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The Raw Material Challenge of Creating a Green Economy

Richard Jeremy Herrington

Centre for Resourcing the Green Economy, The Natural History Museum, London SW75BD, UK; r.herrington@nhm.ac.uk

Abstract: Clean technologies and infrastructure for our low-carbon, green future carry intense mineral demands. The ambition remains to recycle and reuse as much as we can; however, newly mined resources will be required in the near term despite the massive improvements in the reuse and recycling of existing end-of-use products and wastes. Growth trends suggest that mining will still play a role after 2050 since the demand for metals will increase as the developing world moves toward a per capita usage of materials comparable to that of the developed world. There are sufficient geological resources to deliver the required mineral commodities, but the need to mine must be balanced with the requirement to tackle environmental and social governance issues and to deliver sustainable development goals, ensuring that outcomes are beneficial for both the people and planet. Currently, the lead time to develop new mines following discovery is around 16 years, and this needs to be reduced. New approaches to designing and evaluating mining projects embracing social, biodiversity, and life cycle analysis aspects are pivotal. New frontiers for supply should include neglected mined wastes with recoverable components and unconventional new deposits. New processing technologies that involve less invasive, lower energy and cleaner methodologies need to be explored, and developing such methodologies will benefit from using nature-based solutions like bioprocessing for both mineral recovery and for developing sustainable landscapes post mining. Part of the new ambition would be to seek opportunities for more regulated mining areas in our own backyard, thinking particularly of old mineral districts of Europe, rather than relying on sources with potentially and less controllable, fragile, and problematic supply chains. The current debate about the potential of mining our deep ocean, as an alternative to terrestrial sources needs to be resolved and based on a broader analysis; we can then make balanced societal choices about the metal and mineral supply from the different sources that will be able to deliver the green economy while providing a net-positive deal for the planet and its people.

Keywords: green economy; mining; new frontiers; social governance; biodiversity; nature-based solutions; net positive; circular economy

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1. Introduction

There are three key factors driving the current need for the growth in mineral use and resultant renewed mining activity [1]. The first and biggest factor is the use of so-called 'critical minerals' to decarbonize our energy generation, transportation, and industry; these goals are to be achieved largely by employing mineral-hungry technologies [2]. Secondly, the general world economic growth and consumerism, particularly in the economies of the BRIC nations and other less developed nations, stimulate demand for materials as the growing and developing world population rises to per capita material consumption to match that of the more developed world [3]. Thirdly, mining can be shown to be directly implicated in achieving several of the UN's 17 sustainable development goals [4]. Dealing with the last two factors, the World Economic Forum [4] recognized that mining has very direct relevance to a number of the UN's Sustainable Development goals (SDGs), both in a positive and a negative sense. On the positive side, mining is important to providing materials for technologies delivering renewable energy (Goal 7), economic growth (8), and innovation and infrastructure (9). However, negative impacts are noted with respect to goals focused on clean water and sanitation (6) as well as life on land (15).

The metal copper, as an example, is a key enabler of sustainable development since it is an essential metal in housing, transportation, electrification, and appliances, and it underpins both global economic growth and human development [5]. The International Copper Association of India recently announced an 11% increase in the amount of copper used per m^2 in new housing, simply reflecting development and the increased use of domestic consumer electrical appliances in that country. This figure matches the general annual worldwide growth in copper per capita [6], even before the recent rapid increase in demand due to the green energy transition.

2. Mineral Usage Growth Due to the Green Energy, Transport, and Industrial Transition

The key factor driving the growth in the use of minerals is due to the decarbonizing of energy, transport, and industry. Climate change is recognized to be largely driven by the increase in greenhouse gases associated with humankind's use of carbon bound in fossil fuels. Although CO_2 from the burning of carbon is not the only culprit, volumetrically, it is the most important driver of global warming with 2022 reaching a record level of 417.06 parts per million [7], so the reduction of this figure is an essential aspect of tackling global warming. The largest producers of CO_2 are power generation and heating, followed by transportation and then industry, which are collectively responsible currently for around 85% of the global annual production of CO_2 from fossil fuels, as shown in Figure 1.

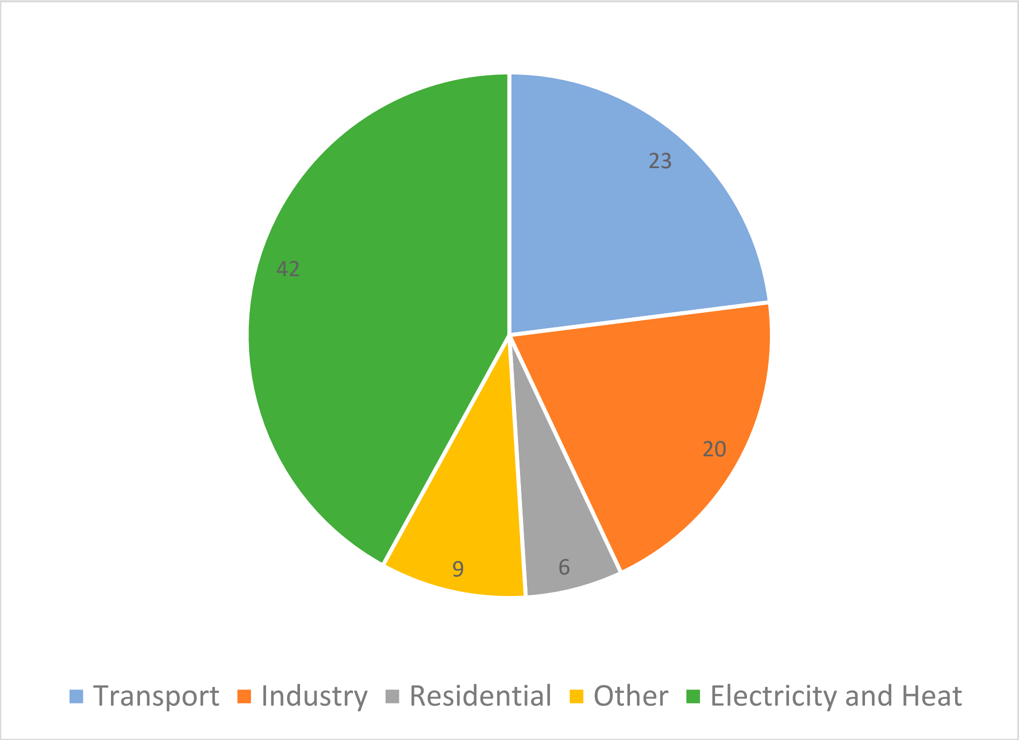


Figure 1. Relative contributions (in percentage terms) of different sectors to the measure of global CO_2 emissions in 2021 [8].

The 2015 Paris Agreement set goals to keep the rise in the mean global temperature below 2 °C (preferably to below 1.5 °C), recognizing that CO_2 emissions need to be cut by roughly 50% by 2030. Many governments have therefore made pledges to drastically reduce emissions, and 44 countries plus the European Union have made 'net-zero' pledges: these countries are collectively responsible for around 70% of current CO_2 emissions [2]. Despite the pledges, global CO_2 emissions grew by 0.9% in 2022 to their highest levels of 36.8 Gt collectively [8]. This increase largely reflected a growth in emissions from energy generation, resulting from a switch to the burning of coal due to the squeeze on gas supplies because of the Ukraine war; the switch added 423 Mt of CO_2 to the emissions budget. Nevertheless, solar and wind energy generation did grow to around 550 TWh of installed capacity, and further bright news is that emissions from industrial processes dropped by 103 Mt, with the deployment of renewable technologies (renewables, EVs, and heat pumps) avoiding the addition of a further 550 Mt of CO_2 release. As a result, the EU saw a significant (70 Mt or 2.5%) reduction in collective CO_2 emissions.

3. How Will We Decarbonize the Economy?

The bulk of industry CO_2 emissions is clearly linked to the generation of heat, and thus, decarbonizing heating processes are identified as key targets [9]. The total world energy consumption in 2022 was around 165,000 TWh with only around 11,000 of this from renewables [10], amounting to 7% of global usage. For electrical production, renewables (including nuclear) accounted for around 38.5%, which was very minimally changed from 2021, partly due to a decline in nuclear power but also a growth in electricity needs due to economic recovery and growth. The renewable sector needs to grow significantly. However, this growth in renewables will put further pressure on the mineral supply. Table 1 shows some of the metal demands for diverse energy sources and metal demands for wind energy that are an order of magnitude or more increased for a range of metals.

Table 1. Calculated metal needs for contrasting energy technologies per megawatt of installed capacity.

Kg/MW	Copper	Nickel	Manganese	Cobalt	Chromium	Molybdenum	Zinc	REE
Offshore Wind	8000	240	790	0	525	109	5500	239
Onshore Wind	2900	404	780	0	470	99	5500	14
Solar PV	2822	1.3	0	0	0	0	30	0
Nuclear	1473	1297	148	0	2190	70	0	0.5
Coal	1150	721	4.63	201	308	66	0	0
Natural Gas	1100	16	0	1.8	48.34	0	0	0

Source of data: [2]; PV = photovoltaics; REE = rare earth elements.

However, the increases in demands for metals and minerals is not limited to so-called ‘critical’ elements. It is also recognized that the energy revolution will demand increases in other major commodities like steel, glass, and concrete [11]. Steel demands are also significantly increased with two times as much metal used in a wind power array and up to three times as much for photovoltaic systems per MW. To put the estimates for increased copper use into a volumetric perspective, a recent study estimated that humankind will need to mine as much copper between now and 2050 as has been mined throughout history [12].

Decarbonizing transportation will also demand increased usage of materials as shown in Table 2. Using those figures, just to replace the entire 31.5 million UK-based private internal combustion engine vehicles today with electric vehicles, assuming they use the most resource-frugal next-generation NMC 811 batteries, would take 207,900 tonnes of cobalt, 264,600 tonnes of lithium carbonate (LCE), and at least 7200 tonnes of neodymium and dysprosium, in addition to 2,362,500 tonnes of copper.

Table 2. Calculated ‘critical mineral’ demands for an average internal combustion engine car versus a battery electric alternative (with industry standard battery chemistry).

Kg/Vehicle	Cu	Li	Ni	Mn	Co	Graphite	Zn	REE	Others
BE car	53.2	8.9	39.9	24.5	13.3	66.3	0.1	0.5	0.31
ICE car	22.3	0	0	11.2	0	0	0.1	0	0.3

Source of data: [2]; REE = rare earth elements; BE = battery electric; ICE = internal combustion engine.

Another important note is that creating a battery electric car fleet will have serious implications for the electrical power generation needed to recharge these vehicles. Based on figures published for the current generation of battery electric vehicles [13] and the average of 328.2 billion miles driven by car owners [14], there will be a demand for an additional 80 TWh or 25% increase in the UK-generated electrical capacity (hopefully to be powered from renewable resources like wind and PV that will further demand metals).

4. Can Recycling or Waste Recovery Deliver Everything We Need?

The long-term ambition would be to bring the 'cradle-to-cradle' philosophy of a truly circular economy into the human use of natural resources. However, the following analysis will show that this is not currently possible and unlikely to happen in the foreseeable future [15]. Firstly, in the case of many metals and minerals we use, the end-of-life recycling exceeds 50%, but for some important commodities, it is currently less than 1%, as shown in Figure 2.

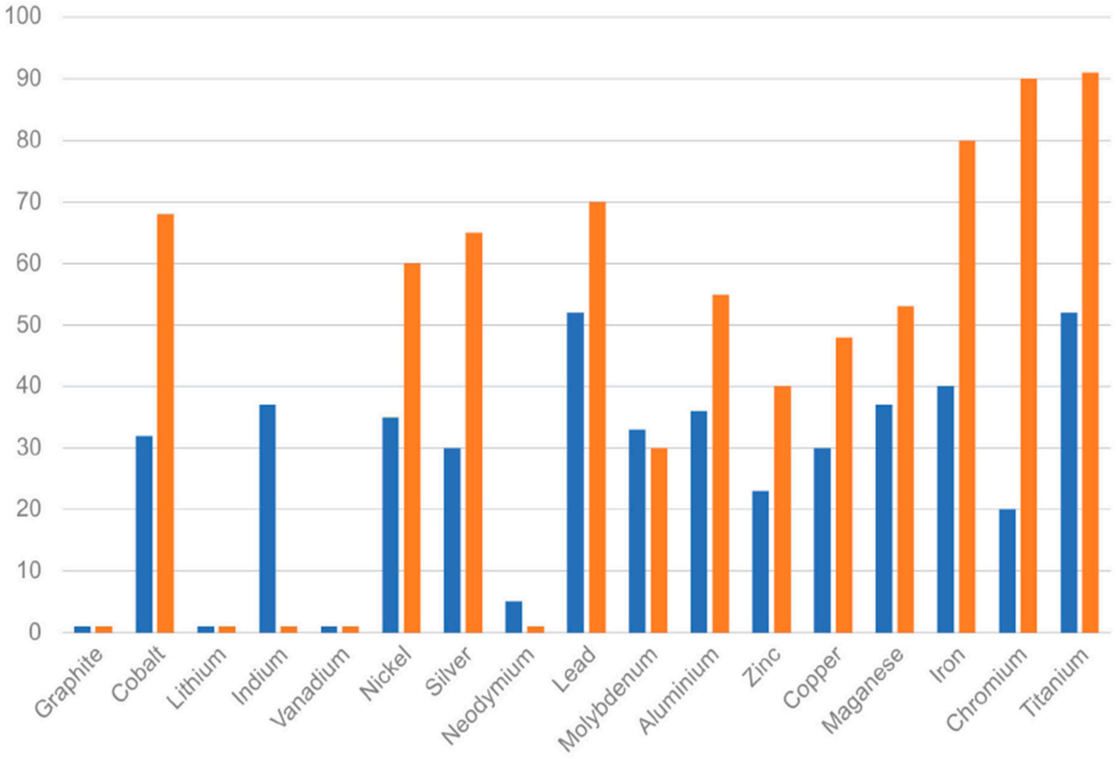


Figure 2. The graph shows (in orange) the rates of the end-of-life recycling for a range of metals and (in blue) the percentages of current material demands that can be met from recycled stock. Author's own compiled figures—various sources incl. [1].

It is acknowledged that it will not be until at least 2035 that stocks of the newly demanded metals like lithium and cobalt will be available as significant stocks to fuel the secondary recycling market, and even then, these will account for less than 50% of the demand for those two metals [16]. Recycled nickel, graphite, and manganese will similarly fall well short of supplying 50% of needs.

Mining annually produces 72 billion tonnes of rock waste and more than 8.8 billion tonnes of processing tailings, and 46% of the volume of tailings comes from the mining of copper where 99% of the mined material goes to waste [17]. The total volume of accumulated tailings worldwide is now more than 282 billion tonnes, and given the inefficiency of mineral processing history, many tailings facilities could have recoverable metals locked within [18,19]. For example, tailings stored at the Bor copper mine in Serbia alone contain more than 200,000 t of Cu, 55,000 t of Mo, and 390,000 t of Zn, sitting, poorly processed, in a tailing storage facility [20]. That material is running at 0.4% Cu, 1100 ppm Mo, and 0.79%

Zn and has a current in situ value of more than $8 billion dollars and compares favourably to the grades of some active mines [21]. It is estimated that tailings from copper mines worldwide could contain up to 43 million tonnes of copper [22]. Nevertheless, even if all the contained copper was all recovered, it would provide only two years of the current world copper production, not enough for what the energy transition demands. However, there are attractions to the processing of tailings since the process of mining and grinding ore itself currently accounts for a significant 2–3% of the current world CO_2 emissions [23], yet mine tailings are already finely grounded, which would significantly reduce the energy consumption of onward processing.

Many of the new metals we need for the green economy are by-products of the mining of another major metal and are therefore what are termed 'companion' metals [24]. Companion metals are often recovered at the processing stage, although in some cases the companion metals may be only partially recovered or not at all and therefore can be found in the waste (see Table 3). The economics of mining operations are largely determined by the primary or host commodity, so the supplies of some critical metals, cobalt being a good example, are at the mercy of the economics of another metal (for cobalt, this could be copper or nickel). More than a third of the EU's 2020 'critical metals and minerals' are recovered as companion metals or mineral by-products. Increasingly, the recognition that some of these companion metals have found their way onto the waste dumps has turned companies toward reprocessing former waste for their contained metals [25].

Table 3. Table showing the geological relationships between the main recovered metals and their metal 'companions'.

Main Host Metal	Companion Elements
Ni	Sc, Co, Ru, Rh, Pd, Os, Ir
Cu	Co, As, Se, Mo, Ag, Te, Re, Au
Fe	V, Sc, La, Ce, Pr, Nd
Zn	Ge, Ag, Cd, In, Tl
Pb	Ag, Sb, Tl, Bi
Al	V, Ga
Ti	Zr, Hf
REE	Y, Th
Mo	Re
Au	Ag, Te

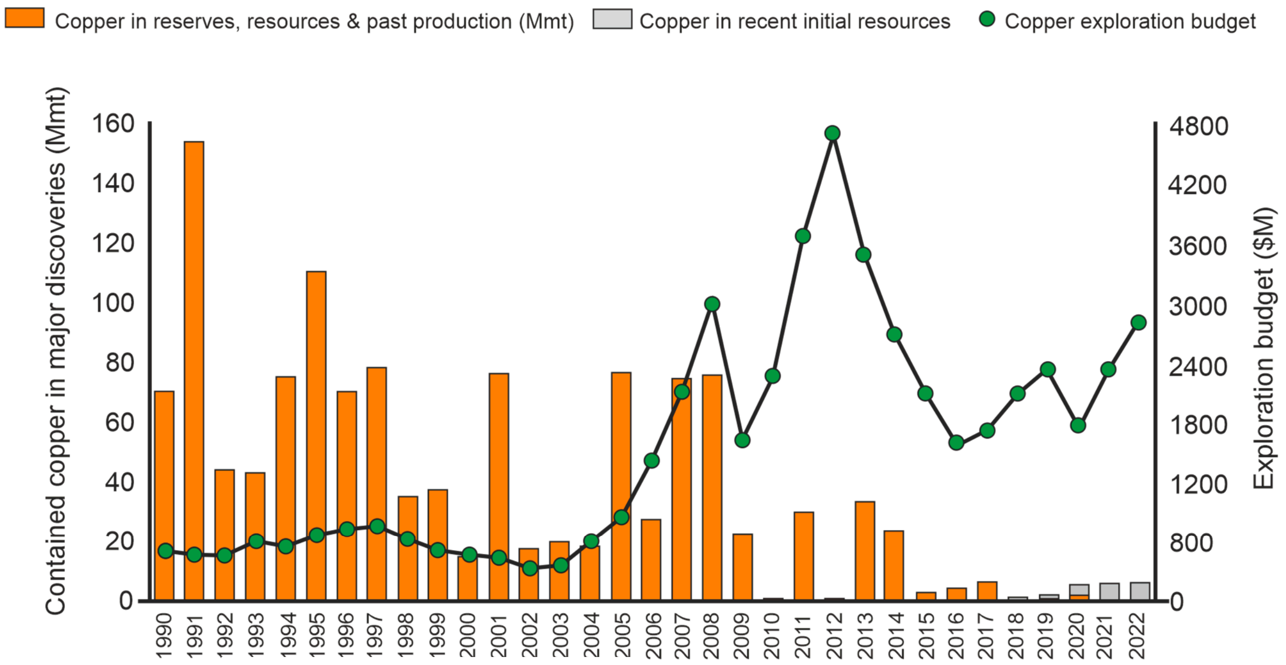
Modified from [25].

While these sources can mitigate the need for newly mined resources, even if combined with optimized recycling and the complete remining of existing mine wastes, new mining will be necessary for many of the larger volume commodities on the critical minerals list [1].

5. The Future for Mining

5.1. Mineral Supply

A number of pessimistic views concerning long-term global mineral supplies have appeared in the literature in the modern era, beginning with the Club of Rome treatise on 'The Limits to Growth' [26] and periodically by other authors since then, e.g., [27–29]. However, it is economics, not geology, that define what companies report as 'reserves' (these are legally defined as 'economically extractable' bodies of mineral resources), and it is these figures upon which pessimistic perspectives declaring that we are 'running out' are erroneously based. Published studies show that geological resources are likely to be much higher than any future demands [30,31] and that the absolute exhaustion of the planet's metals and minerals will not be the major factor limiting the supply of raw materials. Indeed, for copper, the estimates for geologically feasible geological models suggest that currently 'undiscovered' copper deposits are highly likely to constitute more than 40 times the currently identified resources [32,33]. However, the waning success in deposit discovery (Figure 3) suggests that we are not finding these 'undiscovered' resources in a timely fashion.



As of 1st Aug 2023
Mmt = million metric tonnes
Source: S&P Global Market Intelligence
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Figure 3. Mineral exploration budgets (green curve) and resultant discovery rates (orange and grey bars) of new copper deposits in the period 1990–2022 [12].

Despite healthy exploration budgets since the early 2000s, discovery rates are disappointingly small, and therefore, discovery rates need to improve rapidly to fill the supply gap as current mines begin to reach their end of life. This probably reflects the need to explore more effectively in 'new frontiers', which is discussed in Section 5.4 below. A further factor that is causing a squeeze in supply is the ever-lengthening timescale for turning discovered resources into producing mines. Using a demand model driven by the modest scenario of restricting the global temperature rise to +2 °C [34], it is apparent that we will need to mine practically all the known copper resources we have at hand. Therefore, there is extreme pressure to replenish those stocks if we are to satisfy ongoing demands. A recently published study by S&P Global [35] reports that for 127 mines opened since 2003, the average lead time from discovery to production is 15.7 years. The average lead time is variable depending on jurisdiction from only 10 years for Cote d'Ivoire to nearly 22 years for Brazil. Taking geological discovery to a bankable feasibility study appears to be the longest step of the process, averaging around 12 years for all mines. Embedded in this process are the acquisition of the necessary permissions and the successful development of a 'social license' to operate.

5.2. Environmental, Social, and Governance Constraints

Sustainable development has three clear dimensions from which John Elkington coined the term 'Triple Bottom Line' [36]; the three stand for the responsibilities that projects have to the economy, society, and biosphere, and are thus a more holistic analysis of the benefits of any project. The language of this analysis focuses on aligning sustainability and the intentions of a business when it comes to the profitability of projects. Given that the current mineral boom has been demanded by the need to arrest climate change and the knock-on effects for human society, holistic valuations need to be applied to any new mining projects if we are to avoid creating new environmental and social issues whilst we are seeking to solve the planetary emergency resulting from climate change [37]. The Triple Bottom Line concept of Elkington was flipped into the concept of a 'Triple Top Line' [38], where it is proposed that the focus should be to align environmental and social sustainability with business profitability from the inception of any product and work to a circular economy for manufacturing. This same philosophy might be translated from the manufacturing industry that Braungart and McDonough [38] studied, toward improving the business of mining, and this will be discussed below.

In building a societal license to operate, the single most important factor is developing trust with the broader society [39–42]. Building trust in the mining industry among the public at large has been most successful where engagement strategies have emphasized dialogue and relationship building [43,44]. Clearly there are lots of cases where mines have failed in either social or environmental aspects, and thus, trust has been lost through the implementation of improper business practices or other environmental or social equity failures [45].

5.3. Minerals versus Other Natural Capital

It is increasingly recognized that mineral resources in a particular locality are only one part of the 'Natural Capital' (NC) of the site. Ekins et al. [46] usefully defined the NC as follows: "Natural capital is a metaphor to indicate the importance of elements of nature (e.g., minerals, ecosystems, and ecosystem processes) to human society. Natural ecosystems are defined by a number of environmental characteristics that in turn determine the ecosystems' capacity to provide goods and services". This includes all the 'ecological capital' [46] that we can currently measure, including stocks like minerals, fossil fuels, forestry and agriculture, fisheries, and water resources. However, NC also includes the ecosystem services that include the site's ability to provide air and water filtration, flood protection, carbon storage, the pollination of crops, and habitats for wildlife. There are four types of NC: (1) the provision of resources (capital stock like minerals or forests) for production; (2) the absorption of wastes through production (either adding to or eroding the ecological capital); (3) basic life support systems (including ecosystem services); and (4) amenity services (e.g., the values of areas as wilderness or for their outstanding beauty). Apart from capital stock, it is difficult to capture the true value of these in a market sense, so we do not really know how much they contribute to the economy. We often take these services for granted and do not know what it would 'cost' if we lost them. The mining industry understands the need to account for this [47], and there are some recent examples that attempt holistic NC accounting in mining projects [48].

5.4. New Exploration Frontiers and Discovery

Encouragingly, geoscience demonstrates that there are still new classes of mineral deposits to be found for the commodities we require. In 2004, during an exploration for borates, Rio Tinto discovered the Jadar deposit in Serbia where more than 100 million tonnes of a Li and B-bearing mineral, jadarite, entirely new to science, was discovered [49]. The Jadar deposit is a member of the emerging new class of ore deposits known as volcano-sedimentary lithium deposits [50]. Explorations for these types of lithium deposits in the last ten years have already successfully discovered more than 60 million tonnes of contained lithium since the discovery of Jadar, and the prognosis for further similar discoveries is good.

Traditionally, exploration budgets have been focused on the Americas and Australia, countries with strong modern mining traditions. Canada is still the number one country for explorers, but new frontiers are opening up too. Recent trends show increased exploration spending in places like Saudia Arabia, where there has been a more than an 155% increase in exploration spending for 2022 [51], and neglected areas like Central Asia have great potential to deliver many of the minerals we need [52]. It is also healthy for the industry to encourage diversity in the geographic sources of critical materials, since diversifying the sources of supply will help to mitigate the security of supply issues linked to the creation of geographic monopolies [53].

The deep ocean floor has enormous untapped potential for metals and other minerals. Massive sulphides formed at seafloor spreading centres hold estimated resources of at least 6×10^8 tonnes of sulphide minerals [54], and the Solwara 1 deposit off Papua New Guinea alone had a signed off resource of more than a million tonnes of sulphide containing 7% Cu and 6 g/t Au. By far, the biggest prize on the deep seafloor is still the enormous potential for polymetallic nodules containing Mn, Ni, Co, Cu, REE, and other minor metals. The Clarion Clipperton Zone alone holds 21 billion tonnes of nodules with an average grade of 27% Mn, 1.3% Ni, 1.05% Cu, and 0.2% Co that amounts to 10 years of the current global Cu production and, respectively, 300 and 450 years of the current Mn and Co productions. In addition to the nodules, the less well-explored polymetallic crusts are also a potential resource of many metals [55].

Asteroid mining has been proposed as an option to avoid terrestrial mining e.g., [56] although the feasibility of returning metals other than very high-value precious metals is questionable [57], particularly in the foreseeable future, and certainly not in time to address the current 2050 net-zero deadline.

5.5. Brownfields and Deep Geological Discovery

Going deeper into existing mining operations to discover further resources offers a clear opportunity too. A review of historical explorations shows that most mineral discoveries have been made within 300 m of the surface [58], and yet mining is possible, even for base metals, below depths of 2 km (Figure 4). Discovery at such depths is possible using new geophysical and other targeting tools like mineral vectoring [59]. A recent example of new geophysics success is the use of seismic methods, a technique normally restricted to hydrocarbon exploration, in the discovery of deep extensions to the Navan Pb–Zn body in Ireland more than 1 km below the previously known mineralization [60]. Good geological reasoning and carefully targeted deep drilling was responsible for the Resolution porphyry discovery in Arizona, discovered around 1 km below an existing mining operation [61].

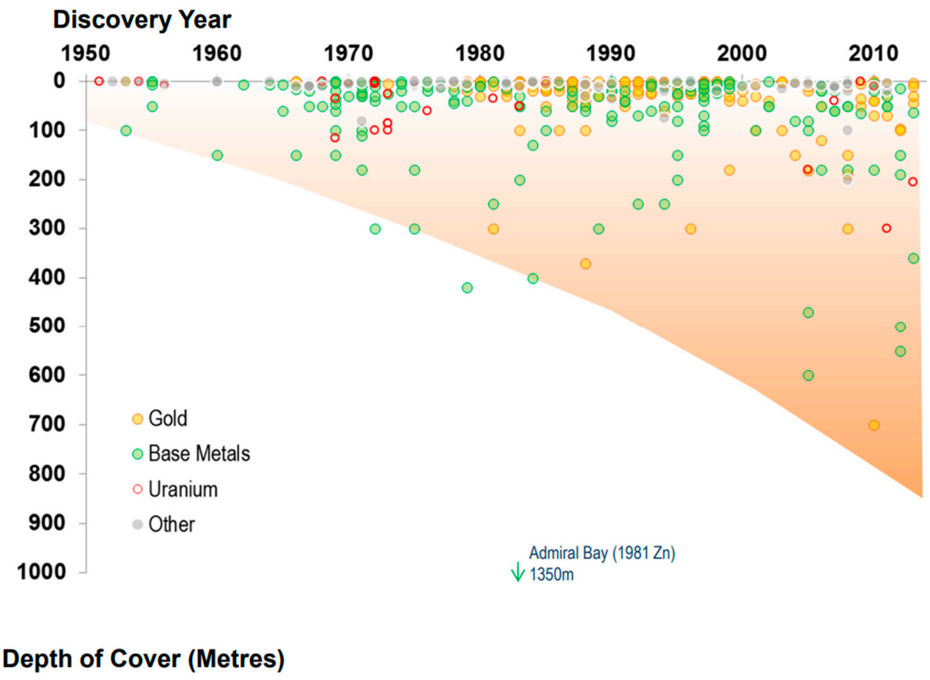

Figure 4. Graphic representation of depths to the tops of new discoveries of significant base and precious metal deposits through time [58].

Former mining camps remain prospective for new deposits. Europe has had a strong history of past mineral production and hosts many significant mineral showings (Figure 5), and there is still much potential with active exploration recorded through the continent [62]. A reassessment of the iron ore deposits of the northern part of Kiruna district resulted in the definition of huge REE resources in apatite-rich iron ores, previously mined only for their iron contents [63]. Likewise, the presence of Li-mica zinnwaldite in Cornish granites was known for many years [64], but the recognition of the distinct Li-rich 'G5′ granite phase [65] coupled with a technology breakthrough suggest that it might be possible to process these ores economically. Li has been discovered in significant amounts in other regions of Europe (not shown in Figure 5).

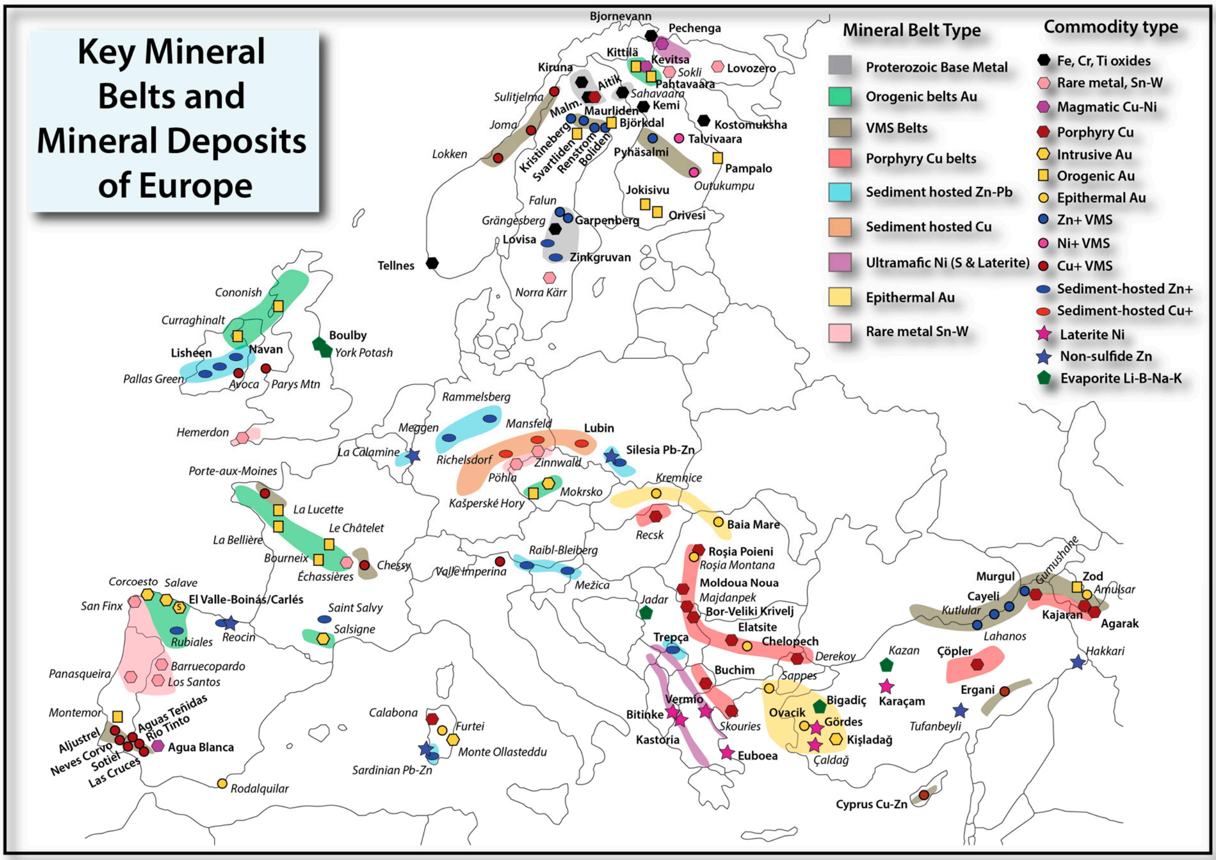

Figure 5. Map of Europe showing the locations of major mineral belts and key deposits (Authors own figure compiled from publically available sources, previously presented in 2013 [66] but unpublished in hard copy).

5.6. Unlocking Potential with Mineral Processing Advances

New processing techniques could be a real game changer for development of new mining projects on existing deposits that remain untapped because of mineral processing issues. It has been suggested there are a number of areas where processing could be improved [67], including using novel solvent extraction/electrowinning, leach processing, bioprocessing, flash smelting, geometallurgy, energy-efficient fine grinding, and introducing underground processing methods.

As an example, ionic liquids and deep eutectic solvents offer an alternative set of lixiviants to those currently used in conventional hydrometallurgy [68,69]. Being both powerful solvents and electrolytes they show great potential to be selective in both dissolution and recovery reactions. Deep eutectic solvents, like choline chloride are environmentally benign compounds, stable, relatively cheap to produce and testwork has shown their direct applicability to extraction of metals from sulfides, tellurides and precious metal minerals [68]. Ionic liquids and deep eutectic solvents have also been proposed to be combined with conventional floatation methods to form new hybrid processing methodologies [69].

Bioleaching is another emerging technology that has the potential to be applied more widely e.g., [70,71]. Overall, around 20% of the world's current copper production is estimated to come from bioleaching [72]. As a technology it is ideally placed for recovery of metals from low grade sulfidic wastes and has successfully been applied to copper, nickel and cobalt bearing sulfide-rich wastes. It also has great potential for the recovery of metals from oxide-rich lateritic ores and valuable oxide wastes [73].

Even conventional mineral processing methods can be improved and there is a strong trend in industry towards decarbonizing existing mining operations with introduction of electrical equipment and renewable energy strategies.

6. Rising to the Challenge—A Way Forward

It must be accepted that the mining industry is not a universally welcomed industry, and in Europe, it probably has the lowest acceptance for any industry sector [62,74]. There are many socially motivated disputes focused on the future development of terrestrial mines [75]. Deep ocean mining, one of the alternatives to terrestrial disturbance, is also a very emotive subject with public opinion largely against allowing operations [76]; although it is currently subject to a de facto moratorium, there is increasing pressure with legal backing to accelerate projects to the mining stage. There are complex and often conflicting arguments that support the choice of mining on land or under the ocean [77]. However, we see the need to mine, and thus, it comes down to a societal choice as to where that mining should be located [1].

What industry clearly needs to establish is an increased level of trust with society, particularly in the assurance that new projects are going to be different from the historical substandard projects and that projects will deliver a positive 'triple top line' as discussed earlier. New mining, therefore, needs to deliver outcomes that are net-positive for people and the planet in addition to being economically viable. A new proposed strategy embraces the concepts of Braungart and McDonough [38] and borrows their terminology in the term 'cradle-to-cradle' mining. This conceptualizes projects that are inherently reconstructive from the start, with project stakeholders embedded from the start, such that impacted communities are part of the decision-making process and thus co-owners of the project, with vested interests in designing something successful for all parties [78]. With such shared equity, the post-mining landscape can be designed as part of the mining process since there will be as many people interested in what happens after mining as there are interested in developing a successful mining venture. Mines are only temporary interventions at a particular site where subsurface minerals of societal need can be recovered at profit; the site itself should have a future that leaves a net-positive nature and people-positive outcome.

There are some positive mine closure examples that have striven to develop sustainable legacies. The Golden Pride operation in Tanzania provides a good case study, where there was strong community and regulator engagement, employee engagement through the closure transition, stakeholder-agreed post-mining land usage, an implemented plan of progressive reclamation, and pit closure that also considered the future needs of small-scale miners [79]. With a new intrinsically regenerative plan for future mining projects, even mines developed closer to home might be more acceptable to European society. Even abandoned and negative legacies have been shown to be able to be repurposed for a net-positive future [80,81].

Even with carefully crafted new project strategies, the 2050 target for net-zero would appear to have material demands that are difficult to deliver, and unless industry becomes more successful at discovering and commissioning new mines in time, it is increasingly recognized that the target of net-zero CO_2 emissions may not be achievable without the use of other interventions such as carbon capture and storage [82,83]. One way to help would be for society to reduce the mineral intensity of its future ambitions by adjusting lifestyles and thereby reducing demands [84]. It seems to be an enormous societal challenge to deliver a net-zero world responsibly, but it is one where geoscientists are clearly front and centre in making sure that its delivery is accomplished in a way that is sustainable, both for the planet and its people.

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