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Securing critical raw materials for the net zero and digital transformation

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The transformation to climate neutrality and the drive towards digitalisation will significantly shape and alter future needs to secure raw materials. While the importance of fossil energy resources is diminishing, demand for both bulk metals such as copper and special metals such as lithium, rare earths and cobalt is growing strongly. These mineral resources play a major role in the expansion of renewable energy, the development of traction motors and batteries for electric mobility, as well as robotics, 3-D printing and other digital technologies.

Europe, and Germany in particular, are heavily dependent on imports of metals and individual industrial minerals. For around a dozen strategically essential minerals, import dependence is as high as 100%. Germany and Europe are increasingly caught between two conflicting trends. On the one hand, the global use of mineral resources for climate-friendly energy technologies will have to increase six-fold by 2040 to achieve the goal of limiting global warming to 1.5°C in accordance with the Paris Climate Agreement. The global digitalisation drive will also increase demand for raw materials. On the other hand, the already high geographic concentration of global raw material production and processing could further intensify against the backdrop of increased competition. In addition, it is already becoming clear that the development of global extraction capacity is not keeping pace with future demand for minerals. For the positioning of European businesses operating in the area of strategic technologies such as lithium-ion batteries and solar technology, China's strong market power poses a particular challenge not just with regard to the supply of raw materials but also with a view to Europe's future technological competitiveness..

As recent shocks have highlighted, the criticality and vulnerability of mineral resources for the competitiveness and sustainability of the economy, the EU and Germany have already taken key steps for greater resource security by amending their natural resource strategies. Now more than ever, the agreed measures need to be fleshed out and swiftly implemented in close collaboration with the business community. In addition to pushing ahead with the drive towards a circular economy and increasing raw materials extraction in Europe, a key approach is to diversify the sources of raw materials – including by forging new strategic alliances with resource-rich countries.

Critical dependencies are a bottleneck for meeting high future raw material requirements

Russia's war of aggression against Ukraine and the resulting efforts to ensure Germany's energy security have painfully illustrated the dramatic consequences that may derive from strong dependencies in the procurement of raw materials. In this respect, Germany is heavily or completely dependent on imports of not just fossil energy sources but mineral resources. While most construction raw materials, particularly sand, gravel and natural stones, as well as various industrial minerals such as potash and rock salt, are extracted from domestic deposits, German companies mostly rely on imports for the supply of metals and individual industrial minerals as well as their intermediate products.[1] The global extraction of mineral resources is marked by high supply country concentration, as is also the case for fossil fuels. Only ten countries account for 70% of global extraction of mineral resources. China is by far the most important production country, generating 18% of total global mining production value, according to most recent figures. Australia follows well behind with a 13% share, ahead of Brazil, Russia, Chile and the USA, each with 5% to 6%. With a mere 0.4% of global mining production, Germany is in 33rd place in the ranking of mining countries.[2] There is strong concentration in raw materials processing as well, with China being the dominant player.

High supply concentration creates procurement and pricing risks for buyers as well as geostrategic dependencies when suppliers exploit their market advantages to exert pressure even in areas that go beyond commodities trading. In the future, advancing digitalisation and the transformation towards net zero emissions being pursued by many industrialised countries will significantly increase the need for mineral commodities. Three questions are highlighted here:

- What impacts do the green transformation and the digitalisation process have on the global demand for raw materials?
- Which materials are susceptible to potential supply risks?
- What strategies exist for increasing raw materials security in Germany and Europe?

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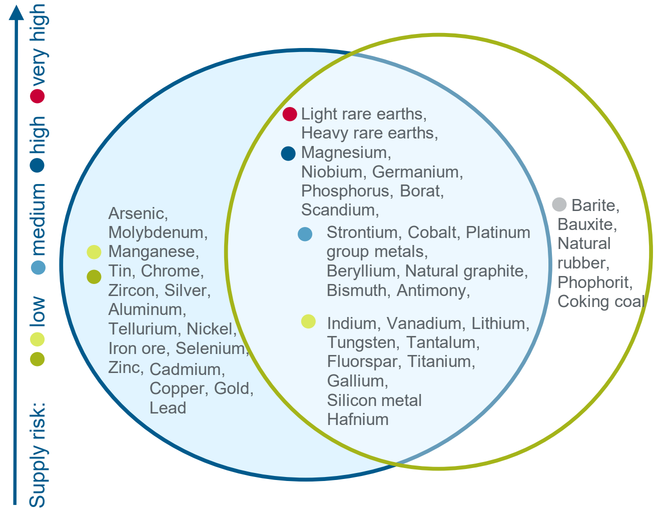
Raw materials for green and digital technologies are already at risk of supply shortages

The technologies needed for decarbonisation and the digital transformation require the input of numerous specific mineral resources. Solar cells for photovoltaic modules, for example, are manufactured using bulk metals such as steel, aluminium and copper, as well as special metals such as silicon, germanium, indium and gallium. Wind turbines need steel, zinc, chrome, manganese and nickel, among other metals, while wind generators with permanent magnets additionally need rare earths such as neodymium and dysprosium. These are also built into motors of electric vehicles that run on lithium-ion batteries, which need nickel, cobalt and graphite in addition to lithium. The grid expansion which is necessary for the integration of renewables requires large quantities of copper and aluminium. And digital technologies draw on almost the whole periodic table of elements, consuming particularly high amounts of copper, gallium, germanium, gold, indium, platinum metals, rare earths and tantalum.[3]

Since 2011 the EU Commission has been publishing a list of critical mineral resources that is updated every three years and provides important indications of supply risks for required raw materials. The list classifies a resource as critical if it is both of essential economic importance for the EU and susceptible to suppy risks.[4] Economic relevance is mainly based on how important the resource in question is for value creation in individual sectors and to what extent it can be substituted. The list bases supply risk on the EU's dependence on imports of the respective material, the country and company concentration of mining and processing, governance indicators of the supplier countries and trade restrictions. The aspects of whether the resource can be substituted and recycled are deemed risk-mitigating factors.

Figure 1: Overview of critical and strategically important materials for the EU

Green oval= critical materials according to the EU (2020a).
Blue oval= materials for strategically important technologies according to the EU (2020).



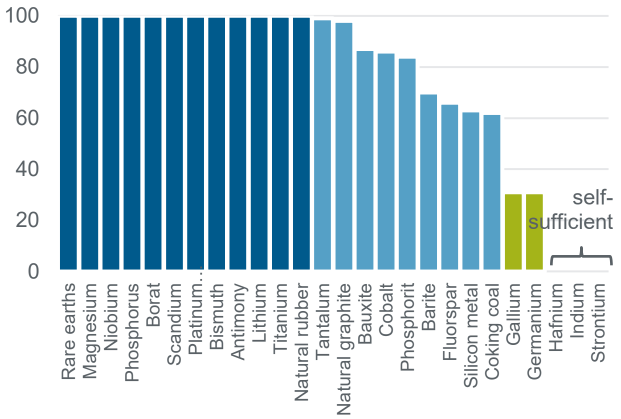
Note: ●=no classification regarding supply risk

Source: KfW Research, EU Commission (2020, 2020a)

The most recent edition classified 30 mineral resources as critical. That number has roughly doubled since 2011. Figure 1 (green oval) provides an overview of the materials currently classified as critical, including several materials that are of high relevance for strategic technologies in the area of climate action and digitalisation (blue oval). Table 2 (see end of this article) lists a selection of these materials with details on their fields of use, most important extraction countries, largest global deposits and annual extraction quantities. These are essentially special metals which, although used in only relatively small quantities in green and digital technologies, are of central importance to their functioning, for example because of semiconducting or magnetic properties.

Figure 2: EU's import dependence on critical raw materials

Import rate in per cent



Note: Import dependence calculated as share of net imports in total obtained from domestic production and net imports. Based on available data.

Source: EU Commission (2020a), KfW Research

EU is highly dependent on China in particular

For the materials classified as critical, supply risks primarily result from the EU's high dependency on imports and the concentration of global production in a handful of countries. It is for only three metals out of the 30 critical raw materials – strontium, indium and hafnium – that the EU is not reliant on imports from outside the union (Figure 2). But even here, it is highly dependent on a small number of EU mining companies.[5] The EU's import dependency stands at 100% in nearly half the resources for which trade data is available. For a further nine metals, the union meets more than half its demand from imports.

China's prominent position in both extraction and further processing of raw materials is significant (see also Box 1). This applies particularly to gallium, graphite, bismuth, tungsten and magnesium. According to the most recent estimates by the U.S. Geological Survey, in 2021 China accounted for at least three fourths of global extraction of these raw materials. Nearly 60% of the rare earths extracted around the world also came from Chinese mines. But low-income countries, too, play a major role for individual minerals. Around 70% of the world's cobalt extraction, for example, comes from the Democratic Republic of the Congo, which is home to nearly 46% of known global deposits. The EU is highly dependent on South Africa for platinum, on Australia and Chile for lithium, and on Brazil for niobium.[6]

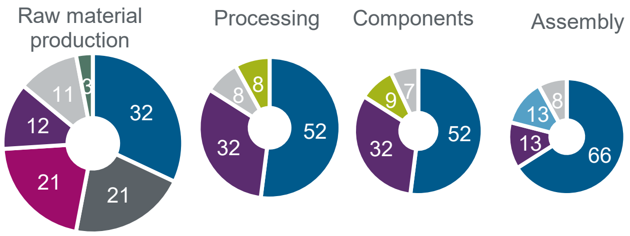
Commodities as (trade) weapons?

In addition to supply risks from exogenous shocks, high geographical concentration may be weaponised and thus presents geostrategic risks. In the recent past, there have been examples of suppliers exploiting market advantages in the supply chain for geostrategic and trade-policy purposes for mineral commodities as well. In 2010 China stopped exporting rare earths to Japan in response to a maritime incident. The conflict was settled by the WTO in 2014.[7] Since then, Japan's dependence on China for imports of rare earths has dropped from 91% to 58%. Besides increasing imports from Vietnam and other countries, Japan has also focused on the further development of technologies aimed at reducing demand, such as smaller motors that require lower quantities of rare earth metals. In 2019 the EU imported 98% and the US 80% of rare earths from China.[8]

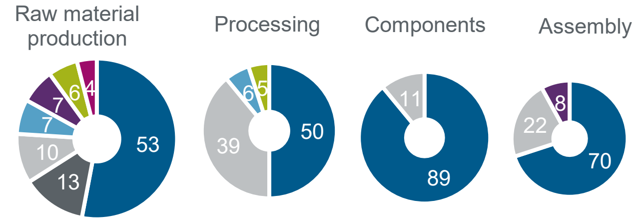
Figure 3: Market shares in selected technologies

In per cent

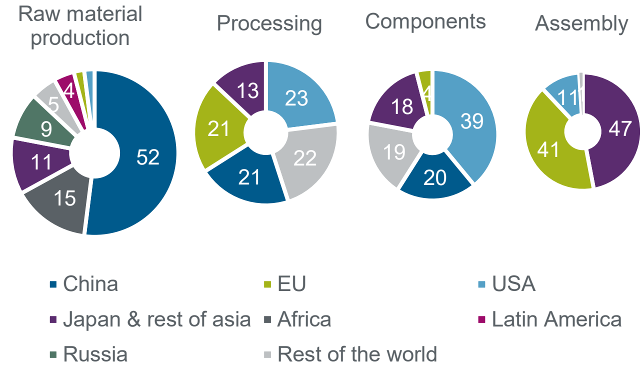
Lithium-ion batteries



Photovoltaics



Robotics



Source: KfW Research, European Commission (2020)

Little diversification across the value chain

High country concentration can be seen not just in the extraction of mineral commodities but also in the downstream value chains of many important technologies that are key to the green and digital transformation.[9] China, for example, dominates the market for photovoltaic modules, both in the extraction of the resources and with regard to processed materials and components (Figure 3, see also Box 1). China's strict zero-COVID strategy has resulted in significant supply bottlenecks for solar components that are also slowing PV expansion in Germany. Another example: Around three quarters of all materials required for the manufacture of lithium-ion batteries, which are used particularly in electric vehicles, stationary storage batteries and mobile digital devices, come from China, Africa and Latin America. Furthermore, China is currently the leading supplier of finished lithium-ion batteries. The EU's global market share in these finished products was less than 1% in 2020. By contrast, the EU occupies a strong position in the last stage of the robotics supply chain, for example, that is, the supply of industrial and service robots, (41% market share in 2020). Here as well, China is the largest supplier of the necessary materials (52%), followed by South Africa (15%) and Russia (9%). The EU is also highly dependent on imports of robotics components.

Box 1: China dominates the global market for many raw materials

The high concentration of global production and processing of mineral resources in China is particularly prominent. Overall, China is the largest producer of 18 of the 30 critical raw materials identified by the EU.[10] Above all, China's quasi-monopolistic position in the market for rare earths, magnesium and bismuth (with more than 90% of EU imports) makes the associated value chain vulnerable.[11] Accordingly, China carries great weight as a supplier of permanent magnets, an important component of wind turbine generators and electric motors for electric vehicles. For photovoltaic technology, China dominates around half of the raw material production and almost all of the component production. China's rise in the solar industry began at the end of the 1990s and coincided with the launch of incentive programmes for rooftop photovoltaic systems in Germany and the resulting increase in demand. It was bolstered, too, by heavy subsidies for producers from the Chinese Government. China also dominates the manufacture of lithium-ion batteries across the value chain and supplies two thirds of the finished batteries sold on the global market. In addition, the country is the largest supplier of raw materials in the areas of robotics and 3-D printing.[12]

But China is not just a producer but also the world's largest consumer of many strategic raw materials and therefore of relevance for setting prices. In 2018, China consumed more than 60% of the world's tungsten, manganese and cobalt. Its consumption of lithium, nickel and chrome was more than 40%. At the same time, China is also dependent on imports for more than a dozen minerals such as niobium, chrome and cobalt.[13] China's own raw materials strategy therefore is based not just on the expansion of raw materials extraction for which it has a local advantage (rare earths, tungsten, molybdenum and antimony) but on securing access to resources classified as critical (besides energy resources and base metals, various special metals such as chrome, cobalt, titanium and metals of the platinum group).[14] Accordingly, the development of extractive projects in the extraction countries embedded in the Belt-and-Road Initiative also plays a central role.[15]

After growing rapidly, China's demand for resources such as cement and steel already peaked in the years 2013–2014.[16] As it continues to industrialise, the growth rates for base metals such as copper, aluminium, zinc and lead are also slowing. On the other hand, demand for many special metals is expected to grow significantly by 2035 as the country pursues its goal of leading the world in the expansion of renewable energy and electric mobility.

The green and digital transformation will greatly increase demand for critical minerals

The EU list of critical resources is primarily a depiction of the status quo. In addition, the EU Commission has presented a study analysing future resource requirements for strategically important technologies – lithium-ion batteries, fuel cells, wind energy, photovoltaics, traction motors, robotics, drones, 3-D printing and digital technologies.[17] Figure 1 (blue oval) contains an overview of the most important resources needed to manufacture these technologies and the EU Commission's classification of the degree of supply risk for each resource (see also Table 2).

The EU analysis of the value chains for the strategic technologies mentioned above shows that resource procurement is the most critical stage for all technologies, as only approx. 3% of the resources required come from within the EU. Demand for the resources analysed is expected to grow significantly in the EU by 2050. The EU Commission has made different assessments of the future supply of each resource. Importantly, China's dominance of the extraction and processing of rare earths is expected to continue into the future. It is also expected that the Democratic Republic of the Congo will remain the most important source of cobalt owing to its considerable deposits. What is questionable is whether the Congo can reliably meet the growing demand under sustainable conditions, given its political instability and the large share of artisan and small mining operations. The EU Commission also regards China's heavy dominance of cobalt ore processing as a critical issue. According to research by the New York Times, 15 of the 19 large Congolese mines were either Chinese-owned or had Chinese investment in 2020.[18]

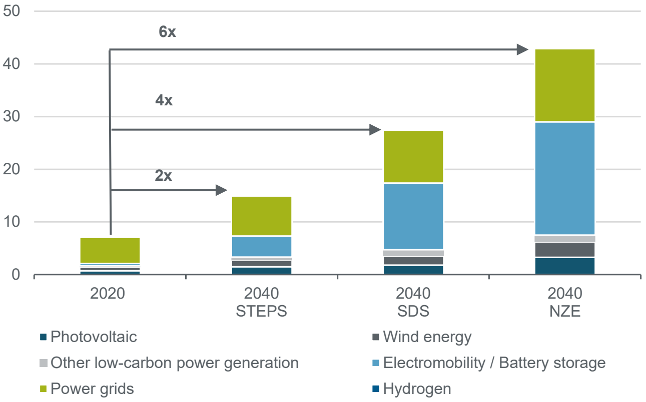
The EU Commission advocates investing more in expanding global mining capacity to meet the increasing demand for high-purity nickel and lithium for battery production in the future. The concentration of natural graphite in China could also be a challenge for the future of battery production. Furthermore, bulk metals such as copper, iron, aluminium, zinc and lead are broadly used in the various strategic technologies. However, the EU Commission does not yet classify their supply situation as critical.

Six-fold increase in resource extraction is needed to meet the 1.5°C target of the Paris Climate Agreement

Global competition for raw materials for key technologies will increase substantially. So far, an estimate has been made only on the additional global demand for mineral resources required for climate-friendly energy technologies, while the requirements for digital technologies have not yet been broadly quantified. In 2021 the International Energy Agency (IEA) quantified the needs for important energy technologies such as photovoltaics, wind energy and electric mobility in different climate scenarios and assuming different development pathways for the material intensity of the relevant technology. The findings illustrate that global resource requirements will depend heavily on the global level of ambition on climate action.[19] Based on the existing or announced climate action measures of the individual states, the IEA expects total demand for mineral resources for climate-friendly energy technologies to double by 2040 compared with the resource consumption of these technologies in 2020 (Figure 4, STEPS scenario). Achieving the target of the Paris Climate Agreement – limiting global warming to well below 2°C – would mean a four-fold increase in raw materials demand by 2040 (SDS scenario). Limiting global warming to 1.5°C would require a six-fold increase in the use of mineral raw materials by 2040 compared with present-day consumption (NZE scenario).

Figure 4: Growing demand for mineral resources for climate-friendly energy technologies

By scenario (in millions of tonnes)



Note: **STEPS**=Stated Policies Scenario; **SDS**=Sustainable Development Scenario (limiting global warming to well below 2°C); **NZE**=Net zero by 2050 Scenario (limiting global warming to 1.5°C). Comprises only mineral resources covered by the scope of the IEA study.

Source: IEA (revised in 2022, first published in 2021), KfW Research

The example of the mean scenario – limiting global warming to well below 2°C – illustrates that the increase in demand differs considerably from one resource to another. In this scenario, lithium will experience the highest growth rate, with demand rising more than 40-fold by 2040, followed by graphite, cobalt and nickel (by a factor of 20-25). Demand for rare earths will rise seven-fold over the same period, while demand for copper will roughly treble. The two drivers of demand for raw materials are electric mobility and battery storage, accounting for nearly half the forecast total demand for mineral resources in 2040. One third of future demand for mineral resources will come from electricity grids in the form of copper alone.

Development of extraction capacity is not keeping up with future global resource demand

The energy transition is making climate-friendly energy technologies the fastest-growing segment of demand for a number of mineral resources. Under the IEA's 2°C scenario, their share in total demand will rise to more than 40% for copper and rare earths, 60 to 70% for nickel and cobalt and almost 90% for lithium by 2040. Electric vehicles and storage batteries have already overtaken consumer electronics as the largest lithium consumer.

The IEA analysis of the raw materials supply side highlights the following: A gap is emerging between the demand for mineral resources required to meet the climate targets on which the international community has agreed and the actual availability of these resources. Current investment plans in the mining sector around the world are essentially geared to a world of gradual change, which means they are out of tune with the needs of an accelerated transformation that is indispensable for meeting the targets of the Paris Climate

Agreement. For example, according to IEA calculations, by 2030 existing mining capacity and sites under development will be able to meet only around half the global demand for lithium and cobalt and 80% of the demand for copper that would be compatible with the 2°C target. The gap is even wider for achieving the 1.5°C target. An inadequate supply of raw materials could delay or increase the cost of the global energy transition.[20]

Transformation requires strategies for securing raw materials in Germany and Europe

In order to prevent the supply of raw materials from becoming a bottleneck to the transformation in Germany and Europe and to enable European companies to participate in the value creation potentials of the necessary technologies, policymakers and businesses need to focus closely on securing a reliable and affordable supply of materials. That means they will have to address a multitude of challenges which have the potential to cause shortages or major price volatility in commodity markets. These include:

- High geographic concentration in the production of numerous mineral resources, some of which is higher than in oil and gas production,
- Prolonged development periods for new mining projects,
- The ecological and social impact associated with the extraction of mineral resources, as much of what is currently being extracted originates in regions with low governance rankings or high emission intensity,
- Declining ore quality in many mineral resources, leading to higher processing costs, emissions and waste quantities, and
- Increasing risks for mining projects from the impacts of climate change (such as water scarcity or floods).

What general options for action exist in Germany and Europe to address potential risks to the supply of strategically important minerals? Key approaches to securing future raw material supplies include (i) diversifying procurement sources, (ii) building resource partnerships with resource-rich countries in compliance with high environmental and social standards, (iii) expanding raw materials extraction in Europe, and (iv) greater financial participation of European companies in international mining projects or processing of raw materials (vertical integration of supply chains). As Germany and Europe import a major portion of the required raw materials as partially processed intermediate products and not in the form of ore or concentrate, efforts aimed at securing raw material supplies should cover the entire value chain of important key technologies.

An important approach: the circular economy

To reduce overall demand for raw materials and, subsequently the dependence on raw material imports, we also have to change the ways in which they are used. Economical and efficient use of materials, as well as increased recycling, can reduce the consumption of primary natural resources, whose extraction and processing is often very energy-intensive. Thus, transitioning to a circular economy is at the same time an essential strategy for achieving the net-zero targets in Germany and Europe. Although recycling critical special metals could be an important approach to resource security in Germany and Europe, its potential has hardly been developed. Recycling of end-of-life electrical appliances and vehicles, for example, remains largely focused on the reclamation of mass metals such as iron, copper and aluminium. Recycling technologies for critical special metals that can be used cost-effectively and on an industrial scale are still largely lacking. These metals are difficult to recycle mainly because of the very small quantities used in end products. Legal and illegal exports of end-of-life products to developing and emerging countries also prevent a regulated material cycle. In order to harness this resource potential more effectively, policymakers need to define frameworks for establishing innovative recycling processes (for example by setting recycling quotas for critical special metals).[21]

Rethinking planning, security and diversification: specific proposals for action

Securing the supply of critical raw materials has become a key topic on the EU agenda for achieving strategic autonomy. The aim is to prevent possible supply chain vulnerabilities with respect to industrial, energy and climate policy. The EU raw materials strategy essentially rests on three pillars:

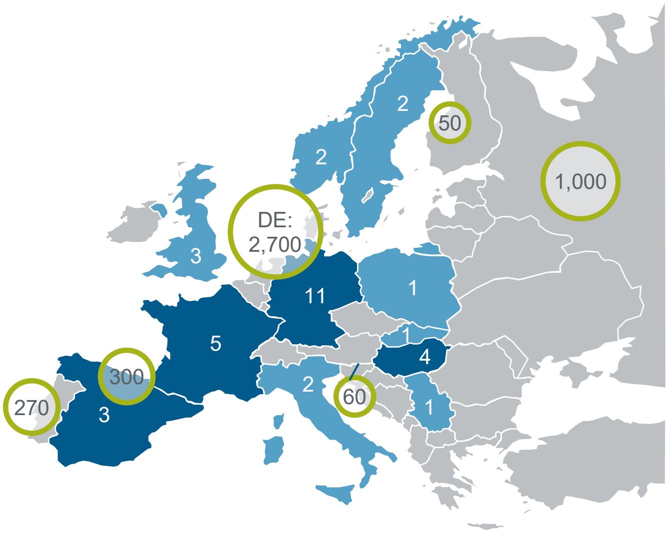
- Capping demand for raw materials by promoting the circular economy,
- Diversifying imports,
- Incentivising mining in Europe.

The greenhouse gas reduction goals agreed under the EU Green Deal lend additional urgency to this endeavour. Another reason the supply of raw materials must be secured is to be able to shape the market of future-facing technologies moving forward. Under the European Chips Act, the EU plans to double its global market share of semiconductors from currently 10% by 2030.[22] Founded in 2017, the European Battery Alliance aims to promote technological development and to significantly expand production capacity along the battery value chain with the aid of gigafactories in Europe. The aim is for the battery market to grow to as much as EUR 250 billion annually to meet EU demand.[23] In addition, a collaboration between the Battery Alliance and the US Li-Bridge Alliance was launched in March 2022 in order to strengthen transatlantic links in the battery value chain.[24]

Lithium is a key resource in the manufacturing of batteries. There are currently ten viable lithium projects in the EU, including in Spain, Portugal and Germany, and more are planned for the coming years (see Figure 5). A EUR 2.2 billion project in Serbia was shelved at the start of the year due to ecological concerns, and resistance is also building in Portugal.[25] The rating agency Fitch nevertheless forecasts that Eastern and South-eastern Europe will assert itself as a regional hub for vertically integrated commercial lithium extraction within the next decade – with close links to European battery manufacturers. Figure 5 illustrates the identified lithium resources (in the circles) according to the U.S. G.S (2022). Fitch also expects production in Germany's Upper Rhine Valley, the largest identified lithium deposit in Europe (2.7 million tonnes), to commence in 2024.[26] At the same time, it must be borne in mind that the as yet underdeveloped European extraction of primary materials must be seen as part of a longer-term strategy that takes into account cost advantages, logistical networks as well as lower environmental and social standards in extractive countries. The potential of raw materials extraction in Europe therefore must always be weighed against the advantages of international integration.

Figure 5: Battery projects and lithium resources in Europe

Number of existing or planned gigafactories for battery production.
In circles: Identified lithium resources in 1,000 tonnes (in 2022)



Source: IPCEI, PV Magazine, U.S. Geological Survey (2022)

Germany’s raw materials strategy is also aligned with the quest for an international level playing field in the supply of raw materials.[27] It includes measures such as research and development as well as initiatives aimed at reviving the extraction of metals in Europe. While corporate responsibility for securing raw materials supplies continues to form of the regulatory framework, trade restrictions, market power concentration and changed social and ecological standards give the state a stronger role to play in the current strategy than in the preceding strategy of 2010. Nevertheless, the business perspective remains decisive for assessing and removing material supply risks.

On the financing side, Untied Loan Guarantees from the Federal Government constitute a key instrument that protects lenders of resources projects outside Germany from economic and political loan default risks and thereby provide a reliable framework for long-term offtake agreements of German companies. In an attempt to give renewed impetus to domestic resource extraction, the Federal Government supported companies with conditionally repayable loans under what is referred to as the Exploration Funding Programme since 2013 but cancelled the programme again in 2015 owing to low demand.

Resource partnerships and cooperation arrangements also form the basis for international dialogue with resource-rich countries such as Mongolia, Kazakhstan, Peru, Australia, Chile and Canada. Their purpose is to pursue a sustainable supply of raw materials in line with social and ecological standards. As in the case of the Supply Chain Act, its ultimate aim includes gaining a better understanding of the ecological, social and governance conditions of raw materials imports along the value chain. This also means internalising the contribution of value added with raw materials to greenhouse gas emissions (see Box 2).

Box 2: Carbon footprint of mineral resources

The calculations of the sharply rising demand for mineral resources for climate-friendly technologies necessarily lead to the question of how well the extraction, processing and transport stages in the securing of raw materials for the climate transition are actually aligned with the objective of net zero emissions. Although it is important to include in the calculations the emissions involved in the production of green technologies, they need not fear comparison with conventional technologies based on fossil energy sources. The emissions released along the value chain of mineral resources do not cancel out the clear climate benefits of sustainable energy technologies. For example, according to World Bank calculations, renewable energy and storage technologies produce only 6% of the carbon emissions of gas and coal-fired power plants over their entire life cycle.[28]

Nevertheless, with a view to the goals of the Paris Climate Agreement, it is becoming increasingly urgent to significantly reduce the emissions caused by the extraction of mineral resources as well, especially since the demand for resources for the green transformation will grow substantially and the extraction of special metals tends to be more energy-intensive than for bulk metals. The short-term strategies for reducing energy-related carbon emissions in mining and resource processing include the use of low-carbon electricity, the shift to clean fuels and measures aimed at improving energy efficiency.[29]

Strategic stockpiling is gaining ground

By reviewing the need for increased state intervention, Europe is following a movement that is making advances at the global level (Table 1). Countries such as the US, China and Japan have, among other things, established public resource companies, increased their stockpiles of strategically important resources, reduced their commodity exports to protect their domestic industry and secured their access to resources in other regions through company takeovers. The US, for example, holds strategic commodity reserves aimed at securing supplies for the defence industry and civilian use. China’s State Reserves Bureau also stockpiles commodities for economic purposes which enables it to actively intervene in pricing, for example in order to smooth volatility or support specific industries.[30] In Europe, too, calls are becoming louder for the strategic stockpiling of metals, most recently from the aircraft manufacturer Airbus, for example, which demanded a stockpile of important metals and minerals for 18 to 22 months to prepare for future geostrategic threats.[31]

Table 1: Overview of global commodity strategies

	Strategies	Definition of critical resources	Stockpile
EU	– Action Plan on Critical Raw Materials (2020) – European Chips Act (2022)[32] – Battery Alliance (2017)	2020 list contains 30 critical materials	None at the level of the EU or EU member states
Germany	2. Raw Materials Strategy of the Federal Government (2020)	see EU	Appraisal of possible strategic stockpiles for metals
China	14th five-year plan on mineral resources (2021–2025)	2016–2020 plan identifies 24 critical resources, including energy	Public stockpiling
USA	– Executive Order 14017 on America's Supply Chains (2021) – Joint Action Plan on Critical Minerals (collaboration with Canada)	2022 list contains 50 critical materials	National Defense Stockpile (NDS) with 37 materials for defence sector
Japan	International Resource Strategy (2020)	32 critical minerals	Both public (70%) and private (30%)

Sources: Nakano (2021)[33], German Federal Government (2020),[34] White House (2021), EU Commission (2020b)

Conclusion

The green and digital transformation will significantly increase demand for both bulk metals and special metals. Extraction and processing of special metals is subject to high country concentration, in some cases even higher than for oil and gas production. With a view to the high relevance of mineral resources for the competitiveness and sustainability of the German and European economy, the EU and Germany have taken important steps for greater resource security under their natural resource strategies. Now more than ever, the agreed measures need to be fleshed out and swiftly implemented in close collaboration with the business community. Apart from pushing ahead with the drive towards a circular economy and weighing the potentials of raw materials extraction in Europe, diversifying the sources of raw materials – including by forging new strategic alliances with resource-rich countries – will play a key role. Companies are called upon to diversify their supply chains by entering into new supply contracts, increasing their engagement in international extractive projects and improving the material efficiency and recyclability of their products. Public stakeholders can make additional resource potentials accessible by, among other things, entering into new partnerships with other countries, or they can support extractive projects and the development of innovative recycling infrastructures with the aid of public promotional funds.

Russia's war of aggression against Ukraine has created a new reality and shown the international community that energy sources and commodities can be used as political weapons despite mutual dependencies and economic ties. Over the past years, several trade disputes in the Asian region have already set precedents for the assertion of market power over mineral resources as a way to weaponise trade. Against this backdrop, the aim of public and private actors must be to subject supply chains to a more rigorous stress test and reduce strong one-sided dependencies. This applies not just to raw materials but to the procurement and sale of goods and services in general, which also includes building strategic stockpiles in critical areas. Of course this comes at a cost. Policymakers and the business community must jointly weigh up cost efficiency against greater supply security. For example, tax incentives could motivate businesses to increase their own stockpiles and maintain stocks for times of crisis.

However, it would be fatal now to radically roll back international economic integration. Rather, the literature on the ways in which supply chain disruptions caused by natural disasters are overcome shows that, at company level, trade and diversification increase resilience in a decisive manner.[35] Given that Germany and Europe are set to remain dependent on imports of many critical raw materials, the advantages of international integration need to be leveraged. At the same time, this needs to be done with the right sense of perspective. Developing and emerging economies that supply resources must be offered attractive forms of cooperation and shown sustainable development prospects – in accordance with international environmental, social and human rights standards. Furthermore, western industrialised countries should cooperate more closely in raw materials matters, for instance in knowledge and technology transfer.

Table 2: Critical resources for green and digital technologies

Selection of critical resources based on the EU (2020) list

Resources	**Technologies**	**Fields of application**	**World's largest producers*** (shares in per cent)	**World's largest deposits**** (shares in per cent)	**Annual production*** (in t of content)
Light rare earths	⛽ 🌀 ⚙ 💻 🤖	Batteries, glass and ceramics	China (60%) USA (15%) Australia (8%)	Relatively common in the Earth's crust but low extractable concentrations China (37%) Viet Nam (18%) Brazil (18%)	280,000 (t REO)
Heavy rare earths	⛽ 🌀 ⚙ 🤖	Permanent magnets for electric motors and electricity generators, lighting phosphors, catalysts			
Magnesium	⛽ 💻 🤖 🖨	Lightweight alloys, desulphurisation agent in steelmaking, automotive and aerospace construction	China (91%) USA (3%) Israel (2%)	Abundant global deposits, e.g. in seawater, natural brine	950,000
Niobium	🔋 🌀 🖨	High-strength steel and super alloys for transportation and infrastructure, high-tech applications (capacitors, superconducting magnets, etc.)	Brazil (88%) Canada (10%) Russia (1%)	Brazil (94%) Canada (9%) USA (1%)	75,000
Germanium	☀ 💻	Optical fibres, semiconductors, infrared optics, satellite solar cells, polymerisation catalysts	China (68%) Canada, Germany, Japan, Belgium, Ukr. (29%) Russia (4%)	Considerable zinc deposits e.g. in the US, but extractable germanium yield difficult to estimate	140
Borate	⛽ 🌀 ⚙ ☀ 💻 🤖 🖨	High-performance glass, permanent magnets, fertilisers	Türkiye (42%) USA (24%) Chile (11%)	Türkiye (refined borate) USA Russia	N.A.
Scandium	🖨	Solid oxide fuel cells, lightweight alloys, water electrolysis, 3-D printing	China (66%) Russia (26%) Ukraine (7%)	Abundant deposits in Earth's crust. Deposits e.g. in Australia, China, Canada	N.A.
Strontium	⛽ 🤖	Ceramic magnets, aluminium alloys	Spain (42%) Iran (25%) China (22%)	Global deposits estimated at over 1 billion t	411,847
Cobalt	🔋 ⛽ 🌀 ⚙ 💻 🤖 🖨	Batteries, super alloys, catalysts, magnets	DR Congo (71%) Russia (4%) Australia (4%)	Congo (46%) Australia (18%) Cuba (7%)	170,000
Platinum group metals	⛽ 💻 🤖	Chemical and automotive catalysts, fuel cells, electronic applications, computing centres, water electrolysis	Platinum and palladium: South Africa (55%) Russia (24%) Zimbabwe (7%)	South Africa (90%) Russia (6%) Zimbabwe (2%)	Palladium: 200 Platinum: 180
Natural graphite	🔋 ⛽ 💻 🤖	Batteries, refractories for steelmaking	China (82%) Brazil (7%) Mozambique (3%)	Türkiye (28%) China (23%) Brazil (22%)	1,000,000
Indium	☀ 🤖	Flat panel displays, photonics, thin film photovoltaics, solders	China (58%) Rep. Korea (22%) Japan (7%)	Rare element. Largest deposits of zinc ores in Canada and China	920
Vanadium	⛽ 💻 🤖 🖨	CCS – carbon capture and storage, redox flow batteries	China (66%) Russia (17%) South Africa (8%)	China (40%) Australia (25%) Russia (21%)	110,000
Lithium	🔋 ⛽ 🤖	Lithium-ion high-performance batteries, solid-state batteries, lightweight alloys for airframe construction, glass and ceramics	Australia (55%) Chile (26%) China (14%)	Chile (42%) Australia (26%) Argentina (10%)	100,000 (without USA)
Tungsten	🤖 🖨	Alloys (e.g. for steel in turbines), light bulbs, electronics	China (84%) Viet Nam (6%) Russia (3%)	China (51%) Russia (11%) Viet Nam (3%)	79,000
Tantalum	🤖	Capacitors for electronic microdevices, super alloys, radiofrequency microchips	DR Congo (33%) Brazil (22%) Rwanda (13%)	Deposits in Australia, Brazil and Canada are estimated to be sufficient	2,100
Titanium	🔋 ⛽ 💻 🤖 🖨	Lightweight high-strength alloys	China (33%) South Africa (12%) Mozambique (11%)	China (31%) Australia (26%) India (12%)	Concentrates: 9,000 (t TiO_2)
Gallium	☀ 💻 🤖	Semiconductors, photovoltaic cells, radiofrequency microchips	China (98%) Russia (1%) Japan (1%)	Global deposits contained in bauxite >1 mn t (10% potentially extractable)	430
Silicon metal	🔋 ⛽ ☀ 💻 🤖 🖨	Semiconductors, photovoltaics, electronic components, silicones	China (71%) Russia (7%) Brazil (5%)	Abundant global deposits, e.g. in quartzites	8,500,000

Symbols:

🔋 Lithium-ion batteries ⛽ Fuel cells 🌀 Wind energy ⚙ Drive motors ☀ Photovoltaics 💻 ICT 🤖 Robotics 🖨 3-D printing

*Last available figure, usually 2021 (estimate) on the basis of U.S. Geological Survey (2022), otherwise 2019 based on ROSYS database. Figures on deposits and production of light and heavy rare earths available in aggregate form only. ** Country figures refer to deposits, i.e. the share of deposits that are economically extractable or producible. Deposits are defined as naturally occurring material in or on the Earth's crust in a currently or potentially economically extractable concentration.

Sources: EU Commission (2020, 2020a), DERA (2021), ROSYS Information System, U.S. Geological Survey (2022).

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