will increase the purity of gallium and also provide an additional vanadium source which was often previously regarded as a waste product.[50] EU support can be crucial to such projects because, at this stage of technology development (between TRL 4 and 7), research institutes and private sector players do not prioritise investment.

This all may seem simple enough but the consequences should not be underestimated. Gallium-based semiconductors, or more precisely gallium

45 8N = N refers to the number of 9s in the purity grade. 99% of purity and 1% contaminating material is 2N, 99.99% purity is 4N, the highest commercially available grade is 9N (99.9999999%) purity.

46 MBE = Molecular-beam epitaxy. A special type of crystal growth or material deposition method used in semiconductor manufacturing and nanotechnology development.

47 Vital Pure Metal Solutions 2024.

48 CMK s.r.o. 2024.

49 TRL = Technology Readiness Level, the 9-grade classification system was originally developed by NASA in the 1970s for space exploration technologies. Level 1 is a basic principle observed and level 9 is an actual system proven in an operational environment.

50 VALORE 2024.

arsenide (GaAs) and gallium nitride (GaN), are vital for the defence industries. GaAs semiconductors can be found in GPS satellites, while GaN is used in many types of cutting-edge radar equipment including missile defence systems. While it is true that the needed resources could be diverted to meet defence industry needs, the same companies which supply space and defence products also rely on sales to the civilian sector.[51] This means that supply problems will affect their profits and thus the potential for them to pursue R&D projects.

When considering the space sector, it is worth noting that space-based capabilities help to manage supply chains while Earth observation satellites can prospect for new potential mineral extraction locations much more quickly and effectively. Optimists also suggest that space itself might be the actual answer to our resource needs because space resource extraction on other planets or asteroids is a viable alternative to extraction on Earth. Others are much more pessimistic, raising the issue of costs and lack of technology. Nevertheless, governments, institutes and corporations are contemplating the possibility of resource extraction in space and are trying to find ways to make it a reality.

MOVING UP THE SUPPLY CHAIN

Even though the above-mentioned minerals are only used in relatively small quantities, their availability is crucial. To better understand this need it is worth examining a few actual products they are used for. Vulnerabilities in the supply of these minerals are not a new phenomenon. A 2018 U.S. Department of Defense report in a dedicated section about the space sector mentions a few applications that are heavily reliant on critical minerals. The first of these is precision gyroscopes. These devices are key components for altitude determination and stabilisation in space vehicles or rockets. The components they use include integrated optical chips and laser diodes, and the production of these components was moving away from the U.S. which can cause loss

[51] FUNAIOLE et al. 2023.

of expertise, delays, or decreased orbital lifetime because of the usage of less reliant substitutes. The situation was even worse for infrared sensors that can be used in space. Only one foreign manufacturer was able to supply the necessary components of sufficient quality. A disruption of the supply of these lasting more than a few months would effectively halt production. The production of special highly radiation tolerant integrated circuits was also in a bad state. These circuits are not used in the civil sector, which leads to low production volumes. Only 1% of the suppliers' revenues came from these products. However, these components are essential for missile warning systems, missile defence, reconnaissance and space situational awareness (SSA).[52]

Research and development efforts are also hindered in many ways. R&D requires large capital investment and unique expertise. The civil sector and private investors are reluctant to build such R&D and manufacturing capacity, so to a certain degree, it is up to the state to develop next generation technologies and create the conditions for their production. The GaN and GaAs semiconductors were also originally developed by DARPA.

A 2014 report that partly concerned solar cells emphasised the extent of dependence on foreign suppliers in this field. The paper mentions rare earth elements and examines the issue of solar cells in particular detail. According to the paper, the production of space-grade solar cells used by satellites would not be enough on its own to maintain a business and pay for the extensive supply chain needed to manufacture them. Therefore, most manufacturers are supported by related commercial, land-based solar panel manufacturers, and their capacity is mostly dependent on China. They also had an incentive to move higher tier production closer to the source of extraction and smelting. In 2014, China accounted for 64% of commercially available solar panel production, compared with just 3% in the U.S.[53] This situation did not improve based on a 2022 International Energy Agency report. The document shows that China produced 79.4% of polysilicon, 96.8% of wafers, 85.1% of cells and 74.7% of

52 U.S. Department of Defense 2018.
53 Autry et al. 2014.

modules. Its average share of global solar panel manufacturing capacity is 84.0% while the country constitutes 36.4% of the global demand.[54]

Some examples in the industry are worth examining. Azur Space Solar Power GmbH is a 250 employee strong company in Heilbronn, Germany. It produces high-end wafers and solar cells[55] and assembles them with glasses and interconnectors for space applications. The company's products can be found in 600 space projects including satellites from Intelsat, Globalsat, Hotbird, ATV, Galileo, Meteosat, GLONASS and GMES. Customers include the ESA, DLR, Airbus Defence & Space, Leonardo, OHB SE, Thales Alenia Space and Mitsubishi Electric. Through them, Azur Space solar cells are also on missions like Hubble Space Telescope, Rosetta, Venus Express, Mars Express, Herschel-Planck and others. To achieve such good results the company uses germanium and gallium as a key component in their panels.[56] The company was acquired in 2021 by 5N Plus Inc. a Montreal based Canadian company providing purified metals and semiconducting compounds. 5N Plus Inc.'s products are also used in infrared and earth imaging applications. This chain of events shows that the company had already been producing valuable, high-tech products and another company providing the refined materials for such manufacturing thought that it would be a viable strategy to tightly integrate the production of the two entities, thus strengthening the position of the joint entities in both relevant tiers of the supply chain.

Due to the strategic importance of its products before acquiring Azur Space, a thorough screening process was carried out, to ensure supply safety. Publicly available shareholder information showed that board members and North American companies owned 41.7% of the shares while 58.3% were owned by the general public.[57] The screening process had to make sure the owners and the

[54] International Energy Agency 2022.

[55] Efficiency rate is between 28% to 32% while commercially available panels are usually between 17% and 20%. The panels are also designed to withstand the harsh space environment, like heat variations, radiation, etc.

[56] Azur Space 2024.

[57] MarketScreener 2024; Simply Wall St. 2024.

companies involved pose no security risk, for example by demonstrating that there are no potentially harmful foreign owners behind the North American companies. However, the screening process must be done on a regular basis to avoid undetected changes in the ownership structure.

COUNTERING RISK

The mention of screening processes offers a good opportunity to briefly look at a different kind of threat to space supply chains. The ownership of the actors in the supply chain is constantly changing, so the risk they carry is also subject to fluctuations. In 2020, the United Launch Alliance (ULA), a major player in the U.S. space sector reported that one of their industrial software suppliers had been found to be partially Chinese-owned. According to the ULA director, the security risk was discovered quickly and no valuable information was leaked. One possible solution to the problem, in addition to regular reviews, is to break down components purchased from other sources into such small parts that no one knows what they are working on.[58]

According to the data analytics firm Govini, in 2020 the presence of Chinese firms in supply chains, especially at the lower end, was significant. Between 2010 and 2019, the number of Chinese-owned suppliers among firms in this section increased by 420%. In 7 of the 18 key industries surveyed, the share of foreign suppliers was as high as 75%, mainly in chemicals and electronic components.[59] Because the presence of Chinese firms is common in all strategic industries, this growth does not seem to have a direct connection with conflicts regarding space activity, like the so-called Wolf Amendment from 2011. It has more to do with general U.S.–China tensions and economic prospects for investors. In 2023 Govini published a more detailed report focusing on the situation in 2022. The space supply chain had 565 Chinese companies out of 27,043 Tier

58 Erwin 2020.
59 Govini 2020.

2 suppliers, and 502 of 7,784 Tier 1 suppliers were Chinese companies.[60] This is not large as a percentage, but it is still a greater share in both Tiers than any other allied country and the report does not give an evaluation of the Chinese positions in the supply network. They could be key players in certain segments and as we can see from ULA's example, their covert influence can be significant, with Chinese entities hiding behind multiple layers of seemingly harmless local companies. The report also warns that the number of patents issued in China in 12 key areas is larger than in the U.S., including in space-related fields, where in 2022 there were more than 60,000 Chinese patents, while fewer than 30,000 were from the U.S.[61]

To counter such vulnerabilities, a number of supply chain reviews are being conducted. Apart from the U.S. space industrial base reports and the EU JRC report, another good example is the U.K. Space Supply Chain document which provides detailed explanations for decision-makers, maps out the location of companies and facilities, and explains the related challenges, etc.[62] There are also efforts to put barriers up against potentially harmful foreign entities. The U.S. Government has placed several companies with close links to the Chinese military on a ban list. Washington has drawn up at least nine lists of people and entities which are in connection with the Chinese military or which may otherwise endanger U.S. interests.[63] These lists are expanded or sometimes shortened when the administration wants to send a message to Beijing.

The West has also embarked on a long process to reduce dependencies by decoupling (U.S. term) or de-risking (EU term). This costly and lengthy process will not result in a full separation, but rather a balanced approach. Experts even talk about the possibility of a patchwork globalisation with different blocks and regions interacting rather than countries and companies. It is worth adding that different kinds of decouplings exist, such as technology decoupling, information

60 Govini 2023.
61 Govini 2023.
62 Red Kite Management Consulting 2022.
63 Dorsey and Whitney 2021.

decoupling and economic decoupling.[64] Space decoupling is at an interesting stage at present, due to the U.S. decision to not cooperate with the Chinese, although the supply chains are still interconnected. A gradual shift can be observed, as in 2023 the U.S. imported more goods from Mexico than from China.[65] Europe has also started a much more limited and gradual space decoupling, as well as increasingly approaching the U.S. in terms of space cooperation where defence needs play a crucial role due to the Russia–Ukraine war.

New initiatives in this regard include the U.S. Space Force's International Reverse Industry Days, such as those held on 25 and 26 October 2023 which involved a discussion between representatives of industry and government agencies from the U.K., Canada, Australia, New Zealand, France, Germany and Japan focusing on shared supply chain problems. Such events are partly classified and partly unclassified.[66]

At the same time, companies are trying to adapt to the new environment, by applying methods and designs that are less reliant on the materials mentioned in this paper. These efforts are also facilitated by recent technological developments. 3D-printed structures were first launched into space in 2015 on the Arabsat-6B satellite. Thanks to the same technology, the aluminium antenna dishes on the intelligence-critical Sentinel satellites are 25% lighter and stronger, while their production time has been halved. SpaceX used 3D-printed parts in its engines as early as 2014. These processes and the constellations of small satellites being built in low Earth orbits are also transforming supply chains. Manufacturers are moving towards the verticalisation of production and the use of readily available off-the-shelf components already used in other devices. Moreover, 3D printing is opening up new horizons for In-Space Manufacturing (ISM), assembly and maintenance. Thanks to the rise of mass production and automation, the need to outsource production is decreasing. For example, 70% of the Falcon rocket components are produced in SpaceX's California

64 Houtari et al. 2021.
65 U.S. Census Bureau 2024.
66 Hitchens 2023.

plant. Thanks to this, production has been accelerated and R&D time has been reduced. Other companies such as Blue Origin are also following this vertical pattern. In addition to manufacturing, they have a facility in Florida for assembly and testing.

Increasingly, companies are experimenting with off-the-shelf technologies and components because of the increasing efficiency of small satellites, as well as their relatively short planned lifetime and therefore their rapid replacement. These are usually sourced from other faster-growing industries (e.g. electronics). Good examples of such readymade components are lithium batteries or on-board computers installed in CubeSats. The battery manufacturers include some firms known specifically in the defence industry, but also civilian companies such as Canon, Molicel, LG or Samsung.[67]

Strategies like nearshoring,[68] friendshoring,[69] reshoring[70] and China Plus One[71] have gained popularity due to companies putting a greater emphasis on managing risk instead of reducing costs. Even if reshoring is expensive for space companies, it is feasible especially with regard to electronics, because lead times are now months instead of weeks, and time is very important. Some companies would rather deliver their product by air instead of using normal shipping. Delays are especially critical for programmes where there is a launch window. Although there has been an increase in the use of off-the-shelf components, special parts are still needed. Because of this, even though space is a small market compared to car manufacturing, aviation and green energy there are significant increases in prices and lengthened lead times.[72] Of course, most companies

67 OECD 2014.

68 A practice where supply chains are focused and relocated into countries geographically closer (usually neighbours) to the given country.

69 A practice where supply chains are focused and relocated into countries which are considered to be political and economic allies.

70 A practice where supply chains are moved back to the country of production/HQ.

71 A practice where supply chains are partly kept in China but also diversified to other countries to mitigate risk. ASEAN countries are very popular destinations for this strategy.

72 Foust 2022.

try to balance security with profits. As a general rule of complacency dictates, a steady and fair-priced supply from China would be highly detrimental to any initiative to find alternatives to China.

REORGANISING AND LEVERAGING THE WEST

In addition to the problem of foreign actors in the supply chains, the space sector also has to deal with its own bureaucratic structures. It is clear that the procurement system for space equipment is too slow and complicated for various reasons, both in Europe and in the U.S. According to an analysis published by the Secure World Foundation in December 2020, one of the Biden Administration's main tasks was to address these challenges. In 2017, more than 60 organisations still had some influence on space procurement in the U.S.[73] It is partly to address this problem that Space Command and, more recently, Space Force have been re-established, with Space Systems Command as one of its departments, and the Procurement Division under it. One of its main tasks was to enhance the security of supply.[74] According to Dr Aaron Bateman, a space policy specialist at George Washington University:

> "The Space Development Agency, now under USSF, has indeed been able to cut through much of the acquisition red tape that has plagued DoD procurement. It is too soon to say if this is indeed a successful model, but thus far SDA's 'move fast' strategy seems to be working."[75]

Western powers have also opted to apply some of the leverage that is available to them to secure supply chains. The whole issue of microchips and semiconductor production revolves around limiting China's and Russia's industrial, defence and space capabilities and their development. Around 2015, the U.S.

[73] Secure World Foundation 2020.
[74] U.S. Department of Defense 2020.
[75] Bateman 2024.

Government began to realise that the West is losing its comparative advantage over China. Taiwan and South Korea are already more advanced than the West in various high-tech fields and China is quickly catching up, while also employing restrictions and subsidies in an attempt to become the leading power. Intel is no longer comparable to TSMC or Samsung and the defence industry needs to buy components from abroad, which poses additional risks of foreign actors tampering with the chips. For this reason, the DARPA applies a zero trust policy and carefully tests every component. China has also started to invest in foreign chipmakers while acquiring their technology or simply stealing it through espionage.[76] In 2020, the U.S. began to impose a "chip choke" on China. These measures have been fairly effective but Miller emphasises that they are only a temporary solution, as countries can find ways around restrictions in a highly connected global market. The U.S. wants to increase its market share, but so does Europe, and leading companies are not ready to give up their positions either. Luckily, leading production sites are based in allied or friendly countries.[77] In 2022, Washington ratified the CHIPS and Science Act and the EU followed with the European Chips Act which entered into force in September 2023.

An interesting shift can be seen in the documents produced by the U.S. It seems that the main attention of its reports has to some extent shifted from supply chain security to technological competition, including space technology. This is also reflected in the reports of the U.S.–China Economic and Security Review Commission. In 2022, section 4 of the report highlighted supply chain vulnerabilities and the concentration of key segments in China. These critical points included active pharmaceutical ingredients, rare earth elements, castings and forgings, etc. while at the same time, the report claims that China is deliberately trying to maintain or increase its influence over U.S. supply chains. The potential risk caused by Chinese counterfeit or corrupted components is also significant. On top of that, due to Beijing's efforts to achieve technological self-reliance, the need to protect intellectual property is also important in this

[76] Miller 2022: 283–295.

[77] Miller 2022: 327–335.

regard, not just the loss of financial revenue. The Commission recommended a coordinated supply chain mapping effort and a more consistent and simpler procurement system.[78] This would serve to improve the resiliency of Western supply chains, so they can adapt and rebound more quickly in case of any unexpected events. The space sector is not directly affected by the mineral trade and sanctions and does not have a stockpile capacity of metals, but it is dependent on the availability of spare parts and on component manufacturers, and therefore stockpiling these items, establishing lean networks with partners and finding off-the-shelf substitutes can mitigate the risks for the sector.

The 2023 report by the same commission report also focuses on supply chain issues, but not to the same degree. In the 785 page long 2022 report, the word supply is mentioned 693 times, while in the 2023 report, it is "only" used 177 times and a special Section is not dedicated to the problem. On the other hand, in the 2023 report, there is a Section about weapons, technology and export control which includes a large segment dedicated to Chinese space capabilities and the importance of striving towards technological self-reliance and a leadership position. The document quotes a testimony given to the Commission by Dr Pollpeter, warning that China's space and missile program can provide a case study of how the country circumvented the attempts of the U.S. to isolate it by simply cooperating with other countries.[79]

CHINESE RESPONSES

As the U.S. and the EU try to reduce their supply chain vulnerabilities so their defence, commercial and space objectives can be achieved while at the same time trying to limit China and Russia in various areas there has been a reaction from these powers. As noted earlier, China's aspiration to become a leading technology powerhouse is backed by a long-standing plan. Since at least 1986,

78 U.S.–China Economic and Security Review Commission 2022.
79 U.S.–China Economic and Security Review Commission 2023.

or more precisely since the announcement of the 863 Program,[80] the Chinese Government has been seeking to move up the value chain and take the lead in several areas. Beijing used to offer various concessions to attract foreign companies to set up operations in the country, but at the beginning of the 2010s, it became more assertive, not only in the area of raw materials. Beijing has been applying political pressure to extract concessions from big companies. For example, in 2014 it launched investigations into Microsoft and Apple. This was only suspended when Apple promised to set up an R&D facility in China. Some software companies have been obliged to hand over source code, and the office responsible for reviewing the security of IT companies is under the Ministry of State Security[81] which is in charge of intelligence. According to the cyber intelligence firm Recorded Future, the same office is linked to APT3, a cyber espionage group.[82]

The new export limitation on gallium and germanium is regarded as a countermeasure to previous U.S. steps limiting the trade of high-end chips or the tools to produce them. Wei Jianguo,[83] a former vice-minister of commerce warned in July 2023 that this limitation is only the beginning and that China has many other tools at its disposal and that things could escalate further.[84] The process of bringing more resources under Beijing's control is well underway. While the West is trying to diversify its supply chains, China intends to further strengthen its influence in mineral mining. In 2023 there was a 131% growth in the country's metals and mining area investment, which is focused heavily on Africa and Latin America.[85] At the same time, according to Pitron, Beijing does not shy away from using coercion, diplomatic actions and economic takeovers to stop rivals from opening new mines.[86] One more crucial parameter for the

80 863 jìhuà, 863计划. Its official name: State High-Tech Development Plan, Guójiā gāo jìshù yánjiū fāzhǎn jìhuà国家高技术研究发展计划.

81 Guójiā Ānquán Bù 国家安全部.

82 U.S.–China Economic and Security Review Commission 2018.

83 Wèi Jiànguó 魏建国.

84 Ma 2023.

85 Wang 2023.

86 Pitron 2023: 170–172.

future of mining is the growing energy needs for extraction. The quality of the ore deposits is decreasing, which entails more work to obtain the same amount of ore, while at the same time, the demand for raw materials is increasing. As a result, China has started to prioritise its own resource needs and can use minerals as a diplomatic tool.[87]

There are also intermediaries at play which can circumvent EU and U.S. restrictions. An example of a country employing this strategy is Morocco. The country has free trade agreements with the U.S. and the EU and has a well-developed infrastructure and a stable political and economic system. This creates a perfect environment for Western and Chinese cooperation. Canadian and South Korean firms have also chosen Morocco as a good location for joint projects with their Chinese counterparts.[88] Of course, such behaviour is not only limited to supply chains. Other countries are also using various strategies to try to cooperate with both the West and China while following their own national interests. Cooperation on different levels can help to mitigate tensions while also producing benefits. One example of a country cooperating with multiple partners is the United Arab Emirates, a signatory of the Artemis Accords, yet at the same time the University of Sharjah signed a memorandum of understanding to take part in the Chinese led International Lunar Research Station (ILRS) project.[89]

Furthermore, China is also making attempts to build up its chip manufacturing capabilities to ensure a higher grade of independence and possibly to capture a share of a market which is still mostly controlled by the Taiwan Semiconductor Manufacturing Company at the high-end part of the market. ASML, a firm based in the Netherlands, is the only company to manufacture the machines that are able to produce these chips. In addition, U.S. companies like Lam Research, KLA and Applied Materials are industry leaders in other

87 Pitron 2023: 159–168.
88 Byamungu 2024.
89 Xin 2023.

tools needed for the chip manufacturing process and they also try to limit cooperation with China.[90]

On a final note, it is worth noting that research and development initiatives and a push to build up a more resilient space commercial sector can also be found in the toolbox of Beijing. The reform of the innovation chain is continuing and the Chinese Government is focusing on strategic areas with numerous grand-scale projects in the background, with the Chinese Communist Party exerting tight control over the goals of the research.[91] Recent analysis has shown that the space industry in China is still strongly interwoven with the state while being supervised closely by the government. The commercial sector is still in its infancy compared to the West but Chinese companies are slowly catching up and the growth potential is very promising.[92]

CONCLUSION

Raw Materials, geopolitics, supply chain security and space capabilities are strongly interconnected. The space industry is unable to function and achieve its full potential without a secure and well-functioning supply chain. In many regards, the space sector is more dependent on supply chains than other industries due to its often unique requirements, smaller and irregular purchases and a constant struggle with skilled workforce shortages. Disturbances in the raw material markets can indirectly affect space companies and government institutions and may result in increased delays, cost overruns, missed launch windows, smaller revenues and in consequence, a smaller amount being available to dedicate to R&D projects. Western governments are attempting to secure critical and strategic mineral supply chains and become more independent from China, while China is working towards opposite objectives, trying to

90 Cheng 2022.
91 Groenewegen-Lau – Laha 2023.
92 Han et al. 2023.

keep and increase its market share and at the same time acquire cutting edge technologies like high-end chip manufacturing expertise. These tensions and trends also affect the space supply chains.

Western stakeholders need to cooperate even more closely and ensure that a more resilient, responsive system is in place to meet the industry's needs. Decision-makers might be advised to acquire a basic knowledge of minerals to avoid making mistakes in the future as they did when they disregarded warnings of a gallium supply risk. Stockpiles, even of materials which seem to have an undisturbed supply, should be built up, especially when sources are close to China. Alternative replacement technologies should be emphasised and supported. The space sector will not do these things on its own but is responsible for communicating its needs to decision-makers and encouraging cooperation with other industry sectors. If current geopolitical trends continue there might be increased impetus for decoupling which will sever a few ties between China, Russia and the West while other dependencies will become covert and less obvious. In terms of space supply chains, the already evident two blocks centring around the U.S. and China might become more solidified and distant from each other, pointing toward technology, R&D and space decoupling.

REFERENCES

AUTRY, Greg – HUANG, Laura – FOUST, Jeff (2014): *An Analysis of the Competitive Advantage of the United States of America in Commercial Human Orbital Spaceflight Markets.* Online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e8e1479ffae-c0a56a4ddfea908da4fc2c4a70229

AYUK, Elias T. – PEDRO, Antonio M. – EKINS, Paul (2020): *Mineral Resource Governance in the 21st Century.* Online: https://www.unep.org/resources/report/mineral-resource-governance-21st-century

Azur Space (2024): *SPACE Solar Cells.* Online: https://www.azurspace.com/index.php/en/products/products-space/space-solar-cells

Barjak, Franz – Bill, Marc – Samuel, Olga (2015): *Evaluation of the Existing Swiss Institutional R&D Funding Instruments for the Implementation of the Space-related Measures.* Online: https://www.researchgate.net/publication/277555874_Evaluation_of_the_existing_Swiss_institutional_RD_funding_instruments_for_the_implementation_of_the_space-related_measures

Bateman, Aaron (2024): Written interview with Dr Aaron Bateman conducted by András Edl on 6 February 2024.

Bowen, Bleddyn E. (2020): *War in Space. Strategy, Spacepower, Geopolitics.* Edinburgh: Edinburgh University Press.

Byamungu, Christian Géruard Neema (2024): Morocco, an Unexpected Winner of China's Strategy to Circumvent the U.S. Inflation Reduction Act. *CSIS,* 23 January 2024. Online: https://www.csis.org/analysis/morocco-unexpected-winner-chinas-strategy-circumvent-us-inflation-reduction-act

Carrara, Samuel et al. eds. (2023): *Supply Chain Analysis and Material Demand Forecast in the Strategic Technologies and Sectors in the EU – A Foresight Study.* Luxembourg: Publications Office of the European Union. Online: https://doi.org/10.2760/386650

Cheng, Evelyn (2022): Chinese Chip Stocks Tumble after U.S. Calls for the New Curbs on High-end Tech. *CNBC,* 10 October 2022. Online: https://www.cnbc.com/2022/10/10/chinese-chip-stocks-tumble-after-us-calls-for-new-curbs-on-high-end-tech.html

CMK, s.r.o. (2024): *CMK recycling.* Online: https://cmk.sk/services/recycling/

Datta, Anusuya (2020): *How Many Satellites Orbit Earth and Why Space Traffic Management Is Crucial.* Online: https://www.geospatialworld.net/blogs/how-many-satellites-orbit-earth-and-why-space-traffic-management-is-crucial/

Dorsey and Whitney (2021): *Biden Administration Revises and Expands Restrictions on U.S. Person Investment in Chinese Companies and Releases New List of "Chinese Military Companies" Under 2021 NDAA Section 1260H.* Online: https://www.dorsey.com/newsresources/publications/client-alerts/2021/06/new-list-of-chinese-military-companies

Erwin, Sandra (2020): Tory Bruno Reveals Chinese Company Tried to Infiltrate ULA's Supply Chain. *Space News,* 15 September 2020. Online: https://spacenews.com/tory-bruno-reveals-chinese-company-tried-to-infiltrate-ulas-supply-chain/

Euroconsult (2023a): *Value of Space Economy Reaches $464 Billion in 2022 Despite New Unforeseen Investment Concerns.* Online: https://www.euroconsult-ec.com/press-release/value-of-space-economy-reaches-424-billion-in-2022-despite-new-unforeseen-investment-concerns-2/

Euroconsult (2023b): *New Historic High for Government Space Spending Mostly Driven by Defence Expenditure.* Online: https://www.euroconsult-ec.com/press-release/new-historic-high-for-government-space-spending-mostly-driven-by-defense-expenditures/

European Space Agency (2023): *Space Debris by the Numbers.* Online: https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

European Union (2023): *Study on the Critical Raw Materials for the EU 2023.* Online: https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

Foust, Jeff (2022): Supply Chain Challenges also Present Opportunities for the Space Industry. *Space News,* 25 May 2022. Online: https://spacenews.com/supply-chain-challenges-also-present-opportunities-for-the-space-industry/

Földessy, János (2020): Kritikus nyersanyagaink. Gallium. *Ásványkincs,* 1 November 2020. Online: https://asvanykincs.hu/megujulas/kritikus-nyersanyagaink-maraton-5-gallium/

Funaiole, Matthew P. – Hart, Brian – Power-Riggs, Aidan (2023): Mineral Monopoly. China's Control over Gallium Is a National Security Threat. *CSIS,* 18 July 2023. Online: https://features.csis.org/hiddenreach/china-critical-mineral-gallium/

Govini (2020): *The Challenge of Reshoring the Defense Department Supply Chain.* Online: https://govini.com/wp-content/uploads/2021/04/Govini-DoD-Reshoring-Challenge.pdf

Govini (2023): *The 2023 National Security Scorecard.* Online: https://govini.com/wp-content/uploads/2023/07/Govini-2023-National-Security-Scorecard.pdf

Groenewegen-Lau, Jeroen – Laha, Michael (2023): *Controlling the Innovation Chain. China's Strategy to Become a Science and Technology Superpower.* Online: https://merics.org/en/report/controlling-innovation-chain

Han, Yuexia – Chen, Zhuang – Hu, Yuxin – Zhang, Liyan – Fu, Huishan – Zhang, Renyong – Zhang, Wei (2023): A PIE Analysis of China's Commercial Space Development. *Humanities and Social Sciences Communications,* 10. Online: https://doi.org/10.1057/s41599-023-02274-w

Hitchens, Teresa (2023): Space Force Launches Effort to Harness Allied Supply Chain. *Breaking Defense,* 19 October 2023. Online: https://breakingdefense.com/2023/10/space-force-launches-effort-to-harness-allied-supply-chain/

Houtari, Mikko – Gunter, Jacob – Hayward, Carl – Zenglein, Max J. – Lee, John – Arcesati, Rebecca – Meinhardt, Caroline – Amela, Ester Cañada – Haar, Tom Groot (2021): *Decoupling – Severed Ties and Patchwork Globalisation.* Online: https://merics.org/en/report/decoupling-severed-ties-and-patchwork-globalisation

Intelsat (2021): *Making of an Intelsat Satellite.* Online: https://www.intelsat.com/resources/blog/the-making-of-an-intelsat-satellite/

International Energy Agency (2022): *Special Report on Solar PV Global Supply Chains.* Online: https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf

Kalantzakos, Sophia (2018): *Kína és a ritkaföldfémek geopolitikája.* Trans. by Judit Gábris and Endre Milán. Budapest: Pallas Athéné Könyvkiadó. (English original: *China and the Geopolitics of Rare Earths.* Oxford: Oxford University Press, 2017.)

Liu, Shuang-Liang – Fan, Hong-Rui – Liu, Xuan – Meng, Jianyin – Butcher, Alan R. – Yann, Lahaye – Yang, Kui-Feng – Li, Xiao-Chun (2023): Global Rare Earth Element Projects: New Developments and Supply Chains. *Ore Geology Reviews,* 157. Online: https://doi.org/10.1016/j.oregeorev.2023.105428

Ma, Si (2023): 独家！商务部原副部长魏建国：中国出口管制芯片重要原材料只是开始，中国反制的工具还有很多 [Exclusive! Former Vice Minister of Commerce Wei Jianguo: China's Export Control of Chips and Important Raw Materials Is Just the Beginning, and There Are Many More Tools for Chinese Countermeasures]. Online: https://cn.chinadaily.com.cn/a/202307/05/WS64a4bfa4a310ba94c5614df0.html

Magnuson, Stew (2020): Mining Company Determined to Restore U.S. Rare Earth Supply Chain. *National Defense,* 20 November 2020. Online: https://www.nationaldefensemagazine.org/articles/2020/11/20/mining-company-determined-to-restore-us-rare-earth-supply-chain

MarketScreener (2024): *5N Plus Inc.* Online: https://www.marketscreener.com/quote/stock/5N-PLUS-INC-1412142/company/

Miller, Chris (2022): *Chip War. The Fight for the World's Most Critical Technology*. New York: Scribner.

Northrop Grumman (2024): *Commercial Communications Satellite. GEOStar.* Online: https://www.northropgrumman.com/space/commercial-communications-satellites

OECD (2014): *The Space Economy at a Glance 2014*. Online: https://www.oecd.org/science/the-space-economy-at-a-glance-2014-9789264217294-en.htm

OECD (2022): *OECD Handbook on Measuring the Space Economy*. Online: https://www.oecd.org/publications/oecd-handbook-on-measuring-the-space-economy-2nd-edition-8bfef437-en.htm

OECD (2023): *The Space Economy in Figures. Responding to Global Challenges*. Online: https://www.oecd-ilibrary.org/sites/fa5494aa-en/1/3/1/index.html?itemId=/content/publication/fa5494aa-en&_csp_=fc1ad0ab064ad99d8868789e9cd71bb8&itemIGO=oecd&itemContentType=book#section-d1e2013-4f512d1978

Okun, Sofia – Cefai, Solomon (2024): Rare Earth Magnet Production Outside Asia Gearing Up. 2024 Preview. *Fastmarkets,* 10 January 2024. Online: https://www.fastmarkets.com/insights/rare-earth-magnet-production-outside-asia-gearing-up-2024-preview/

Orbital ATK (2017): *GEOStar-2 Bus*. Online: https://satsearch.co/products/orbital-atk-geostar-2-bus-a-fully-redundant-flight-proven-spacecraft-bus-designed-for-geosynchronous-missions

Orbiting Now (2024): *Active Satellite Orbit Data. 2024 Day 42*. Online: https://orbit.ing-now.com/

Pereira, Daniel (2023): Japan Challenges China with Rare Earth Metal Extraction from Seabed by 2024. *OODA Loop,* 14 May 2023. Online: https://www.oodaloop.com/ooda-original/2023/05/14/japan-challenges-china-with-rare-earth-metal-extraction-from-seabed-by-2024/

Pitron, Guillaume (2023): *Ritkafémek háborúja*. Trans. by Angéla Dobosi. Budapest: Pallas Athéné Könyvkiadó. (French original: *La guerre des métaux rares.* Paris: Éditions Les Liens qui libèrent, 2018.)

Red Kite Management Consulting (2022): *The UK Space Supply Chain*. Online: https://sa.catapult.org.uk/wp-content/uploads/2022/05/The-UK-Space-Supply-Chain-March-2022_v1.0.pdf

Reece, Beth (2022): DLA Program Introduces Domestic Germanium Recycling Capability. *U.S. Department of Defense,* 29 June 2022. Online: https://www.defense.gov/News/News-Stories/Article/Article/3079217/dla-program-introduces-domestic-germanium-recycling-capability/

Satellite Industry Association (2019): *2019 Top-Level Global Satellite Industry Findings.* Online: https://sia.org/wp-content/uploads/2020/07/SSIR20-SSIR-2-Pager-July-1st-FINAL.pdf

Satellite Industry Association (2020): *Satellite Industry Association (SIA) White Paper: The Future of Space and Space Traffic Coordination and Management*. Online: https://sia.org/wp-content/uploads/2020/09/REVISED-White-Paper20-STCM-Sept-23rd-V1.0.pdf

Satellite Industry Association (2023): *State of the Satellite Industry Report 2023.* Online: https://sia.org/news-resources/state-of-the-satellite-industry-report/

Secure World Foundation (2020): *Space Policy and Sustainability.* Online: https://swfound.org/media/207084/swf_space_policy_issue_briefing_2020_web.pdf

Simply Wall St. (2024): *5N Plus Ownership.* Online: https://simplywall.st/stocks/ca/materials/tsx-vnp/5n-plus-shares/ownership

Space Foundation (2023): *The Space Report 2023 Q2.* Online: https://www.spacefoundation.org/2023/07/25/the-space-report-2023-q2/

SpaceX (2024): *Launches.* Online: https://www.spacex.com/launches/

Su, Yina – Hu, Dewen (2022): Global Dynamics and Reflections on Critical Minerals. *E3S Web of Conferences,* 352. Online: https://doi.org/10.1051/e3sconf/202235203045

The White House (2012): *National Strategy for Global Supply Chain Security.* Online: https://obamawhitehouse.archives.gov/sites/default/files/national_strategy_for_global_supply_chain_security.pdf

The White House (2017): *Executive Order 13817: A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals.* Online: https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals

The White House (2022): *Fact Sheet: Securing a Made in America Supply Chain for Critical Minerals.* Online: https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/

U.S. Census Bureau (2024): *U.S. International Trade in Goods and Services, 2023 December.* Online: https://www.census.gov/foreign-trade/Press-Release/current_press_release/ft900.pdf

U.S. Department of Defense (2018): *Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States*. Online: https://media.defense.gov/2018/Oct/05/2002048904/-1/-1/1/assessing-and-strengthening-the-manufacturing-and%20defense-industrial-base-and-supply-chain-resiliency.pdf

U.S. Department of Defense (2020): *Chief of Space Operations Planning Guidance.* Online: https://media.defense.gov/2020/nov/09/2002531998/-1/1/0/cso%20planning%20guidance.pdf

U.S. Department of Defense (2023): *National Defense Industrial Strategy.* Online: https://www.businessdefense.gov/docs/ndis/2023-NDIS.pdf

U.S. Geological Survey (2020): *Mineral Commodity Summaries 2020.* Online: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

U.S. Geological Survey (2023): *Mineral Commodity Summaries 2023.* Online: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf

U.S.–China Economic and Security Review Commission (2018): *Supply Chain Vulnerabilities from China in U.S. Federal Information and Communications Technology.* Online: https://www.uscc.gov/research/supply-chain-vulnerabilities-china-us-federal-information-and-communications-technology

U.S.–China Economic and Security Review Commission (2022): *2022 Annual Report to Congress.* Online: https://www.uscc.gov/sites/default/files/2022-11/Chapter_2_Section_4—U.S._Supply_Chain_Vulnerabilities_and_Resilience.pdf

U.S.–China Economic and Security Review Commission (2023): *2023 Annual Report to Congress.* Online: https://www.uscc.gov/sites/default/files/2023-11/Chapter_4_Section_2—Weapons_Technology_and_Export_Controls.pdf

Union of Concerned Scientists (2023): *UCS Satellite Database.* Online: https://www.ucsusa.org/resources/satellite-database

VALORE (2024): *Selective Vanadium Recovery from Alumina Refinery.* Online: https://kic-valore.eu/en

Varma, Jules (2023): *Trends in the Space Sector 2023*. Online: https://commercialisation.esa.int/wp-content/uploads/2023/10/Varma_Trends-in-the-Space-Sector.pdf

Vital Pure Metal Solutions (2024): *About VPMS.* Online: https://www.vital-pms.de/about-1

Wang, Christoph Nedopil (2023): *China Belt and Road Initiative (BRI) Investment Report 2023 H1.* Online: https://greenfdc.org/china-belt-and-road-initiative-bri-investment-report-2023-h1/

Worstall, Tim (2023): Don't Worry About China's Gallium and Germanium Export Bans. *The Diplomat,* 10 October 2023. Online: https://thediplomat.com/2023/10/dont-worry-about-chinas-gallium-and-germanium-export-bans/

Xin, Ling (2023): UAE University Joins China's Moon Project After Arab Nation's Initial Bid Killed by US Sanctions. *myNews,* 28 November 2023. Online: https://www.scmp.com/news/china/science/article/3242545/uae-university-joins-chinas-moon-project-after-initial-bid-arab-nation-killed-us-sanctions

Yamazaki, Tetsuo – Nakatani, Naoki – Arai, Rei – Sekimoto, Tsunehiro – Katayama, Hiroyuki (2021): Combined Mining and Pulp-Lifting of Ferromanganese Nodules and Rare-Earth Element-Rich Mud around Minamitorishima Island in the Western North Pacific: A Prefeasability Study. *Minerals,* 11(3). Online: https://doi.org/10.3390/min11030310

Zaleski, Andrew (2023): The Radical New Metal from Outer Space Could Transform Everything from Electric Vehicles to Nuclear Submarines. *Popular Mechanics,* 22 August 2023. Online: https://www.popularmechanics.com/technology/infrastructure/a44785656/new-metal-boosts-batteries/