Mining our green future

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The green energy revolution is heavily reliant on raw materials, such as cobalt and lithium, which are currently mainly sourced by mining. We must carefully evaluate acceptable supplies for these metals to ensure that green technologies are beneficial for both people and planet.

In 2020, amidst the COVID-19 crisis, the World Economic Forum's Great Reset initiative highlighted the crossroads society faces for its post-pandemic rebuild in the context of climate and planetary emergencies and ambitions for a new inclusive social contract. The idea is that the energy industry is transformed and rebuilt in a resilient, equitable and sustainable way, while harnessing the innovations of the fourth industrial revolution. The United Nation's 'race to zero' pledge to cut carbon emissions to zero by 2050, enthusiastically adopted by government and industry alike, further demands a transformation to energy sourced from sustainable technologies rather than the burning of fossil fuels, which fuelled the first three industrial revolutions. However, these green technologies carry intensive mineral demands.

Green technology requires non-renewable raw materials sourced from primary geological resources (mines) or secondary supply (reuse or recycling). The ambition is a fully circular economy, in which demand can be satisfied by reuse and recycling; however, we are not yet at that point. Stocks of secondary supplies and recycling rates are inadequate to meet demand. Even for metals, such as aluminium and cobalt, for which end-of-life recycling is up to 70%, secondary supply still only accounts for 30% of their growing demand; in the case of lithium, recycling currently only accounts for 1% of present demand, as highlighted in the recycling rates of metals status report of the International Resource Panel. Substitution for some of these metals might be possible in alternative technology solutions to reduce reliance on specific commodities, but this is challenging to achieve in such a short timeline. Such alternatives, for example, Li-free multivalent metal-ion batteries to replace Li-ion batteries, are less mature in their development and will take time to industrialize[1]. As a result of these sourcing challenges, mining remains necessary to deliver validated technical solutions needed for the rapid decarbonization demanded in the pledge.

The need for metals and minerals

Internal combustion engine vehicles (ICEVs) are the greatest contributors to carbon emissions in the UK. For transport to hit 'net zero', the internal combustion engine needs to be eliminated from cars, as recognized by the Committee on Climate Change. To switch the UK's fleet of 31.5 million ICEVs to battery-electric vehicles (BEVs), it would take an estimated 207,900 tonnes cobalt, 264,600 tonnes lithium carbonate, 7,200 tonnes neodymium and dysprosium and 2,362,500 tonnes copper, as discussed in a letter by myself and my colleagues, in which we set out the resource challenge of meeting net zero emissions in the UK by 2050. This amount is twice the current annual world production of cobalt, an entire year's world production of neodymium and three quarters of the world production of lithium. Replacing the estimated 1.4 billion ICEVs worldwide would need forty times these amounts. In addition, the energy revolution towards renewables, that is, wind, solar, wave, tidal, hydro, geothermal and nuclear, together with the newly built infrastructure for delivery, are highly reliant on mineral-based technologies[2].

Short- to medium-term demands

The World Bank Report in 2020 highlighted 17 mineral commodities that appear essential for the clean energy transition to renewables. This report analyses that the increase of specific metal or mineral demands depends on the technology; however, the modelling scenarios that limit climate change to a 2 °C temperature increase all show a future reliance on solar and wind energy and the projected increased demand for the 12 most implicated commodities as a result are shown in TABLE 1.

Photovoltaic cells require aluminium, copper, silver and steel (and silica sand[2]) as well as other elements, such as indium, selenium and tellurium, depending on the type of technology. Wind energy demands steel, copper, aluminium, zinc and lead as well as neodymium for turbine magnets. Hydro power demands concrete and steel for basic infrastructure in addition to copper and aluminium for power transmission[1].

Energy storage will be needed for wind and solar electricity generation as well as BEVs. A mixture of graphite, lithium, cobalt, nickel, and manganese is needed for state-of-the-art BEV batteries (90% of the anticipated demand for energy storage), whereas vanadium is the metal of choice for static power storage for industrial needs, such as solar and wind farms (World Bank Report in 2020). A range of battery technologies

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Table 1 | **Anticipated increase in demand for the 12 most needed commodities for delivering a green energy future**

Commodity	% increase in demand in 2050 compared with 2018
Graphite	494
Cobalt	460
Lithium	488
Indium	231
Vanadium	189
Nickel	99
Silver	56
Neodymium	37
Lead	18
Molybdenum	11
Aluminium	9
Copper	7

Data source: World Bank Report in 2020

and hydrogen-powered options are being explored, which allow substitution of one or more of these metals and minerals; however, these technologies are unlikely to make major inroads to displace current Li-ion battery technologies until 2030 at the earliest[3].

Although the projected percentage increase in demand of the major metals is relatively small, it is significant in absolute terms; for example, a 9% increase in aluminium by 2030 would mean an extra 103 million tonnes of aluminium to be mined (more than the world's total annual production of 2019; World Bank Report in 2020).

Wholly sourcing from recycling

In the short-to-medium term, recycling cannot meet this demand. However, by 2035, there may be 245 million BEVs on the road, which, given average car scrappage rates of 6.9%, could provide scrap from 17 million vehicles per year. If the ambition of the Global Battery Alliance on battery specifications are met, these vehicles could provide recoverable metals for a considerable percentage of the world's new BEVs with appropriate recycling strategies (EU H2020 CROCODILE project). With optimal recycling rates, 30–40% of the USA's needs for both lithium and cobalt could be met by recycling after 2035 (according to the Union of Concerned Scientists), yet this clearly leaves a shortfall.

Mining and sourcing of metals and minerals

Although we are not running out in absolute terms[4], there are certainly supply challenges for commodities, such as graphite, cobalt and lithium, for which increases in demand of close to 500% are projected. 62% of the total world annual production of graphite comes from mines in China (according to the US Geological Survey on Mineral Commodity Summaries for graphite). It is suggested that the market needs around 68 million tonnes to be delivered by 2050 (World Bank Report in 2020) and the good news is that China can deliver around half of that from its published reserves alone[5]. Additional graphite could be sourced in Brazil, Mozambique and Madagascar.

More than 60% of the world's cobalt supply comes as a by-product from the mining of copper in the Democratic Republic of the Congo. This mined cobalt is then mainly refined in China before it is available to industry (according to the US Geological Survey on Mineral Commodity Summaries for cobalt). Supply from the Democratic Republic of the Congo has experienced periodic disruption as a result of political instability; in addition, ongoing child labour issues (BBC report on child miners in the Democratic Republic of Congo) have major implications for ethical supply and new social contract ambitions. Alternatively, cobalt may be recovered from the waste material of existing terrestrial mines. Estimates in 2012 concluded that unrecovered cobalt from existing nickel mines in Europe could supply 50% of the metal needed for European Li-ion battery plants coming on stream (highlighted in the 2018 EU report on cobalt). The geology of Europe is favourable for a range of new potential sources for the metal[6]. Perhaps most controversially, deep ocean nodules could offer industry all the cobalt and manganese as well as most of the copper and nickel we may need for the world's BEVs (the Royal Society: future ocean resources).

Around half of the world's lithium comes from hardrock deposits in Australia (US Geological Survey on Mineral Commodity Summaries for lithium). The remainder is sourced from salar brines in Chile and Argentina, although extraction in the fragile Atacama Desert faces its own specific governance issues (Earthworks report). Lithium is not a rare metal[7] and UK-funded research explores diverse new sources (Natural History Museum: LiFT (Lithium for Future Technology)). Areas in the UK, Portugal and Germany show great potential for lithium sourcing from brines and hardrock sources, although it remains to be seen if Europe has the appetite for more mining in its backyards to secure our green future.

Delivering the 'Great Reset'

Clean technologies and infrastructure of a low carbon future carry intense mineral demands. A circular economy would be achievable before 2050, if governments and the private sector get innovation right across the supply chain and ensure that products, such as batteries, can be easily disassembled and recycled. However, growth trends suggest that mining may still play a role, because demand for metals will increase as the developing world reaches the same per capita usage of materials as the developed world.

The ambition remains to recycle and reuse as much as we can; however, new-mined resources will be required in the short term to enable green technologies and infrastructure. There are sufficient geological resources to deliver the required metals, but we must carefully balance the need to mine with the requirement to tackle environmental and social governance issues and to deliver sustainable development goals, ensuring outcomes are beneficial for both people and planet[8]. In the past, the true values of biodiversity loss have not been included in mining project evaluations[9] and a new approach is needed embracing principles outlined in the recent Dasgupta report. Thus, we must carefully, creatively and systematically secure a diverse range of acceptable sources for the metals we demand. New frontiers for supply should include neglected mined waste and seeking more regulated mining areas in our own backyard rather than relying on sources with less controllable, fragile and problematic supply chains[10]. The debate about mining our deep ocean, as alternative to terrestrial sources, needs to be resolved. Based on such a broad analysis, we can then make balanced societal choices about metal and mineral supply to deliver the 'Great Reset' with a good deal for people and planet.

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Competing interests
The author declares no competing interests.

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