CellPress OPEN ACCESS
Gold Standard for the Global Goals
1 ton of CO_2 offset

One Earth

Review

Central Asia is a missing link in analyses of critical materials for the global clean energy transition

Roman Vakulchuk[1,*] and **Indra Overland**[2]
[1]Senior Research Fellow, Norwegian Institute of International Affairs (NUPI), C.J. Hambros Plass 2D, Postboks 7024 St. Olavs Plass, 0130 Oslo, Norway
[2]Head of Center for Energy Research, Norwegian Institute of International Affairs (NUPI), C.J. Hambros Plass 2D, Postboks 7024 St. Olavs Plass, 0130 Oslo, Norway
*Correspondence: rva@nupi.no

https://doi.org/10.1016/j.oneear.2021.11.012

SUMMARY

The energy transition is causing a surge in demand for minerals for clean energy technologies, giving rise to concerns about the sources and security of supplies of critical materials. Although Central Asia was one of the Soviet Union's main sources of metals and industrial minerals, it has been forgotten in contemporary global critical materials analyses. Here we review the Central Asian mineral resource base and assess its current and potential contributions to global supply chains. We find that the importance of Central Asia lies mainly in the diversity of its mineral base, which includes mineable reserves of most critical materials for clean energy applications. This renders the region important in mineral economics, security of supply, and geopolitical perspectives alike. In sum, Central Asia is likely to become a new hotspot for mineral extraction and a major global supplier of selected critical materials for clean energy technologies.

INTRODUCTION

As the world transitions from fossil fuels to renewable energy, the global critical materials landscape will also be transformed. Concerns over security of supply of oil and gas and bottlenecks such as the Straits of Hormuz and Russian natural gas pipelines are likely to recede from attention, while new bottlenecks may appear in the supply chains of scarce minerals and metals essential for clean energy technologies. According to the International Energy Agency (IEA), reaching the 2°C goal of the Paris Agreement will require "a quadrupling of mineral requirements for clean energy technologies by 2040. An even faster transition, to reach net-zero globally by 2050, would require six times more mineral inputs in 2040 than today."[1–3] Along the same lines, the World Bank finds that if the number of EVs reaches 140 million in 2030, this will lead to a 1,000% increase in total demand for aluminum, cobalt, iron, lead, lithium, manganese, and nickel.[2]

The extraction of some minerals is concentrated in a few countries. This can result in dependencies between producers and importers and may also lead to unsustainable mining practices and conflict. A much-cited example of such risks is the Democratic Republic of Congo (DRC), which has the world's largest reserves of cobalt and China as its main buyer.[4–6] Similarly, lithium production is concentrated in Australia, China, Zimbabwe, and the so-called Lithium Triangle, which includes Argentina, Bolivia, and Chile.[7,8]

Since the 1990s, China has taken up a dominant position in global critical materials supply chains.[9–11] In 2010, it imposed an embargo on critical materials exports to Japan amidst a flare-up in tensions between the two countries over disputed islands.[12] Although this incident increased awareness among other countries of the need to diversify production of critical materials, China remains the strongest player in the global critical materials arena. A special report of the journal *Foreign Policy* argued that Beijing's dominance in the global critical minerals sector has "serious implications" for United States national security.[13]

While much of the critical materials literature focuses on China, the neighboring region of Central Asia has received much less attention. Due to its resource wealth and strategic location, Central Asia has been regarded as the object of a "Great Game," an analytical concept that originated in the 19th century and involves geopolitical competition among great powers for political influence and resources in the region.[14–25] Since the collapse of the Soviet Union in 1991, Central Asia's main role in the world economy has been as a source of raw materials, above all oil and gas. The importance of the fossil fuel trade—both to the Central Asian exporters and to their customers—has been stressed so often that it is taken for granted in the literature on the region.[26–30] However, assumptions about the long-term importance of Central Asia's fossil fuels may be unwarranted. Demand could be peaking as both Western and Eastern markets seek to decarbonize and, consequently, there is a growing risk that Central Asian oil and gas resources become stranded assets.[31,32] While the region's fossil fuel resources are becoming less important to the world,[33] growing demand for materials for clean energy technologies could rekindle geopolitical interest in the region.

A global shift from fossil fuels to critical materials may lead to new economic activity and trigger new geopolitical interest in Central Asia. While the energy transition is expected to curb demand for fossil fuels, it is also expected to lead to

Table 1. Critical materials used for clean energy technologies

	Solar power	EVs/storage	Wind power	Projected demand growth (%)	Base year	Target year
Bauxite and aluminum	×	×	×	1,000	2017	2030
Copper	×	×	×	1,200	2020	2025
Iron	×	×	×	1,000	2017	2030
Lead	×	×	×	1,000	2017	2030
Dysprosium (rare earth)		×	×	260	2020	2030
Manganese		×	×	1,000	2017	2030
Neodymium (rare earth)		×	×	300	2020	2040
Nickel	×	×		1,000	2017	2030
Silicon	×	×		46	2020	2027
Zinc	×		×	250	2017	2050
Cadmium	×			700	2021	2040
Chromium			×	122	2020	2050
Cobalt			×	1,000	2017	2030
Gallium	×			2	2019	2050
Germanium	×			8,600	2018	2050
Graphite		×		500	2020	2050
Indium	×			341	2020	2050
Lithium		×		1,000	2017	2030
Molybdenum			×	240	2017	2050
Praseodymium (rare earth)		×		185	2020	2030
Selenium	×			11	2019	2050
Silver	×			52	2019	2050
Tellurium	×			75	2019	2050
Tin	×			[a]		
Titanium		×		40	2020	2050

Sources of data: International Energy Agency,[1] World Bank,[2] Church and Crawford,[45] International Renewable Energy Agency,[50] Dominish et al.,[51] Hund et al.,[52] Alves Dias et al.,[53] Kollmeyer,[54] Intrado,[55] International Tin Association,[56] Carrara et al.[57]

[a] No exact estimates available, but growth predicted.

exponentially rising demand for minerals and metals for clean energy technologies.[34,35] Demand for many materials is expected to rise by more than 1,000% during the 2020s and 2030s, and it has been estimated that demand for germanium will grow by 8,600% by 2050 (see Table 1). Given such developments, Central Asia's critical materials endowment may partially substitute for declining demand for the region's hydrocarbons. As Baurzhan Aitkulov, the head of mining projects at Kazakhstan's main investment agency, Kazakh Invest, noted: "lithium can soon become a second oil for Kazakhstan."[36]

Given the importance of critical materials to the energy transition, it is problematic that the existing literature has so far limited itself to the best-known existing producers and consumers of critical materials. Central Asia is mentioned only in two academic publications out of 42 as a potential geopolitical hotspot for critical minerals (see the section below "geography of the critical materials literature"). This review therefore contributes to research on critical materials for clean energy by assessing the potential role of Central Asia. This land-locked region comprises the post-Soviet republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan.

This review addresses the following questions. What role can Central Asia play in the global supply of critical materials for clean energy technologies? And what roles do Central Asian mineral resources play in the strategic positioning of great powers on critical materials? To answer these questions, we review the mineral resource base of Central Asia; assess the region's reserves and current and potential contributions to the global supply of critical materials; examine the region's exports of selected minerals and major companies and external states involved in critical materials production in Central Asia; and examine global inventories of critical materials to identify Central Asia's role in global supply chains. Through these steps, we close the existing knowledge gap in the assessment of Central Asia's current and potential critical mineral resources. We find that Central Asia could become a new hotspot for mineral exploitation and one of the major global suppliers of selected critical materials but that this would, however, carry multiple socioenvironmental risks for the region. The article's main contributions are twofold. First, by examining a region that has been neglected by the existing literature, we contribute to the body of knowledge on the geopolitics of critical materials for clean energy applications. Second, as China shares a 3,300-km border with Central Asia and invests heavily in the region, the article also contributes to the debate on China's global domination of the critical materials supply chain.[37–42]

THE USES AND CRITICALITY OF MINERAL RESOURCES

Critical materials at a general level can be defined as “raw materials for which there are no viable substitutes with current technologies, which most consumer countries are dependent on importing, and whose supply is dominated by one or a few producers.”[43] However, the topic of this article is not critical materials in general but critical materials specifically for clean energy technologies. Accordingly, the definition of Lee et al. is more appropriate for our purposes: “materials that have proven valuable in supporting the development of low-carbon technology.”[44] Four technologies are expected to play particularly important roles in the energy transition and depend on specific materials: solar panels, wind turbines, electric vehicles (EVs), and grid-scale batteries.[45]

While the European Union (EU), the US Geological Survey, and other entities have published lists of critical materials, they cover critical materials in general and not critical materials specifically for clean energy technologies.[46,47] For example, the EU’s critical materials list includes coking coal.[46] For the assessment of the Central Asian critical materials resource base, we therefore use a list of materials that are considered critical for the production of clean energy technologies. The list was compiled by the International Institute for Sustainable Development (IISD) and is presented in Table 1.[45] While there is no perfect methodology and several different standards and indicators can be used to assess criticality,[48,49] the IISD taxonomy is widely accepted and used by scholars and practitioners alike, including the International Renewable Energy Agency,[50] the European Commission, and 31 academic articles.[44]

Table 1 lists the types of critical materials that go into the production of solar, wind, EVs, and storage technologies and that are therefore expected to experience steep demand growth. Solar energy applications require significant inputs of aluminum, copper, nickel, tellurium, silver, zinc, and other critical materials. Wind turbines use chromium, cobalt, copper, manganese, molybdenum, and zinc. EVs and energy storage systems require copper, cobalt, lithium, manganese, nickel, and titanium inputs. Some elements are used in all four technology types—for example aluminum, copper, iron, and lead. Other elements are only used for one technology—for instance chromium is mainly needed for wind turbines. Some metals are used in combination. For example, a variety of combinations are used in EV batteries: lithium-cobalt oxide, nickel-cobalt-manganese, and lithium-iron phosphate.[44]

Data sources

Obtaining reliable data and statistical information on Central Asia is a serious challenge.[58] We draw on two datasets compiled for the purpose of this article. These datasets contain detailed information on: (1) geological potential and proven reserves by country; (2) current production by country and its share in the global supply and export trends; and (3) production sites and deposits and company ownership.

The first dataset is based on data from the ministries of natural resources of the Central Asian countries, the British Geological Survey, US Geological Survey, Statista, World Mining Data, reports of the Extractive Industries Transparency Initiative, and Soviet and national geological encyclopedias.[59] The second dataset covers 365 mining sites in Central Asia and is based on a broad range of sources, including news media, mining company websites, official government catalogs, and mineral maps.[60] It is not possible to obtain reliable and accurate data on Turkmenistan, and it therefore had to be excluded from our analysis. This means that our estimates of the Central Asian resource base are on the low side and we are in practice erring on the side of caution, as one of the five Central Asian countries is missing from our data.

STOCKTAKING OF CRITICAL MATERIALS IN CENTRAL ASIA

Geological potential

In assessing Central Asia’s geological potential, we use the definition formulated by Taylor and Steven: “high mineral resource potential is deemed to exist where geologic, geochemical, and geophysical characteristics favorable for resource accumulation are known to be present.”[61]

Figure 1 shows the geological potential in Central Asia of 22 critical materials from the IISD taxonomy. Germanium, gallium, indium, tellurium, and graphite are present in only one Central Asian country; all other elements are found in multiple countries. “Low” potential in the Taylor and Steven system does not mean that a mineral is not present in sufficient quantities to be mined.[61] For instance, the potential of Uzbekistan’s graphite reserves is classified as low, yet they are already being mined actively.

In Kazakhstan, 16 out of 22 critical materials have high geological potential, which means that it is a key source country for materials for clean energy technologies in the region. Uzbekistan is the second most endowed country, while Tajikistan and Kyrgyzstan have high potential for selected critical materials.

Proven reserves and production

The proven reserves of critical materials in the Central Asian countries vary substantially. Table 2 summarizes the total volume of proven reserves by country and the total volume for Central Asia. Central Asia holds 38.6% of global manganese ore reserves, 30.07% of chromium, 20% of lead, 12.6% of zinc, 8.7% of titanium, 5.8% of aluminum, 5.3% of copper, 5.3% of cobalt, and 5.2% of molybdenum. All these critical materials are used across a wide range of clean energy technologies (Table 1). The Central Asian countries are also already among the top 20 global producers of many critical materials (Table 3).

In terms of individual countries, Kazakhstan has the world’s largest reserves and is the second-largest producer of chromium (Tables 2 and 3), which is used in wind turbines. The country’s reserves are estimated at 230 million metric tons, while global reserves amount to 570 million metric tons.[62] Kazakhstan has the world’s fifth largest zinc reserves and eighth largest ore reserves, and is one of the top 20 countries in terms of proven copper, cadmium, and bauxite reserves. Reserves of some elements, such as lithium, require further geological exploration in Kazakhstan, as the existing data were collected during the Soviet period and remain incomplete.[36]

Uzbekistan has the world’s 11th largest proven copper reserves, as well as deposits of silver, molybdenum, selenium, cadmium, and lithium that are suitable for large-scale mining.

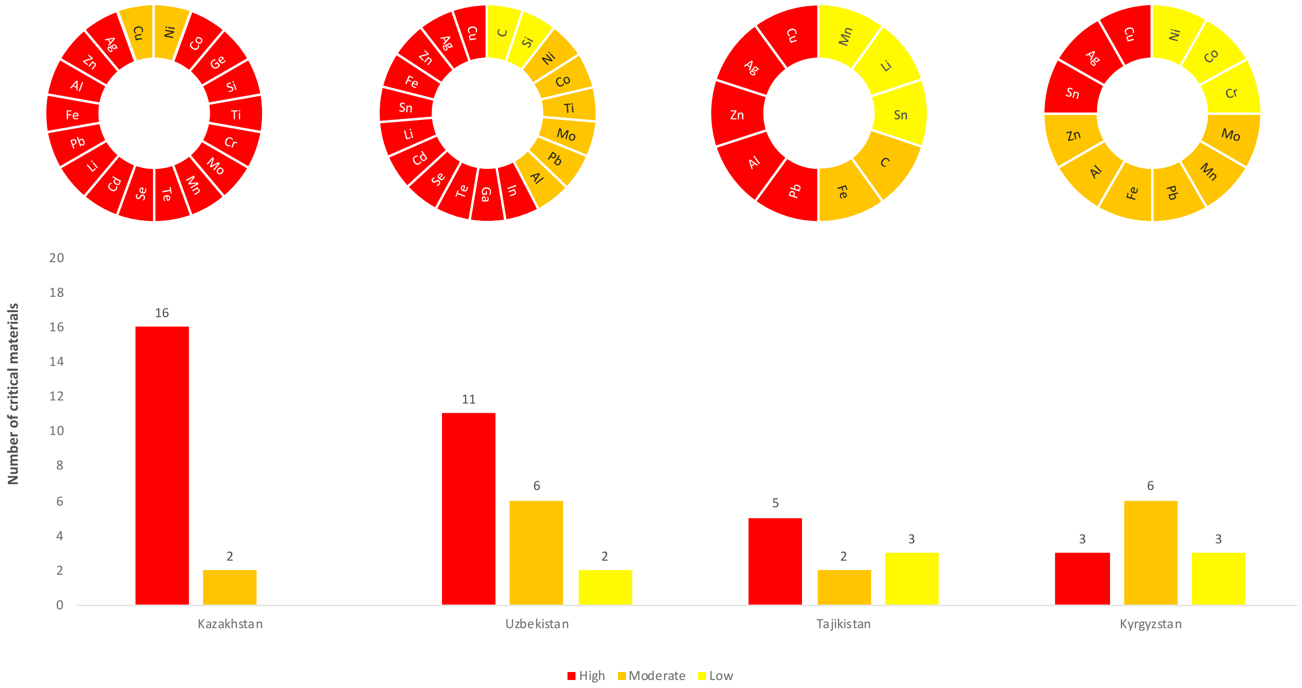

Figure 1. Resource potential of 22 critical materials in Central Asia

This figure shows the geological potential of each critical material by country in Central Asia. The critical materials not included here require further geological exploration. Classification according to Taylor and Steven.[61] Source of data: Vakulchuk and Overland.[59]

Tajikistan is one of the top 20 countries in terms of proven reserves of zinc, and also has vast reserves of aluminum, silver, copper, zinc, and lead. Although Kyrgyzstan's mineral resources are modest compared with those of its neighbors, it still has moderate to high geological potential for large-scale mining of nine critical materials for clean energy technologies (Figure 1). Addressing the first question raised in the introduction, we can argue that the Central Asian region is equipped to play a more prominent role in the global supply of critical materials for decarbonization than it currently does. Accordingly, it also merits greater attention from the critical materials' scholarly community.

Some of the mineral reserve numbers may not look that impressive. For example, Central Asia holds 1.2% of global silver reserves. However, many of these minerals are spread among many countries in the world, 1.2% of global reserves is more than enough for substantial production, and all four Central Asian countries covered here are significant silver producers. Furthermore, Table 3 shows that Kazakhstan and Uzbekistan are already among the world's main producers of some minerals. Kazakhstan's output is particularly significant, putting the country among the ten main producers of eight minerals by volume. Tajikistan, and to a lesser extent Kyrgyzstan, also have significant production volumes of selected minerals.

Finally, an important characteristic of Central Asia's mineral resource base is its diversity, as shown in Tables 2 and 3. Although the region holds insufficient quantities of some minerals to dominate global output, the broad range of minerals available makes the region potentially important as a source of critical metals for global markets. In other words, a major industrial power with access to Central Asia's mineral reserves will be able to cover many of its needs for the production of clean energy technologies. This is especially relevant for China, which has a 3,300-km border with the region, including direct borders with three of the Central Asian countries. Despite rapidly rising military spending, China still has a weaker navy than the major Western powers and has paradoxically remained dependent on the United States for the security of its oil imports from the Middle East. Importing a broad range of critical materials from a land-locked region with which it shares a long, direct border would thus improve China's security of supply of critical materials for clean energy applications, in which it is already successfully vying for a central position as the world's largest producer of photovoltaic solar panels, wind turbines, and other equipment.

CENTRAL ASIAN CRITICAL MATERIALS GEOLOGY AND MINING

Kazakhstan

According to our data, there is a total of 233 mineral production sites and deposits in Kazakhstan (Table 4). Of these, 151 belong to local companies, some state-owned, others private. The largest is the state-owned company Saryarka. The largest deposits are mined by three corporations, jointly owned by local and foreign investors: Eurasian Resources Group (ERG), Kazakhmys Corporation, and Kazzinc. The largest of these companies is ERG, which controlled one-third of the total mining and metals production in the country in 2020. It is the world's largest high-carbon ferrochrome producer and one of the largest producers of aluminum, iron ore, copper, and cobalt in the former Soviet Union.[63] Companies domiciled outside Kazakhstan have full ownership of the development licenses for 11 deposits.

Table 2. Proven reserves of critical materials by country (metric tons) and total share of global reserves (%)

Critical material	Kazakhstan	Kyrgyzstan	Tajikistan	Uzbekistan	Proven reserves in Central Asia	Central Asia's share of global reserves (%)
Manganese	681,342,741	48,816	270,000,000	173,000	951,564,557	38.6
Chromium (ore and concentrate)	230,000,000	390,000	0	0	230,390,000	30.07
Lead	15,473,215	41,000	10,000,000	413,000	25,927,215	20
Zinc	31,436,736	24,000	10,000,000	4,549,000	46,009,736	12.6
Titanium	45,608,070	0	0	350,000,000	395,608,070	8.7
Aluminum/bauxite	309,885,594	42,101,000	1,000,000,000	12,700	1,351,999,294	5.8
Copper	38,582,964	640,000	150,000	741,200	40,114,164	5.3
Cobalt	208,121	373	0	645	20,9139	5.3
Molybdenum	713,827	2,523	0	139,000	855,350	5.2
Iron ore	19,885,503,100	549,000	500,000,000	22,000,000	20,408,052,100	4.8
Nickel	118,000	0	0	3,700	121,700	1.2
Silver (kg)	48,153	672	60,000	37,700	146,525	1.2
Tin	192,375	186,761	45,000	9,500	433,636	0.9
Lithium	50,000	13,923	0	8,334	72,257	0.4
Graphite	488,400	272,215	0	7,600,000	8,360,615	0.3
Silicon	5,090,000	0	0	12,000	5,102,000	0.01
Tellurium	0	1,524.5	0	1,098	2,622.5	0.01
Selenium (refined)	–	2.7	–	–	2.7	[a]
Cadmium	85,233	353.6	–	–	85,586.6	[a]
Gallium	–	–	–	–	–	[a]
Germanium	4,372	–	–	180	4,552	[a]
Indium	–	2,617	–	–	2,617	[a]

Source: Vakulchuk and Overland.[59]

[a] As data are missing for these minerals in these countries, shares of global reserves cannot be calculated.

Kyrgyzstan

As of July 2021, Kyrgyzstan has 43 officially registered critical material deposits and mining sites. Of these, 23 belong to foreign firms and 20 to local companies (Table 4). The largest number of foreign companies is domiciled in China, holding operating licenses for nine production sites; Russia and Cyprus-based companies own two each.

In January 2021, four mining sites were fully operational: Kumtor, Bozymchak, Karakazyk, and Taldybulak Levoberezhnyi. Kumtor, the largest mining deposit—where silver is an accompanying mineral to gold—is jointly owned by the Canadian company Centerra Gold (74% of shares) and the local company Kyrgyzaltyn (26% of shares). The Karakazyk and Taldybulak Levoberezhnyi deposits are both being developed by Chinese companies. Finally, Bozymchak is a copper deposit controlled by the Kazakh-Singaporean company KAZ Minerals.

In 2019–2020, political turmoil and a wave of protests in Kyrgyzstan forced several companies to suspend mining operations. For instance, KAZ Minerals Kyrgyzstan temporarily closed its copper mine in October 2020 following post-election unrest. Since 2010, Kyrgyzstan has experienced regular protests at mining sites related to water contamination and environmental pollution from mining operations, as well as controversies related to mine ownership and licensing arrangements.[64] These protests have often targeted mines operated by Chinese companies and had an anti-Chinese element.

Tajikistan

We identified 17 mining deposits and production sites in Tajikistan (Table 4). The country's largest company of any kind, Tajik Aluminum Company (TALCO), is one of the world's largest aluminum producers. China is the main country where foreign companies operating in Tajikistan are domiciled, and its companies own eight large production sites in Tajikistan. Two particularly large Chinese companies involved in critical minerals extraction in Tajikistan are the Chinese-Tajik Mining Company and Zeravshan. The former is the largest enterprise extracting and processing lead and zinc in Tajikistan and is one of the flagship projects of the Belt and Road Initiative (BRI) in Central Asia. Another foreign company is based in the United Kingdom and owns 49% of the shares in the Tajik state company Aprelevka.

Uzbekistan

We identified 71 mineral deposits in Uzbekistan (Table 4). Only 16 of them are actively mined and they are controlled by state companies. Two enterprises—Almalyk Mining and Metallurgical Complex and Navoi Mining and Metallurgical Combine—are the main producers of critical materials. As of 2021, three deposits in Uzbekistan are being developed by foreign companies. The remaining 52 deposits are state-owned but have been offered to investors since President Shavkat Mirziyoyev came to power in 2016 and Uzbekistan opened up after 25 years under the autocratic rule of former president Islam Karimov.

Table 3. Production of critical materials in Central Asia, 2019

Critical material	Global production (metric tons)	Annual domestic production (metric tons)	Share of global production (%)	Global production rank
Central Asia				
Chromium	407,89,986	5,191,920	12.73	2
Cadmium	25,578	1,573	6.15	2
Selenium	3,832	150	3.91	6
Zinc	12,444,207	710,253	5.71	6
Lead	4,767,954	88,500	2.47	7
Silver	26,261	1,307.7	4.98	7
Copper	20,613,942	883,554	4.29	7
Bauxite	325,998,326	6,104,200	1.87	8
Tellurium	524	48	9.16	8
Manganese	52,968,203	1,674,145	3.16	9
Iron	2,922,511,686	32,670,543	1.12	11
Molybdenum	276,097	750	0.27	11
Rhenium	N/A	900	5.8	11
Aluminum	125,800,000	365,700	0.57	22
Titanium	10,122,351	13,712	0.14	24
Kazakhstan				
Chromium	40,789,986	5,191,920	12.73	2
Cadmium	25,578	1,273	4.98	5
Selenium	3,832	130	3.39	7
Bauxite[a]	325,998,326	6,104,200	1.87	8
Zinc	12,444,207	491,253	3.95	8
Lead	4,767,954	115,956	2.43	9
Manganese	52,968,203	1,674,145	3.16	9
Silver	26,261	102.2	3.89	10
Copper	20,613,942	737,854	3.58	11
Iron	2,922,511,686	32,670,543	1.12	11
Titanium	10,122,351	13,712	0.14	24
Aluminum	62,900,000	255,751	0.41	26
Kyrgyzstan				
Silver	26,261	14.5	0.055	39
Copper	20,613,942	7,200	0.03	47
Tajikistan				
Lead	4,767,954	86,500	1.81	14
Zinc	12,444,207	192,000	1.54	21
Aluminum	62,900,000	100,800	0.16	33
Silver	26,261	11,1	0.42	48
Copper	20,613,942	38,500	0.19	50
Uzbekistan				
Tellurium	524	48	9.16	8
Molybdenum	276,097	750	0.27	11
Rhenium	n/a	900	5.8	11
Cadmium	25,578	300	1.17	14
Selenium	3,832	20	0.52	16
Copper	20,613,942	100,000	0.49	22
Zinc	12,444,207	27,000	0.22	31

(*Continued on next page*)

Table 3. *Continued*

Critical material	Global production (metric tons)	Annual domestic production (metric tons)	Share of global production (%)	Global production rank
Silver	26,261	260	0.99	33
Lead	4,767,954	2,000	0.04	41

Source: Vakulchuk and Overland.[59]

[a]Unlike some countries, Kazakhstan publishes official statistical data on aluminum and bauxite separately.

Export markets for Central Asian minerals

Chinese companies already dominate critical materials extraction in Kyrgyzstan (nine companies) and Tajikistan (eight companies) where they own the majority of licenses. Uzbekistan is a relatively new player in the global critical materials sector. Only after President Shavkat Mirziyoyev came to power in 2016 did the country's mineral deposits become accessible to foreign investors. However, Uzbekistan has the potential to become a leading regional exporter of critical materials for clean energy technologies in the near future.

In Kazakhstan, the sector is dominated by domestic companies, many of which are nominally private but partly owned by the government. However, China is the main export destination of most of Kazakhstan's critical materials output. While the EU and the United States are not among the main importers, Russia plays a notable role. Due to historical ties, Russia was the main importer of minerals from Central Asia in the 1990s and the 2000s, before China took over this role after 2010. Thus, although Chinese companies fully own only three production sites in Kazakhstan—fewer than they own in Kyrgyzstan and Tajikistan—China greatly increased its imports of Kazakhstani zinc, lead, copper, and other minerals after 2017 (Figures 2B–2D). The imports of molybdenum alone (used in the production of wind turbines) from Kazakhstan to China had grown by 444% in 2020 compared with the level of 2017 (Figure 2A).

China's involvement in the Central Asian critical materials sector involves a two-way relationship. On the one hand, China is becoming heavily involved in Central Asian infrastructure, business, and employment. Around the year 2000, few people envisaged that China would come to play such an important role in Central Asia as it has. On the other hand, Central Asia is quietly becoming more important to China. Although Southeast Asia, Western Africa, and Australia remain the largest suppliers of critical materials to China, Central Asia's share in the supply of selected critical materials has been rising rapidly since 2015.[65] Kazakhstan alone became the second-largest exporter of chromium to China after South Africa in 2019.[66] Similarly, Kazakhstan improved its position as a zinc exporter to China from number 18 in 2015 to number 11 in 2019. In 2015, Kazakhstan did not export any nickel to China, but already in 2019 it was ranked as China's 11th largest nickel supplier.[65] The nickel and cobalt that China imports from Central Asia are used in the production of lithium-ion batteries.[67] Central Asia's zinc, lead, molybdenum, and other critical materials are also used as inputs in the production of solar and wind power technologies in China. Given the rapidly growing Chinese demand for critical materials, the lack of competition in Central Asia from other investors and buyers, and the region's convenient and secure location for exports to China, Central Asian mineral exports to China will continue to grow. Along with the mineral exports, the economic and political importance of Central Asia to China is also likely to grow.

According to the IEA, revenues from the production of critical materials for clean energy applications will overtake those from coal production well before 2040.[1] Taking this trend into account, critical material exports could supplement and partly replace Central Asia's role as a supplier of oil and gas to international markets. Kazakhstan is the largest oil and gas exporter in Central Asia. In 2020, 73% of its total exports were oil and gas products. Ferrous metals, copper, aluminum, zinc, uranium, and other minerals constituted more than 20% of the remaining exports.[69] In terms of their economic value, critical materials exports are already becoming more competitive with hydrocarbons. Kazakhstani natural gas and copper exports in 2020 can serve as an example. For both exports, China was the largest buyer, importing natural gas worth US $0.9 billion, and copper worth US $1 billion.

In Tajikistan, critical materials made up 37% of total exports in 2019 (15% aluminum; 11.5% zinc ores and concentrates; 10.5% lead ores and concentrates).[70] For Uzbekistan, critical materials made up more than 11% of total exports. Copper and zinc were the fourth and ninth largest export items, respectively, with China and Russia as the main importers. Although Kyrgyz gold mining alone still contributes more than 50% of total exports and gold is not classified as a critical material for clean energy technologies, critical materials made up 10% of Kyrgyz exports in 2019.

GEOGRAPHY OF THE CRITICAL MATERIALS LITERATURE

Although the five Central Asian countries were among the main sources of metals and industrial minerals for the Soviet Union, we find that they are hardly mentioned in the literature on the geopolitics of critical materials. We searched the academic literature in the Crossref, Scopus, and Web of Science databases using the following search string: "geopolitic* AND energy AND ("critical materials" OR minerals OR "rare earths") AND country name." The search was limited to the 2009–2021 period, as it was after 2009 that adoption of clean energy technologies accelerated.[12] As a result of the search, we identified and analyzed 42 relevant publications (Table S1).

Figure 3 shows which countries are highlighted in the literature as important current or future locations for mining critical materials for clean energy technologies. We found 227 instances of a country or region being mentioned as important in the 42 publications. Kazakhstan was the only one of the Central Asian states that was mentioned, and that was only in two publications.[71,72] The other Central Asian states were not mentioned at all. Another two studies mention significant quantities of critical materials

Table 4. Domiciles of mining companies operating in Central Asia

	Company domicile/name	Minerals	Deposits
Companies operating in Kazakhstan	Kazakhstan[a]		151
	Saryarka	Cu, Fe, Mn, Mo, Ni, Co	14
	Dzharkulskoe	Fe	5
	Arman	Mn	4
	Nadezhdinskoe	Fe	3
	Tau-Ken Samruk	Cu, Fe, Mo, W	3
	Other small local companies	other minerals (see Figure 2)	122
	Multinational		30
	Kazakhmys Corporation and KAZ Minerals (Kazakhstan, Singapore, UK)		
	Kazakhmys	Cu, Zn	25
	KazMinerals Plc Bozshakol	Cu	1
	Idygey Project	Cu	1
	Itauyz Project	Cu	1
	Tamdy-Sainbulak Project	Cu	1
	Kazakhmys and Central Asia Metals	Cu	1
	Eurasian Resource Group (multinational)		28
	TNC Kazchrome	Cr, Mn, Si-Mn	11
	Aluminum of Kazakhstan	Al, Ga	10
	SSGPO	Fe	6
	Kazakhstan Aluminum Smelter	Al	1
	Kazzinc (Kazakhstan, Switzerland)		13
	Kazzinc	Cu, Pb, Zn, Cd, Ag, Se, Te, In	8
	Zhairem GOK (subsidiary of Kazzinc)	Cu, Mn	5
	Russia	Cu, Zn, Pb	5
	China	Fe, Al, Cu	3
	Belgium	Ti	1
	Turkey	Cr	1
	UK	Cu	1
Operating in Kyrgyzstan	Kyrgyzstan (own licenses but mining not started yet)	see minerals in Figure 1	20
	China		9
	Kaidi/Tianyong Mining Development	Cu, Pb, Ag, Zn	3
	Central Asian Tin Company	Sn	2
	Superb Pacific Ltd	Cu, Ag	1
	Kunshen Gornoprom	Pb, Zn	1
	Kichi-Chaarat	Cu, Ag	1
	Noeliya Group	Co	1
	British Virgin Islands	Cu, Pb, Ag	3
	Cyprus	Ag, Fe	2
	Russia		2
	Production Association Computer Engineering and Means of Automation	Mn	1
	BainGeo	C	1
	Bailiwick of Jersey	Ag	2
	South Korea	Li	1
	UK	Mo	1
	Cayman Islands	Al	1
	Canada (Centerra Gold Kumtor)	Ag	1
	Singapore and Kazakhstan (KazMinerals)	Cu, Ag	1

(*Continued on next page*)

Table 4. *Continued*

	Company domicile/name	Minerals	Deposits
Operating in Tajikistan	Tajikistan[a]		10
	Aprelevka (Tajikistan and the UK)	Ag	1
	Other companies	Al, Ag, Zn, Pb, Fe	9
	Chinese majority ownership		8
	Tajik-Chinese Mining Company and Tibet Summit Industry Co.	Ag, Zn, Pb, Cu	5
	China Global New Technology Import and Export	Zn	1
	Broadtec Investment	Sn	1
	Zeravshan (70%/30% owned by Zijing Mining/Tajik government)	Ag	1
Operating in Uzbekistan	Uzbekistan		16
	Stock Company Almalyk Mining and Metallurgical Complex (AMMC)	Cu, Ag, Pb, Mo, Te, Zn	8
	Navoi Mining and Metallurgical Combine	Al, Co, Cu, C, Mn, Mo, Ni, Ag, Zn, U	5
	State Committee of Geology and Mineral Resources of Uzbekistan	Pb, Li	3
	China	Pb	1
	Russia	Li	1
	British Virgin Islands	Pb	1
	recently opened to both domestic and foreign investors	all high/moderate geological potential (Figure 2)	52

Source: [60]

[a] Companies majority owned by the state.

found in the countries of the former Soviet Union, without specifying which countries.[73,74] None of the publications discuss how growing critical materials exports from the region could affect the economies of the Central Asian states by generating new revenues or causing new forms of dependency/resource curse.

The lack of attention to Central Asia is surprising, given that Kazakhstan alone is comparable in size to Western Europe and has one of the world's richest and most diverse mineral resource bases. Out of 110 elements in the periodic table, 99 are present in Kazakhstan.[75] Moreover, Central Asia holds a significant share of global reserves of critical materials such as chromium, manganese, lead, zinc, titanium, aluminum/bauxite, copper, cobalt, molybdenum, and iron ore (Table 2).

The EU and the United States do not yet consider Central Asia a strategic region for critical materials for clean energy technologies.[76–78] Except for Lithuania, none of the EU states is among the top five largest importers of critical materials from the Central Asian countries. The EU's Central Asia Strategy of 2019, the main strategic policy document shaping the relations between the EU and Central Asia, makes no mention of critical materials as an area of joint work.[78] However, individual Central Asian countries are referred to with respect to reserves of particular critical materials in reports funded by the European Commission.[79] Still, the EU already imports some critical materials for clean energy technologies from Kazakhstan. In 2019, Kazakhstan's share in the EU's supply of chromium was 16%, cadmium 7%, and titanium 7%.[46] The EU's total imports, however, are still much lower than those of China and other countries. Moreover, the EU also imports large quantities of some minerals used in other industries from Kazakhstan (Kazakhstan is the largest supplier of phosphorus to the EU, accounting for 72% of EU supplies;[46] phosphorus, however, is not on the list of critical minerals for clean energy technologies), and thus it could build on this minerals trade and consider importing more critical materials for clean energy technologies from Kazakhstan and other countries of Central Asia.[46]

As for China, its growing demand for resources triggered the Chinese government's adoption in 2000 of the Going Out Strategy.[80] This strategy enabled the extension of overseas foreign direct investment to critical materials in Africa and Asia. The BRI has also facilitated large-scale Chinese expansion into international mining markets, especially in Central Asia. In the 2010s, BRI projects in Central Asia were mainly focused on resource extraction.[20,21,106,107,108] By 2021, China had become the largest importer of critical materials from Central Asia.

DISCUSSION

Market potential of selected critical materials

Central Asia is both a mature geological province with some infrastructure in place and a region where significant exploration remains to be done. Yet it remains largely unknown to the clean technology community, which focuses on Argentina, Australia, Bolivia, Chile, China, the DRC, and the United States. The Central Asian geological potential and proven reserves of copper, silver, zinc, aluminum/bauxite, iron ore, lead, tin, cadmium, selenium, manganese, molybdenum, chromium, and titanium

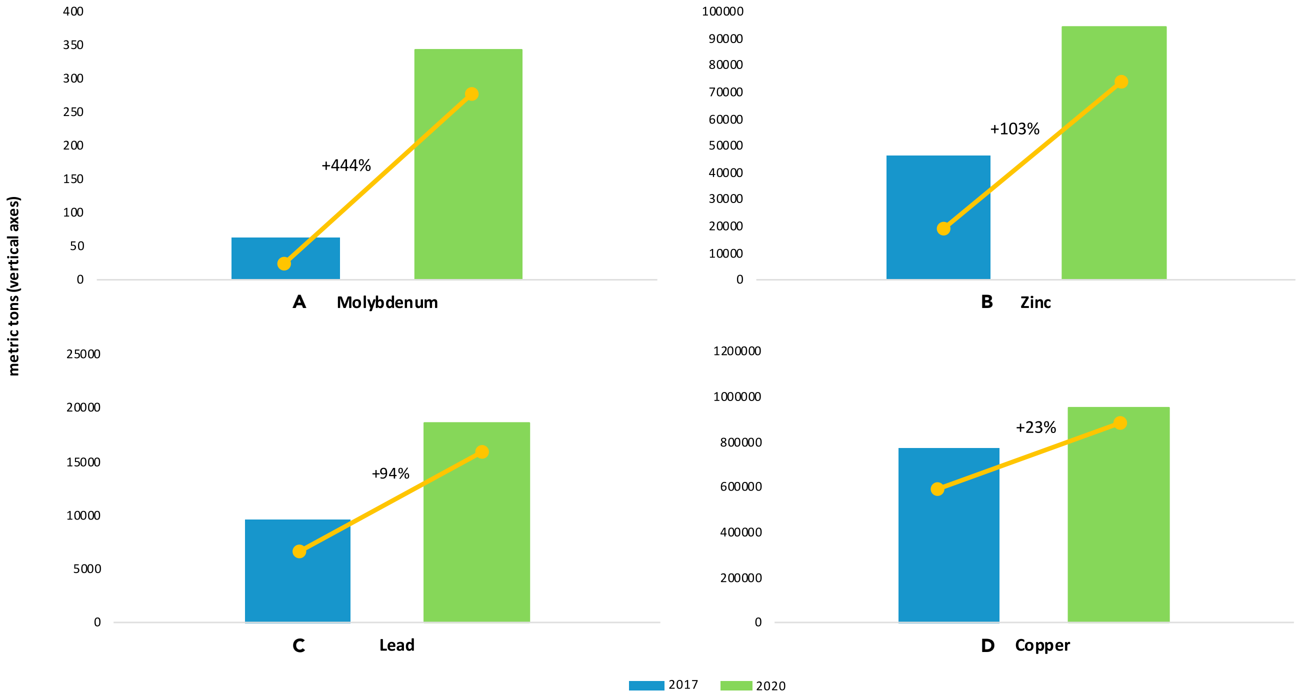

Figure 2. Growth of Chinese imports from Kazakhstan, 2017–2020
(A–D) Changes in China's imports of selected critical materials from Kazakhstan from 2017 to 2020. (A) Molybdenum; (B) zinc; (C) lead; (D) copper.
Source: [68]

can make the region an important global market player. As of 2021, none of these minerals had reached their production peak in any of the Central Asian countries.

According to IEA, "today's supply and investment plans for many critical minerals fall well short of what is needed to support an accelerated deployment of solar panels, wind turbines and electric vehicles."[1] Central Asia's role will likely become more visible as the global demand for critical minerals continues to grow. In 2020, the government of Kazakhstan announced that lithium mining will be prioritized over the next 5 years to ride the wave of global demand for EVs.[36]

Estimates indicate potential shortages of most of the minerals included in the IISD list of critical materials for clean energy applications.[2,81–85] Copper is needed for wind turbines, grid interconnections and EVs. It has been estimated that the demand for copper for EVs may grow 12 times by 2025 and that there will be a global copper deficit by 2030.[54] The global zinc market faced a deficit of 305,000 metric tons in 2018 and 189,000 metric tons in 2019.

As demand for materials increasingly outstrips supply, Central Asia may be the first port of call for China. There are already signs of this. In 2020, the depletion of copper reserves started looming in China and in the DRC, both of which are among the world's leading copper producers. The reserves-to-production ratios indicate that China has 16 years of copper production left, while the DRC has 14 years.[86] This has stimulated increased Chinese interest in Kazakhstan, given the latter's developed copper mining infrastructure and the easy access via the 1,780-km shared border between the two countries. By 2019, China was already Kazakhstan's largest copper importer, increasing its imports by 70% compared to 2018. Exploration may unearth further reserves in China, the DRC, and elsewhere in the world, but lead times from exploration to production are long and uncertain for mining projects.[1,87–89]

Risk factors

Central Asia's known reserves of critical materials are significant. China is the largest investor in and importer of critical materials from the region. It owns the majority of production and operating licenses in Kyrgyzstan and Tajikistan and is in the process of further raising its stakes. Uzbekistan's critical materials endowment and recent opening up to foreign investment also make it a potentially significant player along with Kazakhstan. China enjoys excellent relations with Uzbekistan.

However, the Central Asian countries and their external partners face several risks. The first risk factor is aging mining infrastructure. All the Central Asian countries rely on infrastructural legacies from the Soviet period, when the region served as a resource base for the Moscow-centered economy. While Kazakhstan has managed to upgrade some of its existing infrastructure, Kyrgyzstan and Tajikistan rely on aging infrastructure, with poor environmental and utilization track records. The Tajik aluminum giant TALCO hopes "a Chinese pledge of investment in its aging production facilities will reverse a downward trend in production."[90] Without substantial investment in infrastructure upgrades, further mining of critical materials will be unsustainable and costly.

The second risk is closely tied to the first: mining activities by foreign companies, especially Chinese-owned ones, have been

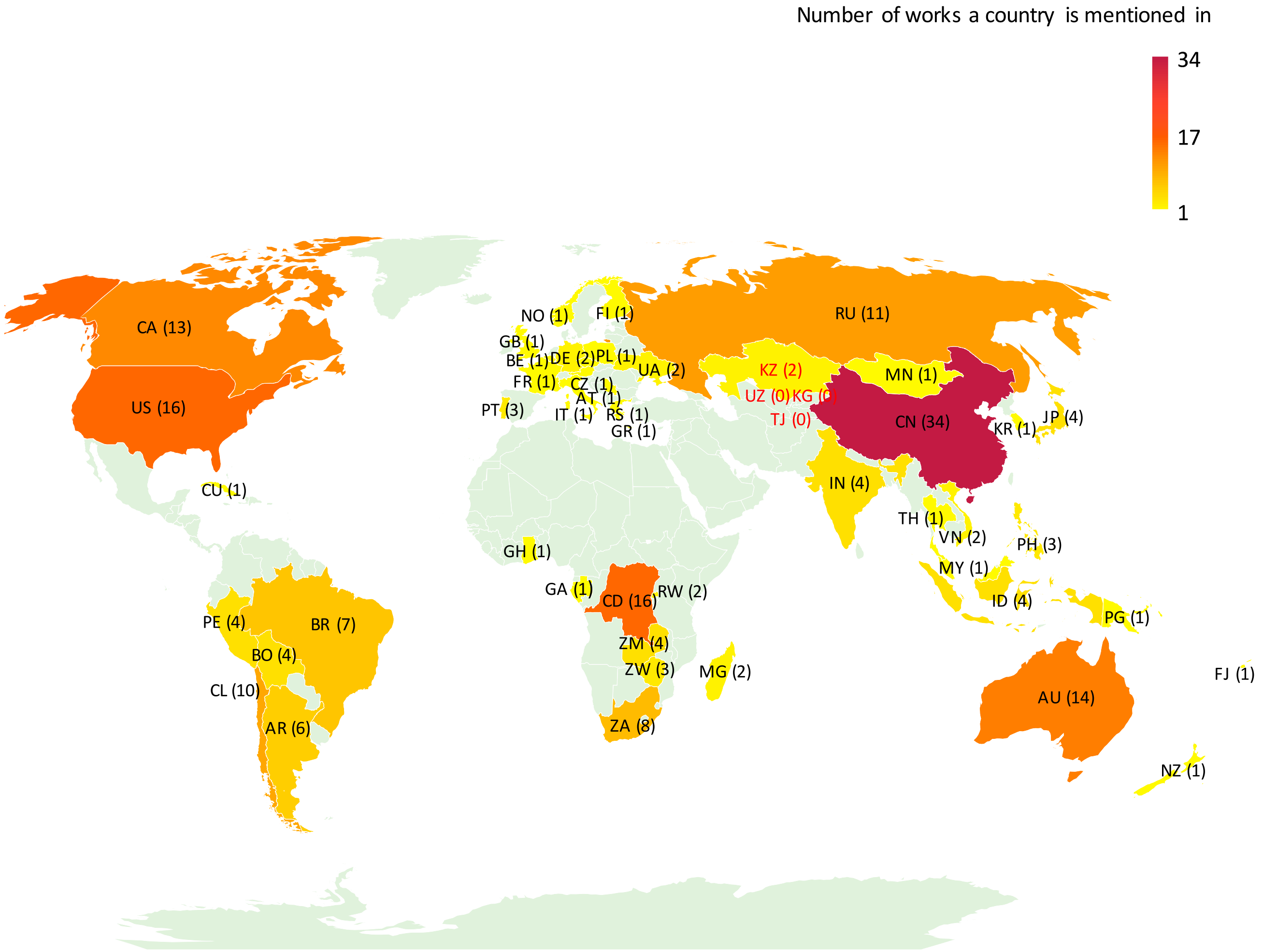

Figure 3. Geopolitical hotspots for critical materials

The map shows countries referred to in the academic literature from 2009 to 2021 as present or future markets, important resource bases, or geopolitical hotspots for critical materials. Sources: see Table S1.

sources of contestation and conflict in Central Asia, particularly Kyrgyzstan, since the region opened up after the collapse of the Soviet Union.[64] Environmental degradation (as a result of mining) and limited community benefits are often among the main complaints. This often results in the suspension of mining projects, as discussed above. If these concerns remain unaddressed, future mining projects are likely to generate further resistance from the local population.

Third, the region has been excessively dependent on raw materials exports for decades. This has resulted in limited economic diversification and an underdeveloped manufacturing base, leaving the region vulnerable to external economic shocks and global fluctuations in oil price. There is a risk that critical materials may slow down the economic diversification of oil-dependent Kazakhstan, which has strived since the early 2000s to develop other parts of the economy, when oil exports became the main source of revenue for the country.[58] Similarly, in mineral-rich Kyrgyzstan, mining contributes to taxes and development, along with corruption, the entrenchment of elites, and political conflict.[64] The case of Canadian Centerra Gold's many years of litigation with the Kyrgyz government regarding the Kumtor deposit is illustrative of such risk. If poorly designed and implemented, expanded mining of critical materials in Kyrgyzstan may be a source of political instability.

Fourth, the region suffers from limited transparency, weak governance, and a high level of corruption. The Natural Resource Governance Index ranks Kazakhstan 25th out of 89 countries in terms of natural resources governance; Kyrgyzstan is ranked 38, Uzbekistan is ranked 80, and Turkmenistan is ranked 88.[91] Thus, while the scores of Kazakhstan and Kyrgyzstan not unduly bad, Uzbekistan and Turkmenistan are among the worst performers. Difficulties in obtaining reliable data, including geological data, are often viewed as serious barriers to investment in these countries. On the one hand, weak governance might deter investors from venturing into Central Asia. On the other hand, mining investors often invest in countries with low governance standards. In countries with higher standards, rules, regulations, and social opposition against new mining sites can be major hurdles for investment. In addition, the countries of Central Asia have some of the most restrictive non-tariff barriers to trade in the world.[92,93] Nevertheless, as we have shown, China and other countries already invest in various minerals in the region.

Fifth, excessive dependence on China, both as an export market and as a financial and industrial partner, is another risk for the region. The closer Central Asia gets to a monopsony situation with China, the deeper will become the region's asymmetric economic dependence on Beijing. Already, the Central Asian countries—Kyrgyzstan and Tajikistan in particular—are heavily indebted to China.[94,95] Moreover, China was accused of taking parts of territories from the two countries as part of opaque business deals or as compensation for loans that the Central Asian states could not repay.[96,97] In 2020, statements were made by prominent Chinese actors that Tajikistan's Pamir region should be "returned" to China.[98]

Since 2013, much news coverage of the BRI has focused on large-scale infrastructure, transport, and connectivity projects in Central Asia.[20,99] Although China's greatly expanded critical materials mining portfolio in Central Asia has remained below the radar, it is poised to become an increasingly important element in bilateral relations.

One scenario is that China could pursue a "minerals-for-loans" deal with Kyrgyzstan and Tajikistan similar to the deal that China struck with the DRC as part of the Going Out Strategy.[80,100] Kyrgyzstan and Tajikistan are already dependent on Chinese loans to the extent that the two countries have been included in the "Chinese debt trap" group of countries, along with Djibouti, Sri Lanka, and others.[94] Critical materials is an area where China can gain control over the mining infrastructure in return for alleviating the debt dependency of the two countries. China plans to start negotiations on debt restructuring with Kyrgyz President Japarov, who was elected in January 2021. Among the items that can be included in a debt payment scheme are licensing rights at various mining sites. As President Japarov noted during the pre-election campaign in 2020, "we can pay for our external debt using our mineral resources. We can pay with ore resources worth USD 1 bln a year. We discussed this option [*with China*]."[101]

CONCLUSIONS AND OUTLOOK

Our findings reveal that Central Asia is already an important mining region but is missing from many of the global overviews of critical materials for clean energy technologies. The first question we set out to answer was: what role can Central Asia play in the global supply of critical materials for decarbonization? We find that the region is already one of the leaders in the production of some critical materials. In particular, Kazakhstan is a major producer of several critical materials and will likely extend its role in the future. Also Uzbekistan has significant potential. As global demand for many critical materials for clean energy is growing exponentially, there will be no lack of demand for Central Asian exports. In particular, active decarbonization in the EU countries and China is likely to raise their demand for critical materials from Central Asia.

The share of critical materials in the countries' exports is already significant and will likely grow further. Critical materials exports may partly replace shrinking fossil fuel exports, as demand for fossil fuels declines due to decarbonization in the main markets for Central Asia's oil and gas exports. If global demand for critical materials continues to grow and Central Asia becomes a more prominent supplier, critical materials will also play an increasingly important role in the exports and GDP of each Central Asian state. As a consequence, these countries may again fail to diversify their economies. Their excessive dependence on fossil fuels may be replaced by a similar dependence on critical materials, thus transitioning from one resource curse to another.

If Central Asia's mineral resource base is further developed, it can increase the region's geopolitical weight and importance in international affairs. Moreover, a possible shift from hydrocarbons to critical materials-based exports may bring reputational benefits. The shift could potentially support the region's internal energy transition and improve its international status, transforming it from an anti-climate fossil fuel zone to a pro-climate critical materials supplier.

Our second question was: what roles do Central Asian mineral resources play in the strategic positioning of great powers on critical materials? Our review shows that the region's geological potential and contribution to global production has been neglected. Because Central Asia has been disregarded, there is limited understanding of the role that the region plays in China's strategic positioning on critical materials. As of late 2021, China had substantially increased its economic clout in the region and above all in the mining sector. This can further strengthen China's already strong position in global critical materials markets.

Russia is another major player in Central Asia and importer of its mineral resources. However, its total share of Central Asian critical materials exports has been declining steadily since 2010 and compared with China it is less significant as a source of investment for the Central Asian mining sector. Other external players have little to do with Central Asian critical materials. The EU and the United States take an insignificant share of Central Asian exports and do not yet see the region as strategically important to their critical materials needs. However, as they become aware of the region's resource base and its rapidly strengthening ties with China, we expect that this will change.

Given Central Asia's lack of visibility on international clean energy technology maps, future research could focus on working out the details of the region's place in the global supply chain of critical materials for decarbonization. For example, this could include analyses of specific mineral reserves in Central Asia and their clean technology uses, markets, and politics. Central Asia's relative proximity to European, East Asian, South Asian, and Middle Eastern markets could be an advantage. Thanks to the broad variety of materials available, the region can serve most critical materials needs for clean energy. This makes it important in mining economics, security of supply, and geopolitical perspectives. Future research could also work out how the region can accommodate its potential growth in critical materials exports and tackle the risk factors outlined in the previous section.

Due to strict regulations and permitting procedures for new mines in developed countries, critical materials in high demand will increasingly be extracted in developing countries with weak governance and low environmental standards.[102] Cobalt mining in the DRC and lithium mining in Bolivia are cases in point.

Critical materials mining in Central Asia should be organized in a way that does not repeat the Congolese scenario, where cobalt mining has come to be seen as a source of environmental destruction, corruption, conflict, poverty, child labor, and ill health.[103–105] Thus, more research is needed on how the international community could extract more critical materials to mitigate climate change while limiting the negative consequences for mining communities and the environment in places such as Central Asia.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Roman Vakulchuk, Senior Research Fellow, Norwegian Institute of International Affairs (NUPI), rva@nupi.no.

Materials availability

This study did not generate new unique materials.

Data and code availability

The used data (Datasets 1 and 2) are available in free access on the Mendeley Data platform as Dataset 1[59] and Dataset 2.[60]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.11.012.

ACKNOWLEDGMENTS

We are grateful to the Central Asia Data-Gathering Team (CADGAT), Aidai Isataeva, and Galina Kolodzinskaya for assisting with obtaining access to and collecting data. We are thankful to the Ministry of Foreign Affairs of Norway (project no. QRS-20/0001). We would also like to thank Ida Dokk Smith for providing insightful feedback on an early draft of the article.

AUTHOR CONTRIBUTIONS

R.V.: funding acquisition, project administration, conceptualization, data curation, formal analysis, methodology, resources, supervision, validation, visualization, writing – original draft, writing – review & editing. I.O.: funding acquisition, conceptualization, methodology, validation, visualization, writing – original draft, writing – review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. International Energy Agency (2021). The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions (International Energy Agency).
2. World Bank (2017). The Growing Role of Minerals and Metals for a Low Carbon Future (World Bank).
3. Bazilian, M.D. (2018). The mineral foundation of the energy transition. Extr. Ind. Soc. *5*, 93–97.
4. Chen, Z., Zhang, L., and Xu, Z. (2020). Analysis of cobalt flows in mainland China: exploring the potential opportunities for improving resource efficiency and supply security. J. Clean. Prod. *275*, 122841.
5. Statista (2020). Global Cobalt Reserves by Country 2020. Statista. https://www.statista.com/statistics/264930/global-cobalt-reserves/.
6. Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A., and Tuma, A. (2016). Import-based indicator for the geopolitical supply risk of raw materials in life cycle sustainability assessments: import-based indicator for geopolitical supply risk of raw materials. J. Ind. Ecol. *20*, 154–165.
7. Heredia, F., Martinez, A.L., and Surraco Urtubey, V. (2020). The importance of lithium for achieving a low-carbon future: overview of the lithium extraction in the 'Lithium Triangle'. J. Energy Nat. Resour. Law *38*, 213–236.
8. Hancock, L., Ralph, N., and Ali, S.H. (2018). Bolivia's lithium frontier: can public private partnerships deliver a minerals boom for sustainable development? J. Clean. Prod. *178*, 551–560.
9. Silberglitt, R., Bartis, J.T., Chow, B.G., An, D.L., and Brady, K. (2013). Critical Materials: Present Danger to U.S. Manufacturing (RAND Corporation).
10. Kalantzakos, S. (2013). Rare Earths: China vs the World: A Case Study in the Geopolitics of Natural Resources in the 21st Century (University of Pelopponese).
11. Nassar, N.T., Brainard, J., Gulley, A., Manley, R., Matos, G., Lederer, G., Bird, L.R., Pineault, D., Alonso, E., Gambogi, J., et al. (2020). Evaluating the mineral commodity supply risk of the U.S. manufacturing sector. Sci. Adv. *6*, eaay8647.
12. Kalantzakos, S. (2018). China and the Geopolitics of Rare Earths (Oxford University Press).
13. Foreign Policy (2019). Mining the Future. How China Is Set to Dominate the Next Industrial Revolution. Foreign Policy https://foreignpolicy.com/2019/05/01/mining-the-future-china-critical-minerals-metals/.
14. Cooley, A. (2012). Great Games, Local Rules: The New Great Power Contest in Central Asia (Oxford University Press).
15. Kim, Y., and Indeo, F. (2013). The new great game in Central Asia post 2014: the US "New Silk Road" strategy and Sino-Russian rivalry. Communist Post-Communist Stud. *46*, 275–286.
16. Pradhan, R. (2021). Energy geopolitics and the new great game in Central Asia. Millennial Asia. https://doi.org/10.1177/09763996211003260.
17. Pradhan, S.K. (2020). Central Asia: geopolitics and "new great game.". In India's Quest for Energy through Oil and Natural Gas: Trade and Investment, Geopolitics, and Security, S.K. Pradhan, ed. (Springer), pp. 87–101.
18. Laruelle, M. (2015). The Chinese silk road and their reception in Central Asia. https://www.uscc.gov/sites/default/files/Laruelle%20Testimony_3.18.15.pdf.
19. Dave, B., and Kobayashi, Y. (2018). China's silk road economic belt initiative in Central Asia: economic and security implications. Asia Eur. J. *16*, 267–281.
20. Vakulchuk, R., and Overland, I. (2019). China's belt and road initiative through the lens of central Asia. In Regional Connection under the Belt and Road Initiative, F.M. Cheung and Y.-y. Hong, eds. (Routledge), pp. 115–133.
21. Aminjonov, F., Abylkasymova, A., Eshchanov, B., Moldokanov, D., Overland, I., and Vakulchuk, R. (2019). BRI in Central Asia: overview of Chinese projects. Central Asia Reg. Data Rev. *20*, 1–5.
22. Collins, N. (2020). Players or spectators? Central Asia's role in BRI. In International Flows in the Belt and Road Initiative Context: Business, People, History and Geography Palgrave Series in Asia and Pacific Studies, H.K. Chan, F.K.S. Chan, and D. O'Brien, eds. (Springer), pp. 147–169.
23. Kassenova, N. (2018). More Politics than Substance: Three Years of Russian and Chinese Economic Cooperation in Central Asia (Foreign Policy Research Institute).
24. Kassenova, N. (2020). Kazakhstan's adaptation to the belt and road initiative: tracing changes in domestic governance. In The Belt and Road Initiative and Global Governance, M.A. Carrai, J.-C. Defraigne, and J. Wouters, eds. (Edward Elgar Publishing), pp. 182–203.
25. Irnazarov, F., and Vakulchuk, R. (2020). The pandemic as a litmus test for (dis)engagement of external powers in central Asia. In Caucasus & Central Asia. Post COVID-19 (Strasbourg Policy Centre), pp. 43–60.
26. Ebel, R., and Menon, R. (2000). Energy and Conflict in Central Asia and the Caucasus (Rowman & Littlefield Publishers).
27. Dorian, J.P. (2006). Central Asia: a major emerging energy player in the 21st century. Energy Policy *34*, 544–555.
28. Kaiser, M.J., and Pulsipher, A.J. (2007). A review of the oil and gas sector in Kazakhstan. Energy Policy *35*, 1300–1314.
29. Laruelle, M., and Peyrouse, S. (2009). China as a Neighbor: Central Asian Perspectives and Strategies (Central Asia-Caucasus Institute).
30. Palazuelos, E., and Fernández, R. (2012). Kazakhstan: oil endowment and oil empowerment. Communist Post-Communist Stud. *45*, 27–37.
31. van de Graaf, T., and Bradshaw, M. (2018). Stranded wealth: rethinking the politics of oil in an age of abundance. Int. Aff. *94*, 1309–1328.
32. Van de Graaf, T. (2018). Battling for a shrinking market: oil producers, the renewables revolution, and the risk of stranded assets. In The Geopolitics of Renewables, D. Scholten, ed. (Springer International Publishing), pp. 97–121.

33. Van de Graaf, T., and Verbruggen, A. (2015). The oil endgame: strategies of oil exporters in a carbon-constrained world. Environ. Sci. Policy *54*, 456–462.
34. Habib, K., Hamelin, L., and Wenzel, H. (2016). A dynamic perspective of the geopolitical supply risk of metals. J. Clean. Prod. *133*, 850–858.
35. Cimprich, A., Karim, K.S., and Young, S.B. (2018). Extending the geopolitical supply risk method: material "substitutability" indicators applied to electric vehicles and dental X-ray equipment. Int. J. Life Cycle Assess. *23*, 2024–2042.
36. Bizhikeeva, M. (2020). Бауыржан Айткулов: Литий может стать второй нефтью для Казачстана. Деловой Џортал Kapital.kz. https://kapital.kz/experts/91508/bau-yrzhan-aytkulov-litiy-mozhet-stat-vtoroy-neft-yu-dlya-kazakhstana.html.
37. Olivetti, E.A., Ceder, G., Gaustad, G.G., and Fu, X. (2017). Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule *1*, 229–243.
38. Rabe, W., Kostka, G., and Stegen, K.S. (2017). China's supply of critical raw materials: risks for Europe's solar and wind industries? Energy Policy *101*, 692–699.
39. Wilson, J.D. (2018). Whatever happened to the rare earths weapon? Critical materials and international security in Asia. Asian Security *14*, 358–373.
40. Gulley, A.L., Nassar, N.T., and Xun, S. (2018). China, the United States, and competition for resources that enable emerging technologies. PNAS *115*, 4111–4115.
41. Kalantzakos, S. (2020). The race for critical minerals in an era of geopolitical realignments. Int. Spectator *55*, 1–16.
42. Andersson, P. (2020). Chinese assessments of "critical" and "strategic" raw materials: concepts, categories, policies, and implications. Extr. Ind. Soc. *7*, 127–137.
43. Overland, I. (2019). The geopolitics of renewable energy: debunking four emerging myths. Energy Res. Soc. Sci. *49*, 36–40.
44. Lee, J., Bazilian, M., Sovacool, B., Hund, K., Jowitt, S.M., Nguyen, T.P., Månberger, A., Kah, M., Greene, S., Galeazzi, C., et al. (2020). Reviewing the material and metal security of low-carbon energy transitions. Renew. Sustain. Energy Rev. *124*, 109789.
45. Church, C., and Crawford, A. (2018). Green Conflict Minerals: The Fuels of Conflict in the Transition to a Low-Carbon Economy (International Institute for Sustainable Development (IISD)).
46. European Commission (2020). Study on the EU's List of Critical Raw Materials (European Commission).
47. Fortier, S.M., Nassar, N.T., Lederer, G.W., Brainard, J., Gambogi, J., and McCullough, E.A. (2018). Draft Critical Mineral List—Summary of Methodology and Background information—U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359 (U.S. Geological Survey).
48. Graedel, T.E., and Reck, B.K. (2016). Six years of criticality assessments: what have we learned so far?: six years of criticality assessments. J. Ind. Ecol. *20*, 692–699.
49. Schrijvers, D., Hool, A., Blengini, G.A., Chen, W.-Q., Dewulf, J., Eggert, R., van Ellen, L., Roland, G., Goddin, J., Habib, K., et al. (2020). A review of methods and data to determine raw material criticality. Resour. Conserv. Recycl. *155*, 104617.
50. International Renewable Energy Agency (2019). A New World. The Geopolitics of the Energy Transformation (International Renewable Energy Agency (IRENA)).
51. Dominish, E., Teske, S., and Florin, N. (2019). Responsible Minerals Sourcing for Renewable Energy (Institute for Sustainable Futures, University of Technology).
52. Hund, K., La Porta, D., Fabregas, T.P., Laing, T., and Drexhage, J. (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition (World Bank).
53. Alves Dias, P., Bobba, S., Carrara, S., and Plazzotta, B. (2020). The Role of Rare Earth Elements in Wind Energy and Electric Mobility: An Analysis of Future Supply/Demand Balances (EU Publications Office).
54. Kollmeyer, B. (2020). There's not enough copper for a green wave. Buy these miners, says Jefferies. Barron's https://www.barrons.com/articles/these-miners-are-a-buy-because-the-copper-market-cant-keep-up-with-demand-51606233159.
55. Intrado (2021). Outlook on the silicon metal global market to 2027—opportunity analysis and industry forecasts. GlobeNewswire https://www.globenewswire.com/fr/news-release/2021/03/26/2199987/28124/en/Outlook-on-the-Silicon-Metal-Global-Market-to-2027-Opportunity-Analysis-and-Industry-Forecasts.html.
56. International Tin Association (2020). Tin. Global Resources & Reserves (International Tin Association).
57. Carrara, S., Alves Dias, P., Plazzotta, B., and Pavel, C. (2020). Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System (EU Publications Office).
58. Vakulchuk, R. (2014). Kazakhstan's Emerging Economy (Peter Lang).
59. Vakulchuk, R., and Overland, I. (2021). Critical Materials for Clean-Energy Technologies in Central Asia: Geological Potential, Reserves, Production and Export (Mendeley Data). https://doi.org/10.17632/wy54s5tpxb.1.
60. Vakulchuk, R., and Overland, I. (2021). Critical Materials Mining in Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan: Deposits, Ownership and Companies (Mendeley Data). https://doi.org/10.17632/mp328hh34n.1.
61. Taylor, R.B., and Steven, T.A. (1983). Definition of mineral resource potential. Econ. Geol. *78*, 1268–1270.
62. Statista (2020). Chromium Reserves Worldwide by Country 2020. Statista. https://www.statista.com/statistics/1040749/reserves-of-chromium-worldwide-by-country/.
63. Eurasian Resources Group (2021). About the Eurasian Resources Group. Eurasian Resources Group. https://www.erg.kz/en/content/o-kompanii/obzor-deyatel-nosti-erg.
64. Sternberg, T. (2020). Conflict and contestation in Kyrgyz mining infrastructure. Extractive Industries Soc. *7*, 1392–1400.
65. UNCTAD (2021). UN Comtrade Database. UNCTAD. https://comtrade.un.org/data.
66. Kozhanova, N. (2019). Kazakhstan is one of world leaders in chromite mining, production and reserves, says U.S. Geological Survey. Astana Times https://astanatimes.com/2019/09/kazakhstan-is-one-of-world-leaders-in-chromite-mining-production-and-reserves-says-u-s-geological-survey/.
67. Reuters. (2021). Казачстанский Џроизводитель никеля и кобальта Battery Metals Џланирует листинҐ в ГонконҐе и Астане. Reuters.
68. International Trade Center (ITC) (2021). List of Importing Markets for a Product Exported by Kazakhstan. International Trade Center. https://www.trademap.org/.
69. Ministry of Economy (2020). Export Statistics. Kazakhstan Ministry of National Economy. https://www.gov.kz/memleket/entities/economy?.
70. UNCTAD (2020). General Profile: Tajikistan. UNCTADstat. http://unctadstat.unctad.org/countryprofile/generalprofile/en-gb/762/index.html.
71. Rosenau-Tornow, D., Buchholz, P., Riemann, A., and Wagner, M. (2009). Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends. Resour. Policy *34*, 161–175.
72. Dewulf, J., Blengini, G.A., Pennington, D., Nuss, P., and Nassar, N.T. (2016). Criticality on the international scene: quo vadis? Resour. Policy *50*, 169–176.
73. Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., and Kirchain, R.E. (2012). Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ. Sci. Technol. *46*, 3406–3414.
74. Exner, A., Lauk, C., and Zittel, W. (2015). Sold futures? The global availability of metals and economic growth at the peripheries: distribution and regulation in a degrowth perspective. Antipode *47*, 342–359.
75. Ministry of Ecology, Geology and Natural Resources (2019). Документы. Ministry of Ecology, Geology and Natural Resources. https://www.gov.kz/memleket/entities/ecogeo/documents/1?lang=kk.
76. US Department of Energy (2010). Critical Materials Strategy (US Department of Energy).
77. Humphries, M. (2015). China's Mineral Industry and U.S. Access to Strategic and Critical Minerals: Issues for Congress (Congressional Research Service).
78. European Commission (2019). The EU and Central Asia: New Opportunities for a Stronger Partnership (European Commission).
79. Moss, R., Tzimas, E., Willis, P., Arendorf, J., and Tercero Espinoza, L. (2013). Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies (Publication Office of the EU).
80. Gulley, A.L., McCullough, E.A., and Shedd, K.B. (2019). China's domestic and foreign influence in the global cobalt supply chain. Resour. Policy *62*, 317–323.
81. Junne, T., Wulf, N., Breyer, C., and Naegler, T. (2020). Critical materials in global low-carbon energy scenarios: the case for neodymium, dysprosium, lithium, and cobalt. Energy *211*, 118532.

82. Månberger, A., and Stenqvist, B. (2018). Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development. Energy Policy *119*, 226–241.
83. Deetman, S., Pauliuk, S., van Vuuren, D.P., van der Voet, E., and Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ. Sci. Technol. *52*, 4950–4959.
84. Tokimatsu, K., Wachtmeister, H., McLellan, B., Davidsson, S., Murakami, S., Höök, M., Yasuoka, R., and Nishio, M. Energy modeling approach to the global energy-mineral nexus: a first look at metal requirements and the 2 C target. Appl. Energy 207, 494–509.
85. World Wide Fund for Nature (2014). Critical Materials for the Transition to a 100% Sustainable Energy Future (World Wide Fund for Nature (WWF)).
86. Mines and Metals (2020). DRC and China are burning through their copper reserves fastest in the world. Mines and Metals https://www.minesandmetals.com/2020/04/the-worlds-copper-reserves-ranked-by-country/.
87. De Geoffroy, J.G., and Wignall, T.K. (1985). Designing Optimal Strategies for Mineral Exploration (Springer).
88. Marjoribanks, R. (2010). Geological Methods in Mineral Exploration and Mining (Springer).
89. Cook, B. (2010). Gold miners & explorers face serious supply problems. https://www.mining.com/gold-miners-explorers-face-serious-supply-problems/.
90. Oxford Analytica (2018). China Deal Could Double Tajikistan's Aluminium Output (Emerald Expert Briefings *oxan-db*).
91. National Resource Governance Institute (2021). Country Profiles. National Resource Governance Institute. https://resourcegovernanceindex.org/country-profiles/.
92. Vakulchuk, R., and Knobel, A. (2018). Impact of non-tariff barriers on trade within the Eurasian economic union. Post-Communist Econ. *30*, 459–481.
93. Vakulchuk, R., and Irnazarov, F. (2014). Analysis of Informal Obstacles to Cross-Border Economic Activity in Kazakhstan and Uzbekistan (Asian Development Bank).
94. Fernholz, T. (2018). Eight countries in danger of falling into China's "debt trap". Quartz https://qz.com/1223768/china-debt-trap-these-eight-countries-are-in-danger-of-debt-overloads-from-chinas-belt-and-road-plans/.
95. Laruelle, M. (2018). China's Belt and Road Initiative and its Impact in Central Asia (The George Washington University).
96. Blank, S. (2002). China's defeats in Central Asia. Central Asia Analyst https://www.cacianalyst.org/publications/analytical-articles/item/7025-analytical-articles-caci-analyst-2002-8-14-art-7025.html?tmpl=component&print=1.
97. Kabarlar. (2020). Китай забрал у Таджикистана 1 тыс. кв. км земли за долҐи. ТеЦерь забирает трансЦортные маршруты и месторождения. КАБАРЛАР. https://kabarlar.org/news/117566-kitaj-zabral-u-tadzhikistana-1-tys-kv-km-zemli-za-dolgi-teper-zabiraet-transportnye-marshruty-i-mestorozhdenija.html.
98. Goble, P. (2020). Beijing Implies Tajikistan's Pamir Region Should Be Returned to China. The Jamestown Foundation. https://jamestown.org/program/beijing-implies-tajikistans-pamir-region-should-be-returned-to-china/.
99. Kassenova, N. (2017). China's silk road and Kazakhstan's bright path: linking dreams of prosperity. Asia Policy *24*, 110–116.
100. Kaplinsky, R., and Morris, M. (2009). Chinese FDI in sub-Saharan Africa: engaging with large dragons. Eur. J. Dev. Res. *21*, 551–569.
101. Radio Azattyk (2020). ЖаЦаров: Обсуждается вариант выЦлатить долҐ Китаю сырьем с месторождения Жетим-Тоо. Радио Азаттык (КырҐызская служба Радио Свободная ЕвроЦа/Радио Свобода) https://rus.azattyk.org/a/30944009.html.
102. Prakash, A., and Dolsak, N. (2021). Blind spots in climate policy: EV supply chain and climate adaptation. Forbes https://www.forbes.com/sites/prakashdolsak/2021/01/05/blind-spots-in-climate-policy-ev-supply-chain-and-climate-adaptation/.
103. Sovacool, B.K. (2019). The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. Extr. Ind. Soc. *6*, 915–939.
104. Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.-M., Nawrot, T.S., et al. (2018). Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. *1*, 495–504.
105. Ross, N. (2017). The cobalt boom: recharging trouble in the Congo. Foreign Brief https://www.foreignbrief.com/africa/cobalt-boom-recharging-trouble-congo/.
106. Aminjonov, F., Abylkasymova, A., Eshchanov, B., Moldokanov, D., Overland, I., and Vakulchuk, R. (2019). BRI in Central Asia: rail and road connectivity projects. Central Asia Reg. Data Rev. 1–18, 21.
107. Aminjonov, F., Abylkasymova, A., Eshchanov, B., Moldokanov, D., Overland, I., and Vakulchuk, R. (2019). BRI in Central Asia: energy connectivity projects. Central Asia Reg. Data Rev. 1–14, 22.
108. Aminjonov, F., Abylkasymova, A., Eshchanov, B., Moldokanov, D., Overland, I., and Vakulchuk, R. (2019). BRI in Central Asia: mineral and petroleum exploration, extraction and processing projects. Central Asia Reg. Data Rev. 1–13, 23.

One Earth, Volume *4*

Supplemental information

Central Asia is a missing link in analyses of critical materials for the global clean energy transition

Roman Vakulchuk and Indra Overland

Supplemental Information

Table S1. **Countries referred to in the academic literature as present or future markets, important resource bases, or geopolitical hotspots for critical materials**

Countries	Sources
Australia, Canada, Chile, China, Indonesia, **Kazakhstan,** Peru, Poland, Russia, USA, Zambia	[1]
Australia, Canada, China, DRC, South America, USA	[2]
China	[3]
China, Commonwealth of Independent States (CIS), DRC, USA	[4]
China, USA	[5]
Argentina, Chile, Bolivia, Serbia, USA	[6]
Argentina, Bolivia, Chile, China, DRC, Russia	[7]
China, Japan, South Korea	[8]
China, Japan, Mongolia	[9]
Brazil, China, Indonesia, Russia, South Africa	[10]
Russia, USA	[11]
Canada, DRC, USA, Zambia	[12]
Canada, China, OECD, South Africa, USA	[13]
Australia, China, USA	[14]
Australia, Canada, China, DRC	[15]
DRC, G7 countries, BRICS, the EU-27 countries	[16]
Australia, Bolivia, Brazil, Canada, Chile, Fiji, Indonesia, Madagascar, New Zealand, Peru, the Philippines, Portugal, South Africa, USA	[17]
Australia, Brazil, China, Gabon, Ghana, India, **Kazakhstan,** Malaysia, South Africa, Ukraine	[18]
Australia, Brazil, China, India, Russia, South Africa	[19]
China, the EU, Japan, USA	[20]
Australia, Canada, China, Czech Republic, Germany, Russia, USA, Zimbabwe	[21]
Australia, Canada, China, DRC, Peru, Russia	[22]
Austria, Bolivia, Canada, China, Portugal, Russia, Rwanda, Thailand, Vietnam	[23]
China	[24]
Australia, the EU	[25]
Brazil, Canada, Chile, China, India	[26]
China, South Africa	[27]
Belgium, Chile, DRC, Finland, Indonesia	[28]
Australia, Canada, China, the EU, France, Germany, Greece, India, Italy, Japan, Norway, UK, USA	[29]
Argentina, Australia, Chile, China, the United States	[30]
China, DRC, Russia, Rwanda	[31]
China, DRC, the Philippines, South Africa	[32]
China, DRC, Papua New Guinea, Zambia	[33]
Australia, Argentina, Brazil, Canada, Chile, China, Cuba, DRC, Madagascar, Peru, the Philippines, Russia, South Africa, Ukraine, the US, Vietnam, Zambia, Zimbabwe	[34]
China	[35]
China	[36]
China, DRC	[37]
Argentina, Australia, Brazil, Canada, Chile, China, DRC, Portugal, USA, Zimbabwe	[38]
China	[39]
Argentina, Chile, China, DRC, Russia	[40]
China, DRC	[41]
China	[42]

Supplemental References

1. Rosenau-Tornow, D., Buchholz, P., Riemann, A., and Wagner, M. (2009). Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends. Resources Policy *34*, 161–175.

2. Buijs, B., and Sievers, H. (2011). Critical Thinking about Critical Minerals. Assessing risks related to resource security (Bundensanstalt fuer Geowissenschaften und Rohstoffe).

3. Eggert, R.G. (2011). Minerals go critical. Nature Chem *3*, 688–691.

4. Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., and Kirchain, R.E. (2012). Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies. Environ. Sci. Technol. *46*, 3406–3414.

5. Buijs, B., Sievers, H., and Tercero Espinoza, L.A. (2012). Limits to the critical raw materials approach. Proceedings of the Institution of Civil Engineers - Waste and Resource Management *165*, 201–208.

6. Kesler, S.E., Gruber, P.W., Medina, P.A., Keoleian, G.A., Everson, M.P., and Wallington, T.J. (2012). Global lithium resources: Relative importance of pegmatite, brine and other deposits. Ore Geology Reviews *48*, 55–69.

7. Kushnir, D., and Sandén, B.A. (2012). The time dimension and lithium resource constraints for electric vehicles. Resources Policy *37*, 93–103.

8. Achzet, B., and Helbig, C. (2013). How to evaluate raw material supply risks—an overview. Resources Policy *38*, 435–447.

9. Wübbeke, J. (2013). Rare earth elements in China: Policies and narratives of reinventing an industry. Resources Policy *38*, 384–394.

10. Moss, R.L., Tzimas, E., Kara, H., Willis, P., and Kooroshy, J. (2013). The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. Energy Policy *55*, 556–564.

11. Bustamante, M.L., and Gaustad, G. (2014). Challenges in assessment of clean energy supply-chains based on byproduct minerals: A case study of tellurium use in thin film photovoltaics. Applied Energy *123*, 397–414.

12. Exner, A., Lauk, C., and Zittel, W. (2015). Sold Futures? The Global Availability of Metals and Economic Growth at the Peripheries: Distribution and Regulation in a Degrowth Perspective. Antipode *47*, 342–359.

13. Coulomb, R., Dietz, S., Godunova, M., and Nielsen, T.B. (2015). Critical Minerals Today and in 2030: An Analysis for OECD Countries.

14. Riddle, M., Macal, C.M., Conzelmann, G., Combs, T.E., Bauer, D., and Fields, F. (2015). Global critical materials markets: An agent-based modeling approach. Resources Policy *45*, 307–321.

15. Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Shigetomi, Y., and Suh, S. (2015). Global Mining Risk Footprint of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum in Japan. Environ. Sci. Technol. *49*, 2022–2031.

16. Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A., and Tuma, A. (2016). Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments: Import-based Indicator for Geopolitical Supply Risk of Raw Materials. Journal of Industrial Ecology *20*, 154–165.

17. Hatayama, H., and Tahara, K. (2015). Evaluating the sufficiency of Japan’s mineral resource entitlements for supply risk mitigation. Resources Policy *44*, 72–80.

18. Dewulf, J., Blengini, G.A., Pennington, D., Nuss, P., and Nassar, N.T. (2016). Criticality on the international scene: Quo vadis? Resources Policy *50*, 169–176.

19. Habib, K., Hamelin, L., and Wenzel, H. (2016). A dynamic perspective of the geopolitical supply risk of metals. Journal of Cleaner Production *133*, 850–858.

20. Rabe, W., Kostka, G., and Stegen, K.S. (2017). China’s supply of critical raw materials: Risks for Europe’s solar and wind industries? Energy Policy *101*, 692–699.

21. Martin, G., Rentsch, L., Höck, M., and Bertau, M. (2017). Lithium market research – global supply, future demand and price development. Energy Storage Materials *6*, 171–179.

22. Grandell, L., Lehtilae, A., Kivinen, M., Koljonen, T., Kihlman, S., and Lauri, L.S. (2016). Role of critical metals in the future markets of clean energy technologies. Renewable Energy *95*, 53–62.

23. Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., et al. (2017). EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. Resources Policy *53*, 12–19.

24. Frenzel, M., Kullik, J., Reuter, M.A., and Gutzmer, J. (2017). Raw material ‘criticality’—sense or nonsense? J. Phys. D: Appl. Phys. *50*, 123002.

25. Calvo, G., Valero, A., and Valero, A. (2018). Thermodynamic Approach to Evaluate the Criticality of Raw Materials and Its Application through a Material Flow Analysis in Europe: Evaluation of Critical Raw Materials Using Rarity. Journal of Industrial Ecology *22*, 839–852.

26. Cimprich, A., Young, S.B., Helbig, C., Gemechu, E.D., Thorenz, A., Tuma, A., and Sonnemann, G. (2017). Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles. Journal of Cleaner Production *162*, 754–763.

27. McCullough, E., and Nassar, N.T. (2017). Assessment of critical minerals: updated application of an early-warning screening methodology. Miner Econ *30*, 257–272.

28. Nansai, K., Nakajima, K., Suh, S., Kagawa, S., Kondo, Y., Takayanagi, W., and Shigetomi, Y. (2017). The role of primary processing in the supply risks of critical metals. Economic Systems Research *29*, 335–356.

29. Gemechu, E.D., Sonnemann, G., and Young, S.B. (2017). Geopolitical-related supply risk assessment as a complement to environmental impact assessment: the case of electric vehicles. Int J Life Cycle Assess *22*, 31–39.

30. Sun, X., Hao, H., Zhao, F., and Liu, Z. (2017). Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation & Recycling *124*, 50–61.

31. Kolotzek, C., Helbig, C., Thorenz, A., Reller, A., and Tuma, A. (2018). A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications. Journal of Cleaner Production *176*, 566–580.

32. Gaustad, G., Krystofik, M., Bustamante, M., and Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. Resources, Conservation and Recycling *135*, 24–33.

33. Gulley, A.L., McCullough, E.A., and Shedd, K.B. (2019). China's domestic and foreign influence in the global cobalt supply chain. Resources Policy *62*, 317–323.

34. Månberger, A., and Johansson, B. (2019). The geopolitics of metals and metalloids used for the renewable energy transition. Energy Strategy Reviews *26*.

35. Wang, P., Chen, L.-Y., Ge, J.-P., Cai, W., and Chen, W.-Q. (2019). Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition. Applied Energy *253*.

36. Ioannidou, D., Heeren, N., Sonnemann, G., and Habert, G. (2019). The future in and of criticality assessments. Journal of Industrial Ecology *23*, 751–766.

37. Campbell, G.A. (2020). The cobalt market revisited. Miner Econ *33*, 21–28.

38. Leader, A., Gaustad, G., and Babbitt, C. (2019). The effect of critical material prices on the competitiveness of clean energy technologies. Mater Renew Sustain Energy *8*, 8.

39. Kim, J., Lee, J., Kim, B., and Kim, J. (2019). Raw material criticality assessment with weighted indicators: An application of fuzzy analytic hierarchy process. Resources Policy *60*, 225–233.

40. Wang, P., Li, N., Li, J., and Chen, W.-Q. (2020). Metal-energy nexus in the global energy transition calls for cooperative actions. In The Material Basis of Energy Transitions (Elsevier), pp. 27–47.

41. Renner, S., and Wellmer, F.W. (2020). Volatility drivers on the metal market and exposure of producing countries. Miner Econ *33*, 311–340.

42. Hao, M., Wang, P., Song, L., Dai, M., Ren, Y., and Chen, W.-Q. (2020). Spatial distribution of copper in-use stocks and flows in China: 1978-2016. Journal of Cleaner Production *261*.