doi:10.2533/chimia.2024.616 Chimia 78 (2024) 616–617 © Swiss Chemical Society

Chemical Education

Division of Chemical Education

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Critical Materials: A Changing Horizon

Catherine E. Housecroft*

**Correspondence*: Prof. C. E. Housecroft, E-mail: catherine.housecroft@unibas.ch
Department of Chemistry, University of Basel, BPR 1095, Mattenstrasse 22, Postfach, CH-4002 Basel.

Abstract: New and emerging technologies impact on the global demand for raw materials, and 30–40 minerals/materials are classed as 'critical'. This article examines what this means and how it affects the future.

Keywords: Chemical education · Elements · Energy transition · Resources · Sustainability

Most readers of this article will be aware and will appreciate that climate change is a reality, and that committed action to mitigate its effects is essential. The United Nations defines net zero as "cutting carbon emissions to a small amount of residual emissions that can be absorbed and durably stored by nature".[1] The decarbonization of industries and the transition from fossil fuels to sustainable sources of energy have necessarily driven the development of many new technologies. As technologies change, so too does the global demand for raw materials. The global supply of elements and minerals is limited, and 30–40 (depending upon the source of assessment) are classed as critical elements, critical minerals or critical materials. A much-cited example is the development and use of rechargeable lithium-ion (Li-ion) batteries. In addition to applications in electronic devices (*e.g.* laptop computers, tablets, mobile phones), electric bicycles and scooters, and cordless power tools, Li-ion batteries are the mainstay of the current battery electric vehicle (BEV) industry with electrode materials typically comprising graphite combined with $LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$, $LiCo_{0.10}Mn_{0.10}Ni_{0.80}O_2$, $LiAl_{0.05}Co_{0.15}Ni_{0.80}O_2$, or $LiCo_{1-0.666}Mn_{0.333}Ni_{0.333}O_2$. Li, Co, Mn, Ni and graphite appear on the list of critical materials published in 2022 by the U.S. Geological Survey (USGS).[2]

How is 'critical' defined? Importantly, 'critical' does not simply mean a very low terrestrial abundance, although many elements vital to new and emerging technologies are indeed poorly abundant. The terrestrial abundances of the elements are shown in Fig. 1, but these data only allow one to appreciate the dominance of a few elements. Elements with abundances >2% in Fig. 1 fall into the category of rock-forming, with silicates being the most common naturally occurring minerals. Fig. 2 displays the relative terrestrial abundances of elements with data presented as atoms of each element per million atoms of silicon. Fig. 2 also reveals metals of major industrial importance (in red in Fig. 2), precious metals (in purple), and lanthanoid metals (in blue). Fig. 2 originates from 2002[3] and elements essential to new technologies, including rechargeable batteries, are not highlighted in the figure.

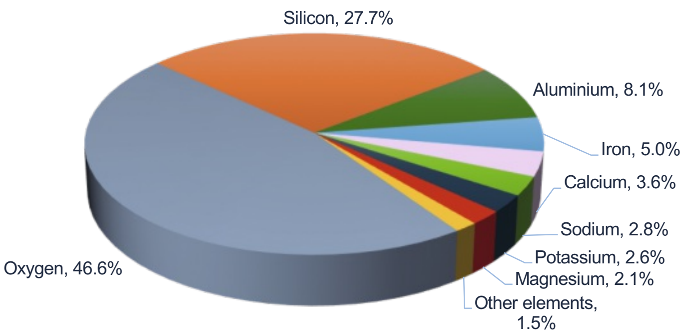

Fig. 1. Abundances of the elements in the Earth's crust.

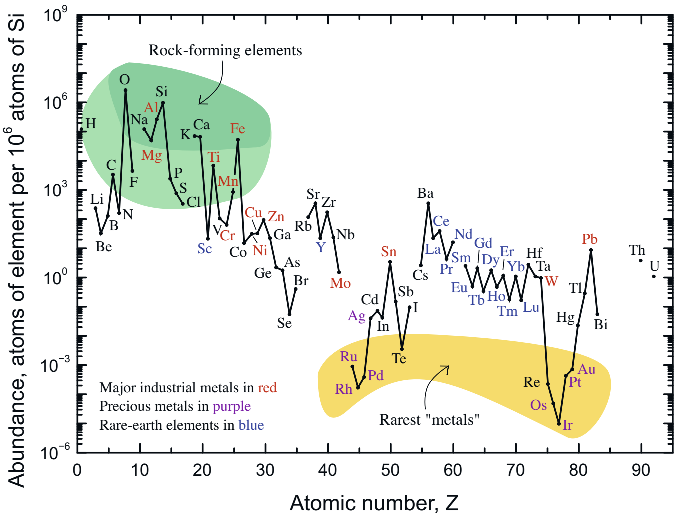

Fig. 2. Relative abundance of elements in the Earth's upper crust. Not shown: noble gases, Tc, Pm, and all elements after Bi, except for Th and U. [https://commons.wikimedia.org/wiki/File:Elemental_abundances.svg]

The terms *critical minerals, materials or elements* are used by some organizations to mean that the material is critically endangered. For example, the American Chemical Society (ACS) categorizes 'endangered elements' as those with "(i) a limited terrestrial availability and an associated future risk to supply, (ii) a rising threat from increased use, and (iii) a serious threat in the next 100 years".[4] On the other hand, use of the word *critical* is also used to refer to minerals, materials or elements that are of critical importance to the energy transition. The U.S. Energy Act of 2020 defines a *critical material* as "any non-fuel mineral, element, substance, or material that the Secretary of Energy determines: (i) has a high risk of supply chain disruption, and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy". It further defines a *critical mineral* as "any mineral, element, substance, or material designated as critical by the Secretary of the Interior, acting through the director of the U.S. Geological

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Survey".[5] As in the U.S., mining operations in Australia are carried out on a huge scale, and Geoscience Australia defines a *critical mineral* as "a metallic or non-metallic element that has two characteristics: (i) it is essential for the functioning of our modern technologies, economies or national security and (ii) there is a risk that its supply chains could be disrupted". As of February 2024, the Australian Government classified 31 resources as critical minerals.[6] The European Union (EU) compiles its own list of critical materials, and it is significant that many of these raw materials are imported into the EU from restricted sources. This adds a different dimension to the meaning of critical: regional and geopolitical risks. For example, the EU's supply of heavy rare-earth elements (lanthanoids) is imported from China, and 71% of the EU's supply of Pt and >71% Ru, Rh and Ir come from South Africa.[7] The above and other definitions of critical materials or minerals all address terrestrial abundance balanced against current and future technological needs and supply chain risks. A recent report from the Swiss Academies of Arts and Sciences[8] gives several key messages: (i) Switzerland is strongly dependent on imported critical minerals and materials; (ii) supply risks are geopolitical because the extraction of raw materials as well as their processing are focused in a few countries with China playing a major role; (iii) Switzerland should capitalize on trading relationships, particularly with the EU, to ensure secure and sustainable supply chains; (iv) Switzerland should support environmental, social and health standards associated with mining raw materials; (v) emerging Swiss technologies should strive to replace critical materials and to develop efficient recycling protocols.

Although lists of critical materials, minerals and elements vary depending upon the source, Li, Co, Ni, Ga, In, Te, Ag, Cd, Ru, Rh, Ir, Pd, Pt, Cu and the lanthanoid metals (in particular Nd and Dy) are invariably included. Table 1 shows how these elements feature in clean energy-related technologies. Analysis of supply and demand of these elements indicates that requirements resulting from the transition from carbon-based to sustainable sources of energy can be met, but only if supply concerns are taken into account. Kamran *et al.* conclude that the future demand for cobalt (principally for Li-ion batteries and based on current levels of Co consumption) is expected to exceed the current level of geological reserves before 2050. Ways to mitigate the supply risk include reducing the cobalt content of electrode materials (*e.g.* using $LiCo_{0.10}Mn_{0.10}Ni_{0.80}O_2$ in place of $LiCoO_2$), using cobalt-free materials (*e.g.* $LiFePO_4$), making battery recycling much more efficient, and encouraging the use of public transport.[9] The global production of lithium increased by *ca.* 23% from 2022 to 2023.[10] Traditionally, lithium has been obtained as Li_2CO_3 from underground brines in Chile, Argentina and Bolivia. After pumping brines to the surface, evaporation ponds are left for up to two years for the water to evaporate. However, the environmental and societal impacts of water wastage has led to fears concerning the sustainability of this extraction method as the demand for lithium continues to grow. Direct lithium extraction (DLE) is a new technology for the selective extraction of Li^+ from brines which negates the need for evaporation ponds.[11] Hard-rock mining of silicate minerals (principally spodumene, $LiAlSi_2O_6$) is carried out in Australia, Chile and China, but mined ore is processed mainly in China. Global resources of lithium are currently estimated to be *ca.* 105 Mt, and ongoing geological surveys aim to locate additional resources. However, there remains a need to increase lithium production and processing to meet future demands. This has to be balanced against the environmental and societal constraints mentioned above.

Table 1 lists copper as a critical material. Electrical devices of all types rely on copper because of its high electrical conductivity. Demand for copper is expected to rise sharply in the future, not only to meet the needs of the energy transition, but also because of increased demand from developing countries.[9]

Table 1. Energy-related applications of some critical materials.[9]

Element	Applications
Li, Co, Ni	Electrode materials in Li-ion batteries
Nd, Dy	Permanent magnets *e.g.* in electric motors and wind turbines
Ga, In, Cd, Ag, Te, Se	Photovoltaic technologies including CdTe and CIGS (copper indium gallium diselenide) thin films
Pt, Rh, Ir	Catalysts for electrolytic H_2 production
Cu	Electrical applications

Despite being the most abundant metal on Earth (Fig. 1), aluminium appears in the 2022 USGS list of critical minerals and was added to the EU's list in 2023. The metal occurs in aluminosilicates and bauxite (a mixture of hydrated oxides), and world bauxite resources are estimated to be *ca.* 55–75 billion tonnes. However, these considerable resources are largely confined to Africa, Australia, Guinea, South America and Asia.[12] Thus, both the US and EU are heavily dependent upon imported bauxite. The need for primary metal production can be offset by recycling, and in the US, recycled aluminium has overtaken primary production. Nonetheless, demand for aluminium during and after the transition to a low-carbon economy is expected to grow enormously, for example in the body-parts of BEVs, frameworks of solar panels, and components of wind turbines, in addition to conventional uses including aircraft parts, window frames, cans, and aluminium foil. The widespread applications of aluminium originate from its exceptional properties: it is lightweight, ductile, malleable, easily machined, and exhibits high resistance to corrosion.

This Column has focused attention on critical materials, minerals and elements for the energy transition. Importantly, 'critical' does not simply refer to a very low abundance of an element in the Earth's crust. In addition to consideration of geological resources, supply risks must also take into account geopolitical, environmental, and societal factors. The development of more efficient recycling and/or repurposing protocols is needed both to prevent wastage of materials and to alleviate supply risks.

Acknowledgement

I thank Michael T. Jarvis (U.S. Geological Survey) for his helpful comments.

Received: July 16, 2024

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