Technology Critical Elements and their Relevance to the Global Environment Facility

A STAP Background Document
November 2020

STAP SCIENTIFIC AND TECHNICAL ADVISORY PANEL
An independent group of scientists that advises the Global Environment Facility

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UN environment programme

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ABOUT STAP:
The Scientific and Technical Advisory Panel (STAP) provides independent scientific and technical advice to the GEF on its strategies, programs and projects. https://stapgef.org

ABOUT GEF:
The Global Environment Facility (GEF) was established on the eve of the 1992 Rio Earth Summit to help tackle our planet's most pressing environmental problems. Since then, the GEF has provided close to $20.5 billion in grants and mobilized an additional $112 billion in co-financing for more than 4,800 projects in 170 countries. Through its Small Grants Programme, the GEF has provided support to nearly 24,000 civil society and community initiatives in 133 countries. http://www.thegef.org

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ABBREVIATIONS

ASM	artisanal and small-scale mining
GEF	Global Environment Facility
REE	rare earth element
STAP	Scientific and Technical Advisory Panel
TCE	technology critical element

EXECUTIVE SUMMARY

Technology critical elements (TCEs) are the geological sources of the metals, alloys and chemical compounds used in the production of modern technology, including nearly all green technologies. Products containing TCEs are used in renewable energy, energy security, energy storage, electronics, urban development, and farming, among many other applications, and are therefore crucial in many current strategies to reduce greenhouse gas emissions and mitigate climate change.

Demand for TCEs for green and other technologies is expected to increase – and dramatically so – in the coming years. However, there are notable challenges in maintaining TCE supply, and TCE extraction and processing itself can have a significant detrimental ecological impact. There is an urgent need to reduce demand for virgin TCEs and minimize negative environmental impacts through the entire life cycle of TCE usage.

The availability of TCEs will be essential in almost all Global Environment Facility (GEF) projects that promote a transition to green technologies. This report looks at the environmental implications of TCE extraction, processing and supply and how the GEF can support strategies that reduce the ecological impact of these activities – particularly in, or close to, GEF project locations – while maintaining the availability of the TCEs for necessary uses.

ADVERSE ENVIRONMENTAL IMPACTS OF TCEs

The negative environmental impacts of TCE extraction, processing and supply can be illustrated in several key areas:

Biodiversity and forests. The direct vegetation and soil clearance and deforestation that accompanies mining can lead to direct habitat loss and land degradation. In addition, the cumulative impacts of mining (e.g., through mining infrastructure, air, water, soils, and land pollution) can indirectly adversely affect biodiversity even in other forests kilometres away.

Water. Mining of TCEs may lead to the formation of acid mine drainage. This acidification can kill marine and freshwater organisms, disturb aquatic biodiversity and harm ecosystems. Furthermore, the processing of TCEs generates huge amounts of wastewater, which may contaminate groundwater, be discarded into adjacent valleys and streams, or be washed into international waters.

Soils and land. In addition to impacts on soil and land associated with TCE extraction, e-waste dumping can release significant quantities of TCEs and other toxic elements into subsoils and groundwater.

Air. TCE mining activities can release dust containing TCEs, other toxic metals and chemicals into the air and surrounding water bodies, with consequent negative effects on soil, wildlife, vegetation and humans.

Climate change. The mining of TCE, like other minerals mining activities, emits considerable quantities of greenhouse gases from burning fossil fuels and ore processing. Deforestation caused by mining also result in release of stored carbon.

Human health. TCEs leached into the air, soil and water through e-waste and mining waste have significant implications for human health, exacerbated by some TCEs containing substantial amounts of radioactive elements, such as uranium and thorium. In addition, the chemicals used in TCE ore processing can present health hazards to workers and local residents. Specific health hazards have also been associated with exposure to rare earth metals (respiratory and lung-related diseases), selenium (selenosis), cadmium (acute and chronic intoxication due to biomagnification) and beryllium (lung cancer).

Socioeconomic impact. Among many recent examples of the socioenvironmental impact of TCEs is the urban street dust of Zhuzhou, China, which has

Uganda: Wolframite (Tungsten) mining. Alex Tyson

shown very significant concentrations of rare earth elements (REEs), related to REE ore processing. This reveals the gravity of REE pollution, particularly in industrial cities. There have also been several reports of REE occupational exposure that resulted in bioaccumulation of REEs and adverse effects to respiratory tracts.

FRONTIER AREAS OF TCE SUPPLY FOR GEF PROJECT DEVELOPMENT

Strategies to reduce demand for virgin TCEs and to minimize the environmental impact of TCE mining are at various stages of implementation and development. This report introduces five frontier areas of TCE supply that may be of particular relevance to the GEF:

Recycling. The volume of TCEs being recycled is still very low, mainly because of two key challenges: (a) the concentration of TCEs in materials that are to be recycled is often low (especially true for REEs) and their extraction from the rest of the material matrix can be complex and (b) there is not enough stock available for recycling to meet demand due to insufficient take-back and collection systems in some areas.

There is particular potential for the recycling of batteries (of increasing importance as e-mobility systems grow), platinum group metals in automotive catalysts (present in high concentrations) and TCEs from electrical and electronic equipment waste. Bioleaching – the biological conversion of an insoluble metallic compound into a water-soluble form – shows promise for extracting used metals from both e-waste and mining waste. In addition, upstream mining activities offer recycling opportunities, such as the small-scale reprocessing of tailings.

Green mining. Green mining technologies, best practices and mine processes aim to reduce the environmental impacts associated with the extraction and processing of metals and minerals. Not only do they have potential to reduce greenhouse gas emissions, ecological footprint, and chemical and water use, they can reduce operating costs and enable companies to remove staff from dangerous working conditions. Example green mining strategies include:

- Efficient use of water. The extraction of TCEs uses large quantities of water. Water use can be reduced through water control and recycling, water substitution (use of wastewater or grey water) and use of real-time calculation to predict and manage actual water needs.

- Improved mine closure. Poorly rehabilitated mines – including those for TCEs and REEs – can leave the mined land in a devastated state. The negative effects of mine closures can be reduced by the development and implementation of smart and effective closure and rehabilitation plans to ensure public safety and health, and environmentally stable conditions compatible with the surrounding environment.

- Forest-smart mining. This type of green mining aims to protect forests and forest values, which can be particularly devastated by mining. Forest-smart mining principles relate to good governance, improved understanding and approaches, capacity-building, and widening the participants engaged in forest-smart practices.

Alternative technologies and materials. Alternative technologies are innovations that, through improved design or manufacturing processes, enable reduced or different material use. In so doing, they decrease demand for virgin TCEs and may provide a more secure supply of the technology that was formerly reliant on a particular element.

Alternative materials are also being developed as substitutes to critical elements. The Critical Materials Institute at the U.S. Department of Energy, for example, has a targeted research programme focused on dematerialization of key elements with constrained supply, such as the heavy REEs used in magnets. Polymer substitutes are also being considered, but for synthetic materials such as these, the environmental impact of using fossil fuels versus biofuels in their production must be evaluated.

Phytomining. Certain plant species, known as "hyperaccumulators", accumulate metals and metalloids in their shoots in quantities hundreds, or often thousands, of times greater than other plants. Phytomining (or "agromining") entails planting swathes of such plants in metal-rich areas and deriving economically valuable, high-purity metals or metalloids from the plant biomass.

Hyperaccumulator plants can provide natural concentration of the desired elements and exclude unwanted elements. The economic feasibility of phytomining, however, depends on the ability to recover the metal(loid)s of interest from the harvested biomass. The extraction of certain elements has been trialled in experimental settings; however, testing is required at field scale to assess phytomining's broad commercial potential. As greater funding becomes necessary for upscaling, phytoextraction and phytomining may be important avenues for encouraging investment in the innovation impact areas of GEF proposals.

Oceanic minerals. Given the rapid rise in demand for minerals and the declining ore reserves on land, attention is turning to the potential extraction of marine mineral deposits. The environmental impact of oceanic mining remains widely contested, and particular attention should be given to determining the impact of sediment dislocation and plumes being generated by mining activity, the impact of mining activity and noise on biodiversity, the potential release of deep-sea carbon through extractive activity, and the impact of mining on fisheries and resultant livelihoods.

The GEF may well be called on to consider the intersectionality of its conservation activities with such extractive industries. Furthermore, GEF projects in small island developing States may need to consider oceanic minerals and help realize any win-win opportunities that balance extraction revenues with conservation efforts.

The impacts and benefits of oceanic mining in comparison with terrestrial mining deserve attention. Preliminary data suggests, that the carbon footprint of oceanic polymetallic nodules extraction is less than for land ores. Waste generation may also be less for oceanic mineral extraction. Biodiversity impacts, particularly on microbes, remains a major concern and will likely require further research in coming years under the auspices of the International Seabed Authority which is required to set aside reference areas for conservation equivalent to any proposed mining region.

RECOMMENDATIONS TO IMPROVE THE ECOLOGICAL FOOTPRINT OF TCEs

The mining and processing of TCEs, as well as the disposal of TCE products, could negatively impact the GEF's work in the areas of biodiversity, land, forest, international waters and food security. Since the GEF is funding projects that use TCEs, a possible role for the GEF could be to help direct the course of the technology used in such projects to ensure that it does not result in negative environmental impacts. In general terms, the GEF could:

- Support policies and actions that promote the sustainable extraction, processing and use of TCEs.
- Facilitate the improved design of products to promote the efficient use of TCEs.
- Promote circular economy approaches and life cycle assessments to improve TCE recycling and material efficiency.
- Support efforts to quantify the demand for, the material and energy needs of, and the environmental implications of emerging applications that could increase global dependence on TCEs.
- Raise awareness of the possible environmental and health impacts of continued unsustainable production and consumption of TCEs.
- Collaborate with and support partnerships focused on sustainable TCE production and consumption.

The GEF could also look at project-specific activities, such as:

- Supporting projects that help avoid deforestation due to TCEs mining.
- Supporting afforestation with hyperaccumulator plants in degraded soils and encouraging investment in phytomining.
- Encouraging infrastructure and project development to facilitate TCE recycling.
- Working with small island developing States to balance extractive revenues with conservation efforts.
- Employing:
  - Life cycle assessments to identify the impacts of TCE extraction, processing, use and disposal and develop mitigation measures.
  - Environmental risk assessments to identify and minimize impacts on human health and welfare.
  - Supply chain risk assessments to evaluate whether uncertainties associated with the scarcity of TCEs could impact the durability of project activities such as renewable energy, e-mobility and food security.
- Ensuring that mining activities embedded in GEF projects are subject to responsible mining methods and to comprehensive socioecological assessments.

Polytmetallic oceanic nodule.
Deep Green Metals

1. BACKGROUND AND RELEVANCE TO THE GLOBAL ENVIRONMENT FACILITY

Technology critical elements (TCEs) – the geological sources for the metals, alloys and chemical compounds used in the production of modern technology – are critical in the production of nearly all green technologies. The relevance of TCEs to the work of the Global Environment Facility (GEF) is twofold: (a) TCE extraction can have detrimental ecological impact in, or close to, GEF project areas, and (b) the TCEs themselves will be critical in many GEF projects that focus on a transition to green technologies. This report discusses the environmental implications of TCE extraction, processing and supply and how GEF financing can reduce the ecological impact of these activities while maintaining the availability of the TCEs for green technologies.

TCE extraction, processing and supply. The current TCE supply chain is highly interlinked with the supply chains of other base metals and is concentrated in areas of major ore deposits, many of which are in regions of high biodiversity, such as the Congo and Amazon basins. As these conventional deposits become increasingly depleted, exploration of new deposits may also be undertaken in sensitive ecosystems. In particular, there is great interest in developing mineral deposits in oceanic systems. The marine explorations are likely to become more relevant to GEF operations as efforts towards a new legally binding instrument on "conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction" are gaining momentum under the Law of the Sea Convention.[1]

TCE importance to green technologies. A range of green technologies – particularly solar and wind power – require TCEs, and finding the most environmentally appropriate means of sourcing them should be an important consideration for GEF projects. Such means could include the development of better recycling infrastructure in cities and

1 The draft text of the treaty (also referred to as the BBNJ Treaty), with comments from Member States, is available at: www.un.org/bbnj/sites/www.un.org.bbnj/files/textual_proposals_compilation_-_28_feb_2020.pdf.

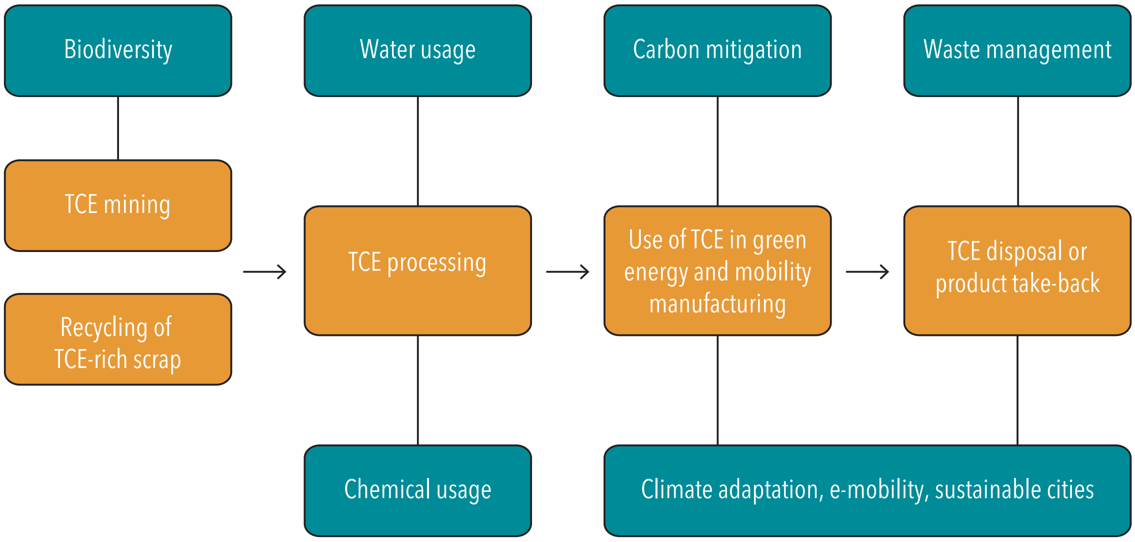


Figure 1. Interface between the TCE supply chain (orange) and dominant GEF project areas (teal).

greater resource efficiency in urban areas with high concentrations of scrap metal.

An initial Scientific and Technical Advisory Panel (STAP) report (Rejeski, Leonard and Libre, 2018), subsequently refined in a peer reviewed paper (Bierbaum et al., 2020), considered the potential nexus of TCEs with all areas of GEF activity. In the current report, we have narrowed down the nexus with the GEF to those areas that are most directly salient at the project level and hence need to be prioritized. Thus, for example, links between phosphorus and food security are not included in this report because the connection to GEF project-level activity is relatively small. Figure 1 presents the overall framework for our analysis, showing the relationship between the TCE supply chain and GEF work areas.

1.1 DEFINING CRITICALITY

Vast amounts of technology minerals exist in the Earth's crust in varying concentrations, meaning there is, in theory, no risk of physical supply shortage beyond the extremely far term. In practice, however, financial, geopolitical and technical issues – such as concentration of production in a small number of countries; those countries' geopolitical, social and regulatory structures; and whether the material is produced on its own or is dependent on the demand for another material – render the supply at much nearer-term risk of shortage (Sovacool et al., 2020).

Recycling and substitution have been vigorously pursued as important facets of this supply problem, but the enabling technologies for these options are not sufficiently mature to deliver the required quantities of TCEs (Ali et al., 2017). Consequently, mining remains the paramount means of producing a reliable global supply of these minerals, and the practical scarcity of supply of most of them represents a significant obstacle to the future of renewable and energy-efficient technologies.

The U.S. National Research Council proposed a framework for evaluating material "criticality" based on the risk and the impact of a supply restriction of a given material. Since 2008, different international organizations have built on that framework to evaluate critical raw materials (Glöser et al., 2015). Other criticality frameworks and methodologies also exist, assessing materials' criticality to a single corporation, a sector or a selected technology of importance, or to entire national or regional economies (Eggert, 2017). Some assessments of TCEs also consider the environmental implications throughout the life cycle (cradle to gate) of materials production (Nuss et al., 2014).

Complicating assessments of criticality is that supply and demand change over time; therefore, the list of TCEs can change with each assessment. Such changes could be the result of new technological breakthroughs (resulting in a sudden increase in demand), shifting production patterns, and the opening and closing of certain mines. Critical shortages can also eventuate if no material subsidies are available in cases of market failure, and problems with the recovery and recyclability of material at the end of life (Speirs, 2015).

For our purposes, particularly with reference to environmental concerns, the most appropriate criticality framework is the Yale metal criticality framework developed by Graedel et al. (2015), shown in figure 2.

1.2 TCEs AND GREEN ENERGY TECHNOLOGY IN THE LITERATURE

In studies on TCEs and green energy thus far, most attention has been given to solar photovoltaic, wind and electric vehicle technologies, as primary sources for a low-carbon future. Figure 3 exhibits the number of TCE studies conducted by energy technology type.

The demand scenarios for TCEs are widely debated in the literature as well as among industry practitioners, largely owing to uncertainty over new technologies under development, which could use a variety of metals and recycled sources. Any forecasting of such technologies needs to consider the existing manufacturing infrastructure and modularity, which will likely delay the uptake of new technologies. For example, although replacements for cobalt in lithium-ion batteries are aggressively being developed, the wide-scale manufacturing infrastructure for these batteries, as well as the cars and other electronics that are based on these established designs, may not easily be adapted to new technologies.

Overall, the absence of a comprehensive picture addressing TCEs, including high-criticality elements, in present and future technologies suggests that further investigation is still required to understand TCE future dynamics and their impacts (Watari et al., 2020 and 2021).

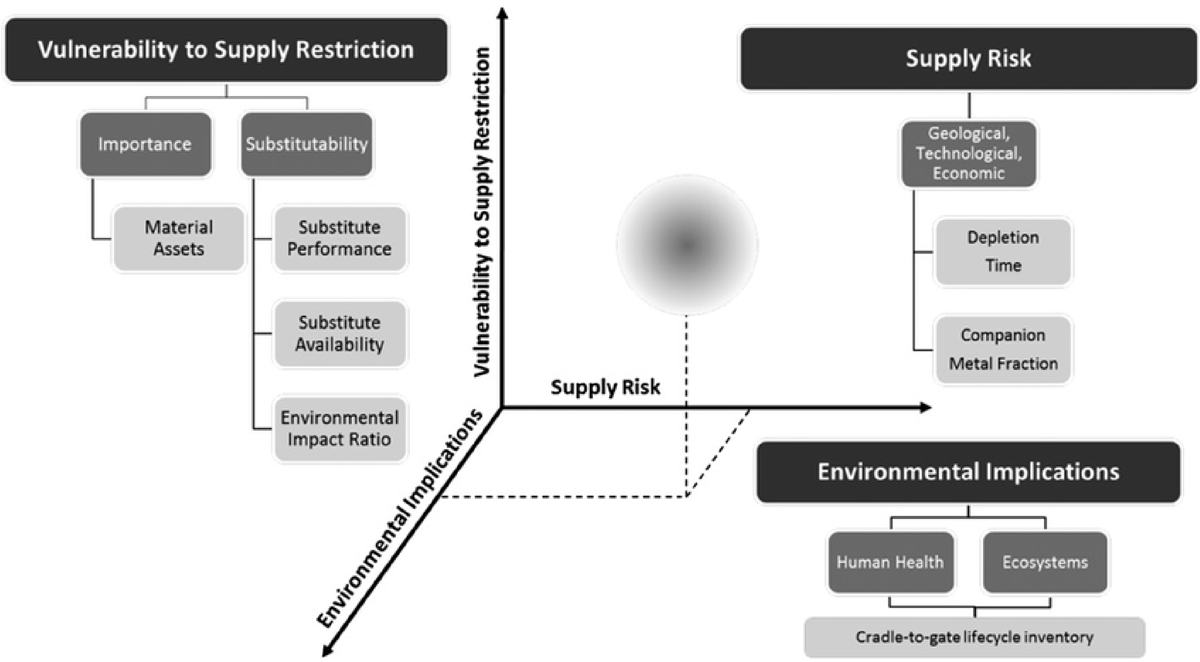


Figure 2. Yale metal criticality framework. Source: Graedel et al., 2015.

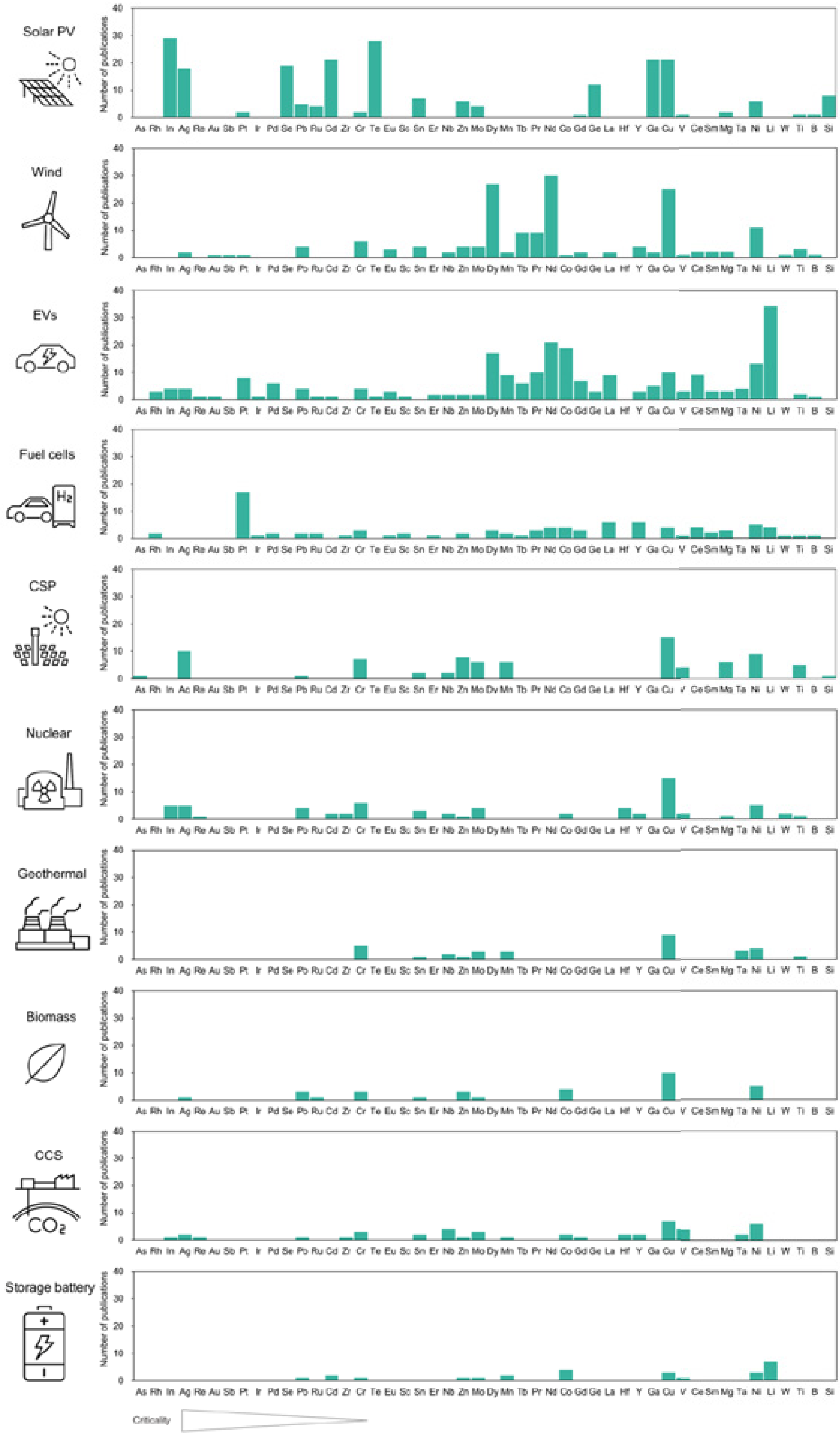


Figure 3. Number of publications related to critical metal outlook by technology type. CCS = carbon capture and storage; CSP = concentrated solar power; EV = electric vehicle; PV = photovoltaic. Source: Watari et al., 2020.

1.3 CRITICAL METALS AND THE "GREEN CURSE" NARRATIVE

Since the 2011 rare earth metals pricing crisis and the World Trade Organization case brought by the European Union, Japan and the United States of America against China, there has been far greater global attention paid to supply constraints of TCEs. In this case, the proponents argued that China, which holds 90% of the mined supply of rare earth minerals (lanthanides and actinides in the periodic table), was restricting supply to raise prices and exert geopolitical influence. China argued that it was engaging in environmental clean-up of many mining sites that had been accused of pollution, particularly in Jiangxi Province. The World Trade Organization decision against China highlighted that trade arguments may hold more sway than environmental control arguments in such contexts.

This was the start of a growth of literature on the "green curse": the necessity of using certain metals in green technologies whose mining is potentially damaging to the environment. In December 2019, the Norwegian Research Council started to fund a three-year research project on this topic, aimed at understanding the political economy of metals such as cobalt for green technologies and the impact of obtaining those metals on environmental decline and conflict.[2]

There has been specific concern about the extent of mining for cobalt and other TCEs near areas with high biodiversity. Figure 4 shows the major cobalt mines and cobalt mine development and exploration areas worldwide. The map's background colouring shows the Human Footprint indicator, which is a measure of wilderness. The greener areas have less human disturbance and hence greater

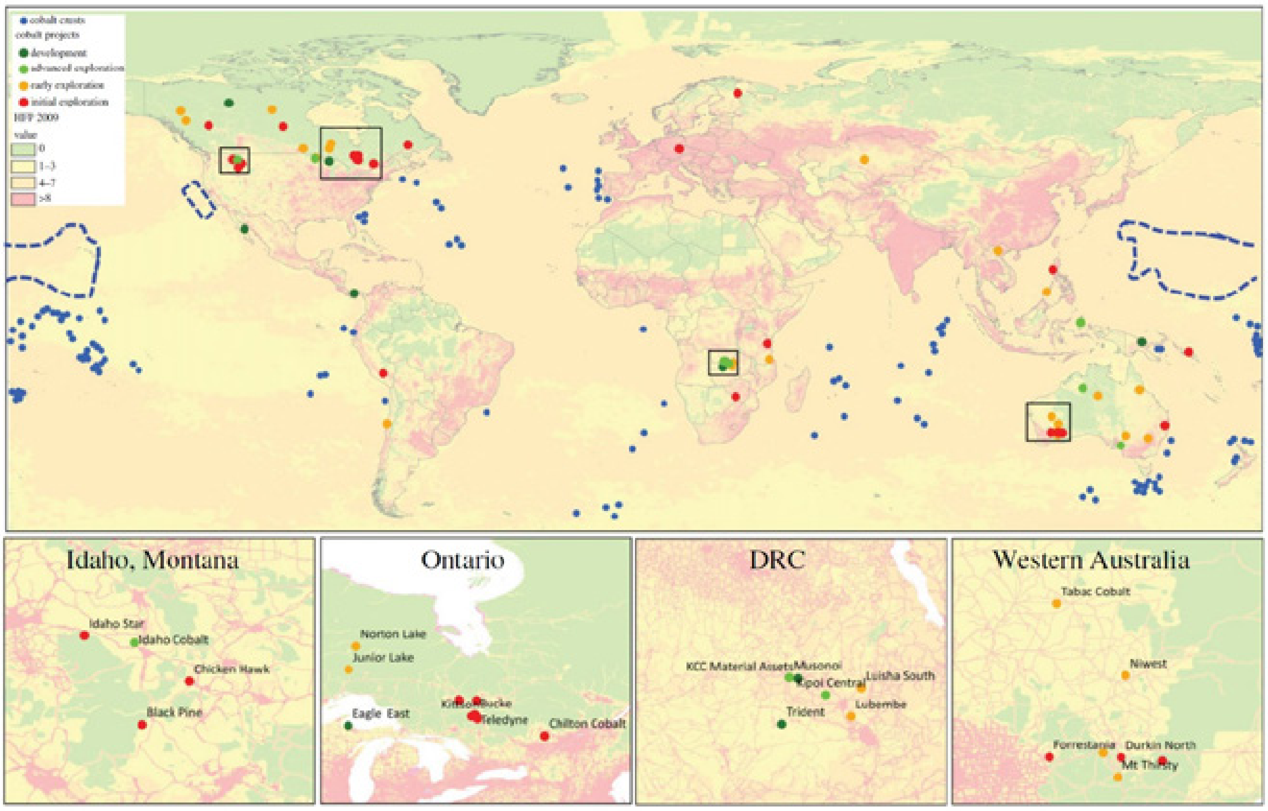


Figure 4. Cobalt mines and exploration areas overlaid on Human Footprint (HFP) indicator data. Adapted from: Sonter, Ali and Watson, 2018.

2 The project is being led by the Peace Research Institute (Oslo): www.prio.org/Projects/Project/?x=1878.

wilderness and ecosystem preservation. Four of the most active cobalt exploration sites, in Australia, Canada, the Democratic Republic of the Congo and the United States of America, are shown in greater detail. Also notable is the extent of oceanic cobalt deposits, which come with a separate set of environmental challenges that will need to be addressed.

Desert ecosystems have traditionally been more resilient to mining than other ecosystems and have lower biodiversity as well. However, deserts are water scarce, making the processing of mineral ores challenging in such regions (Kobayashi, Watando and Kakimoto, 2014). Mining in forested areas poses more direct challenges to biodiversity and ecosystem integrity, and international donors have been endeavouring to develop methods for "forest-smart mining" (Maddox et al., 2019). Figure 5 shows mining areas, many of which are for TCEs, in protected areas or within 50 km of protected areas.

It can be extrapolated from figure 5 that many TCE mining projects are located in forested areas with high biodiversity. In particular, the Amazon and the Democratic Republic of the Congo, which are both within the purview of the GEF's Sustainable Forest Impact Programs (approved in 2019), deserve particular attention: both have mining sites in protected areas and within 50 km of protected areas. As GEF projects develop in these areas, it will be important to consider how these mining sites could be monitored for impact and where possible mitigation measures could be instituted. Possible mitigation measures and policies are discussed later in this report (sections 4 and 5).

1.4 INTERNATIONAL INITIATIVES

A range of international efforts are under way to consider the ways in which TCEs can be more effectively managed at a global level. Two such initiatives are highlighted in the following sections.

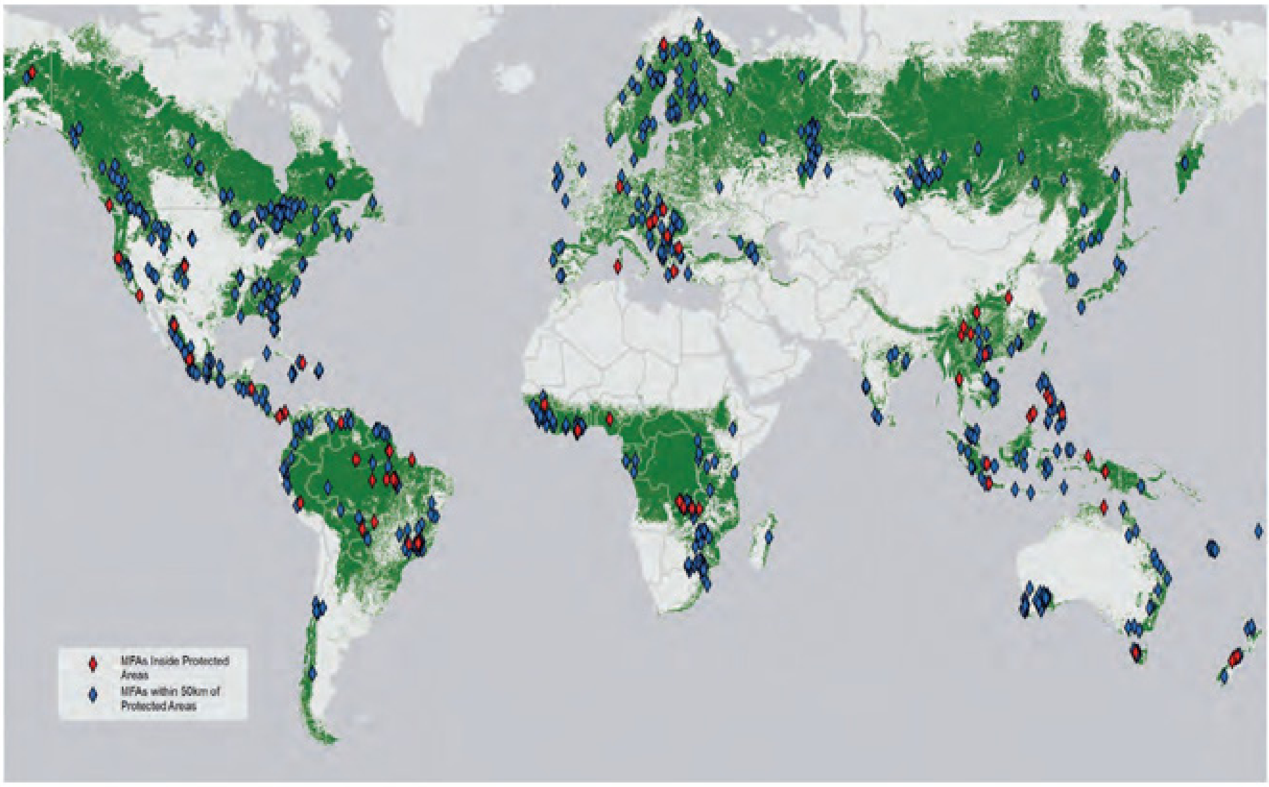


Figure 5. Mining in forested areas (MFAs) inside, and within 50 km of, protected areas. Source: Maddox et al., 2019.

1.4.1 EIT RawMaterials

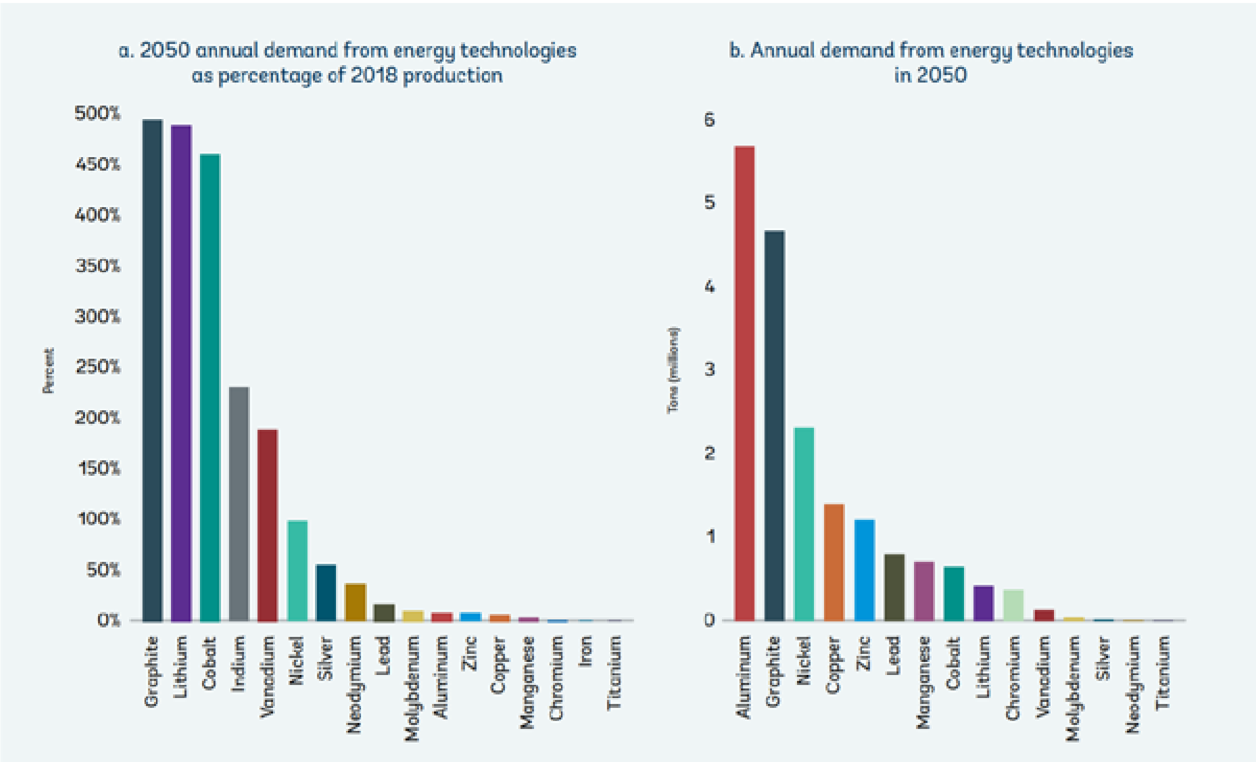
The European Institute of Innovation and Technology launched the EIT RawMaterials initiative in 2014. The programme brings together more than 120 core and associate partners and over 180 project partners from leading industry organizations, universities and research institutions in more than 20 European Union countries.

1.4.2 Climate-Smart Mining Initiative

In May 2019, the World Bank launched the Climate-Smart Mining Initiative, which aims to "help resource-rich developing countries benefit from the increasing demand for minerals and metals, while ensuring the mining sector is managed in a way that minimizes the environmental and climate footprint" (World Bank, 2018).

The World Bank report *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* emphasizes the importance of TCEs for tackling climate change and for achieving Sustainable Development Goal 7 (affordable and clean energy for all) (Hund et al., 2020). Given the high concentration of TCEs in renewable energy technologies, this study presented the growth in mineral demand for energy technologies in 2050 under the two-degree warming scenario (figure 6). A cautionary note here is that the aggregate carbon footprint of mining and processing of TCEs also needs to be considered, as these activities produce considerable emissions. Recent research has also shown that the emissions per unit of ore production have been increasing owing to declining ore grades (Azadi et al., 2020).

There is particular opportunity for the GEF to partner with this World Bank initiative on projects where the World Bank is the lead agency but more broadly for financing leveraging with a range of donors who are supporting the trust fund associated with the facility.



Note: 2DS = 2-degree scenario.

Figure 6. Projected annual demand from energy technologies in 2050 under two-degree warming scenario. Source: Hund et al., 2020.

2. GLOBAL ENVIRONMENTAL AND TECHNOLOGICAL BENEFITS OF PROJECTS INVOLVING TCEs

Products containing TCEs are used in renewable energy, energy security, energy storage, electronics, urban development, and farming and military equipment, among many other applications, and thereby contribute to many global environmental benefits – particularly in the reduction of greenhouse gas emissions and the mitigation of climate change. Their use in technology products facilitates easy communication, improved transportation and increased agricultural productivity and produces a multitude of other socioeconomic benefits. This section summarizes the global environmental and technological benefits associated with TCEs.

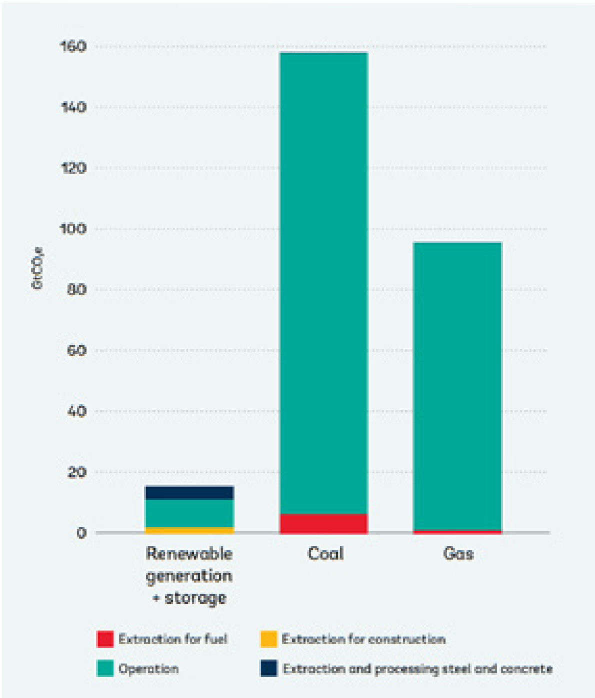
2.1 ENVIRONMENTAL BENEFITS: CLIMATE CHANGE MITIGATION

The drive towards the mitigation of and adaptation to climate change has resulted in an increase in demand for renewable energy technologies. Some of these technologies use TCEs such as neodymium, dysprosium, cadmium, gallium, indium, hafnium, niobium, molybdenum, selenium, tellurium and vanadium, as well as more common materials such as copper, tin, silver and nickel (Moss et al., 2011; World Bank, 2017).

As examples, hafnium and zirconium contribute to climate change mitigation by improving the efficiency of microelectronics and capacitors, as well as through their use in solid oxide membranes for clean metal production. Niobium enables the construction of robust, safe structures using less steel, which in turn produces better fuel efficiencies and lower carbon dioxide emissions in the transport sector (Alkane Resources, 2019).

The greenhouse gases emitted from agriculture (6 billion tonnes in 2011, 13% of total global emissions [Gilbert, 2014]) may be reduced through improved agricultural practices, including the application of TCEs, particularly rare earth elements (REEs) (Chel and Kaushik, 2011), thereby minimizing fertilizer use and reducing the amount of land that would otherwise be cleared.

Avoided CO_2 emissions from renewable energy were estimated at 215 Mt for 2018, attributed to the transition to renewables in the power sector (IEA, 2019). According to the World Bank, emissions from the production and operation of renewable energy and storage technologies are equivalent to 6% of emissions from coal and gas generation under a two-degree warming scenario and a total of 16% of CO_2-equivalent cradle-to-gate emissions up to 2050, as shown in figure 7 (Hund et al., 2020). As the world continues fighting climate change, the demand for TCEs is expected to increase.



Note: Extraction for construction includes the cradle-to-gate emissions from the 17 minerals included in the analysis. Extraction and processing steel and concrete includes cradle-to-gate emissions for steel and concrete and are included because of the scale of emissions from these two minerals compared to the 17 minerals included in the analysis. $GtCO_2$ = gigatons of carbon dioxide, GWP = global warming potential.

Figure 7. Cumulative global warming potential through 2050 from cradle-to-gate mineral extraction and processing, operations of renewable electricity generation, and energy storage technologies compared with fossil fuel technologies through 2050. Source: Hund et al., 2020.

Metallic Mining site in the middle of the Guyana Shield rainforest, South America. Saleem H. Ali

2.2 TECHNOLOGICAL BENEFITS

TCEs are used in high tech products and in everyday consumer products, such as cell phones, thin layer photovoltaics, lithium-ion batteries, fibre-optic cable and synthetic fuels. Many advanced engineering applications – including clean energy production and storage technologies, communication systems, computing applications, wind turbines and solar panels – use TCEs. TCEs are also used in the transportation industry, for example in aerospace technologies and electric vehicles, particularly in electric motors and batteries, both of which contain lithium. Many electric motors use high-powered magnets containing neodymium and dysprosium.

Emerging technologies such as automation and robotics and the Internet of Things also use different TCEs in the data networking systems of smart devices, vehicles and buildings. Automation and robotics will increasingly be used in artificial intelligence, which will also involve use of TCEs (Speirs, 2019).

As more countries develop and people become more affluent, the demand for the high tech and consumer products will increase, hence increasing demand for TCEs.

Tables 1 and 2 summarize the applications in which TCEs and REEs are being used.

Table 1.
Example areas of use of technology critical elements

Element	Compounds	Areas of use
Gallium	GaAs, GaN	Wafers for (a) integrated circuits in high-performance computers and telecommunications equipment and (b) LEDs, photodetectors, solar cells and medical equipment
	Trimethyl Ga, triethyl Ga	Epitaxial layering process for the production of LEDs
	CuNbGaSe (CIGS)	Thin film for solar cells
Germanium	Ge	Substrate for wafers for high-efficiency photovoltaic cells
	Ge single crystals	Detectors (airport security)
Hafnium	Hf	Aerospace alloys and ceramics
	Hf oxide	Semiconductors and data storage devices
Indium	Indium tin oxide	Transparent conductive thin film coatings on flat-panel displays (e.g. liquid crystal displays)
	CuNbGaSe (CIGS)	Thin film solar cells
Niobium	HSLA ferro-Nb (60 % Nb), Nb metal	High-grade structural steel for vehicle bodies
	NiNb	Superalloys for jet engines and turbine blades
	Nb powder, Nb oxide	Surface acoustic wave filters (sensor and touch screen technologies)
	Nb3Ge, Nb3Sn, SbTi	Superconducting magnets in particle accelerators
Platinum group elements	Pd, Pt, Rh metals	Catalytic converters for the car industry
	Pt metal	Catalyst refining of petroleum and magnetic coating of computer hard discs
	Ir	Crucibles for the electronics industry
	Os alloys	High wear applications such as instrument pivots and electrical contacts
Tantalum	Ta oxide	Capacitors in automotive electronics, personal computers and cell phones
	Ta metal	Pacemakers, prosthetic devices
Tellurium	CdTe	Solar cells
	HgCdTe, BiTe	Thermal cooling devices and electronics products
Zirconium	Zr	Ceramics for solid oxide fuel cells, jet turbine coatings and smartphones

Source: Cobelo-García et al., 2015.

Table 2.
Example areas of use of rare earth elements

Area	Applications
Electronics	Television screens, computers, cell phones, silicon chips, monitor displays, long-life rechargeable batteries, camera lenses, LEDs, compact fluorescent lamps, baggage scanners, and marine propulsion systems
Manufacturing	High strength magnets, metal alloys, stress gauges, ceramic pigments, colourants in glassware, chemical oxidizing agents, polishing powders, plastics creation, additives for strengthening other metals, and automotive catalytic converters
Medical science	Portable X-ray machines, X-ray tubes, MRI contrast agents, nuclear medicine imaging, cancer treatment applications, genetic screening tests, and medical and dental lasers
Technology	Lasers, optical glass, fibre optics, masers, radar detection devices, nuclear fuel rods, mercury-vapour lamps, highly reflective glass, computer memory, nuclear batteries, and high temperature superconductors
Communication	Energy efficiency communication through fibre-optic signal amplification
Renewable energy	Permanent magnets in wind turbines, eliminating the need for gear boxes and improving reliability (particularly important for offshore wind power generators) and facilitating larger wind power generator designs
Electric vehicles	Magnets in electric motors (mitigates CO_2 from the transport sector)
Energy storage	Nickel-metal hydride batteries for electric and hybrid vehicles and rechargeable electronic devices
Lighting	Energy-efficient lightning (fluorescents and LEDs)
Transport and energy	Hydrogen storage alloys for clean energy and transport, and ceramics for hydrogen fuel cells vehicles and power generation; an estimated 1 kg of rare earth elements can be found inside a typical hybrid automobile
Greenhouse gas mitigation	Catalytic converters to reduce harmful emissions in exhaust gases
Other	Europium: identification of legitimate Euro bills to dissuade counterfeiting Holmium (highest magnetic strength of any element): creation of extremely powerful magnets, reducing the weight of many motors

Source: Alkane Resources, 2019.

3. ADVERSE ENVIRONMENTAL IMPACTS OF PROJECTS INVOLVING TCEs

TCE analysis is often considered difficult and time-consuming owing to TCEs' typical ultratrace concentrations (Chen et al., 2018; Yadav, Yadav and Kumar, 2014). As such, there are significant knowledge gaps regarding TCE environmental levels, fate, and potential (eco)toxicological impact. The current and future expanded use of TCEs makes their unknown toxicity and potential as inorganic contaminants a substantial concern. Although some studies have tried to disaggregate REE ore into various useful and "waste" materials (see figure 8; Ali, 2014), more studies are needed to increase knowledge of the transport and fate of TCEs in the environment.

Increasing need for TCEs will inevitably increase environmental impacts, whether through their initial extraction, processing, usage or disposal. There is an urgent need to minimize demand for virgin TCEs – through alternative materials, recycling, reuse and other means – and minimize negative environmental impacts through the entire life cycle of TCE usage. This section looks at some of the environmental impacts that can be associated with TCEs.

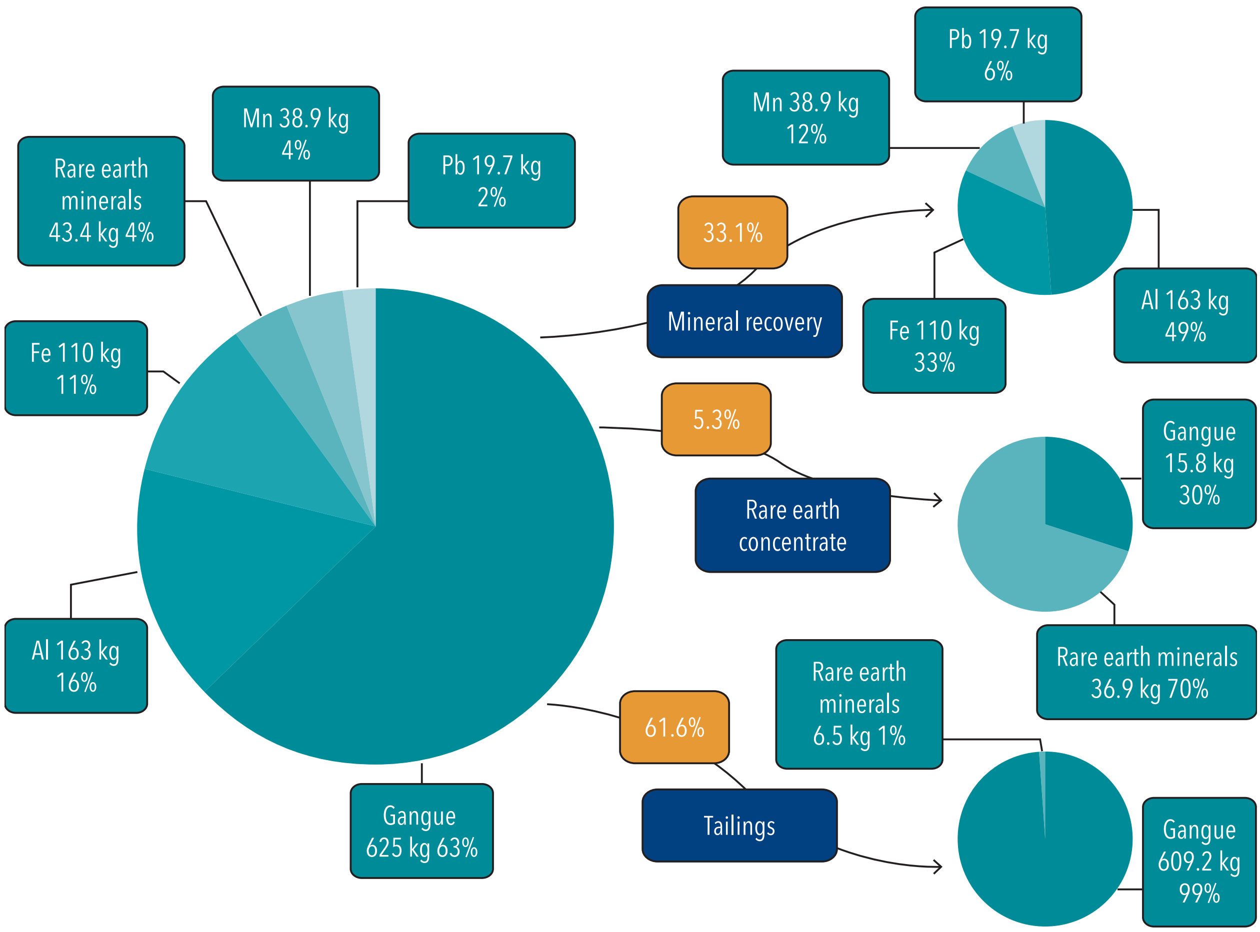


Figure 8. Waste generation from a rare earth mine in China. Source: Ali, 2014.

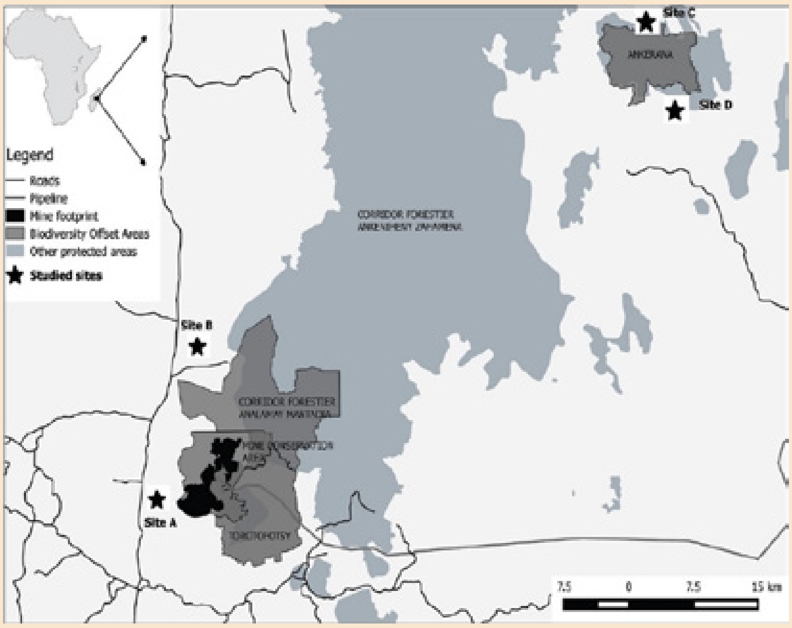
3.1 IMPACT ON BIODIVERSITY AND FORESTS

The impacts of TCE extraction on biodiversity and forests are the same as those caused by mining other minerals. Such impacts include loss of biodiversity through direct land clearance and deforestation, which lead to direct habitat loss and land degradation, thereby changing abiotic and biotic conditions, among other effects. Up to 300 m^2 of vegetation and topsoil were removed for every tonne of rare earth oxide extracted (Kissinger, Herold and De Sy, 2012; ICMM, 2017; Sonter et al., 2017; Sonter, Ali and Watson, 2018). Minimizing such effects requires the implementation of biodiversity offsets to achieve "no net loss" or even a "net gain" of biodiversity (Dickinson and Berner, 2010), as demonstrated by the Ambatovy nickel and cobalt mine in Madagascar (box 1).

Improperly disposed of gadgets containing TCEs may leach these elements into the environment. However, the study by Carpenter et al. (2015) shows that significant quantities of REEs would have to be released into the environment to attain potentially toxic levels.

BOX 1. CASE STUDY: AMBATOVY NICKEL AND COBALT MINE IN MADAGASCAR

The Ambatovy nickel and cobalt exploitation operation, which includes open cast mining, is close to the ecotone between lowland eastern and montane forest, near Moramanga, Madagascar. It is a forest mosaic of largely intact to heavily disturbed patches. The key biodiversity components include structurally distinct forest types (azonal, transition, zonal) linked to different substrates, streams and seasonal ponds. The zone is biotically diverse, with at least 1,367 flora species and 214 vertebrate species, including 13 confirmed lemur species (Dickinson and Berner, 2010).



Location of the Ambatovy mine and its biodiversity offset portfolio.
Source: Bidaud et al., 2017.

The impacts on biodiversity come from progressive forest clearing. To minimize this environmental footprint, the Ambatovy project has implemented a stringent biodiversity management plan for the area surrounding the mine, which also overlaps the Torotorofotsy Ramsar site. The plan is based on International Finance Corporation Performance Standard 6 on biodiversity conservation and sustainable natural resource management. It commits the project to avoiding species extinction, minimizing impacts to natural resources, realizing a net increase in the conservation of rare habitats,

BOX 1. CASE STUDY: AMBATOVY NICKEL AND COBALT MINE IN MADAGASCAR, CONT.

assuring the viability of priority habitats by maintaining or increasing habitat connectivity, and linking project actions in support of biodiversity with other regional biodiversity initiatives.

To that end, the project has adopted a landscape approach to forest management that considers both the high level of biodiversity and the local population's dependence on natural resources as a means to sustain their livelihoods. The programme includes a biodiversity offset initiative with projected conservation outcomes leading to no net loss to biodiversity through impact avoidance and minimization and through reclamation measures.

Impact avoidance was achieved by creating a forest conservation zone that includes two tracts of distinctive azonal forests overlying the ore body. Impact minimization was attained through paced and directional forest clearing associated with taxa-specific salvaging and monitoring activities. Specific management programmes for plants, lemurs, frogs and fish were designed and implemented.

In parallel, a multifaceted biodiversity offset programme was developed with the establishment of a large conservation zone, with biodiversity components similar to the impacted site. Other offset activities include buffer zone protection with joint Ambatovy community management of forest corridor linkages, wetland protection and revegetation activities. The mine closure plan uses a progressive revegetation process, which re-establishes a multifunctional replacement forest with restored biodiversity values.

Preliminary results suggest that activities implemented based on the landscape approach can be an effective means of decreasing human pressure on areas of high conservation importance.

3.2 IMPACT ON WATER

Mining of TCEs may lead to the formation of acid mine drainage, which is characterized by high total dissolved solids, high sulfates and high levels of heavy metals, in particular iron, manganese, nickel and cobalt (Ochieng, Seanego and Nkwonta, 2010). This acidification can kill marine and freshwater organisms, disturb aquatic biodiversity and harm ecosystems. Furthermore, processing of TCEs generates huge amounts of wastewater. For every tonne of rare earth oxide extracted, up to an estimated 1,000 tonnes of contaminated wastewater, and 2,000 tonnes of tailings are generated, and this waste may contaminate groundwater, be discarded into adjacent valleys and streams, or be washed into international waters (Kaiman, 2014). Al-Rimawi, Kanan and Qutob (2013) have observed very high concentrations of REEs and several other metals in groundwater samples from southern West Bank/Palestine; however, the authors did not state the source of these elements.

3.3 IMPACT ON SOILS AND LAND

In addition to impacts on soil and land associated with TCE extraction, e-waste dumping is leading to the release of significant quantities of TCEs, and other toxic elements, into subsoils and groundwater (Haxel, Hedrick and Orris, 2002). In 2016, the world generated 44.7 million Mt of e-waste, estimated to increase to 52.2 million Mt in 2021 (Balde et al., 2017). Only 20% of e-waste is being recycled. The increasing demand for electronics goods and services will inevitably increase the amount of e-waste generated and hence the amount of TCEs released into the environment. These impacts are another reason to promote the recycling, reuse and urban mining of TCEs (Balde et al., 2017).

3.4 IMPACT ON AIR

TCE mining activities, such as cutting, drilling, blasting, transportation, stockpiling and processing, can release dust containing TCEs, other toxic metals and chemicals into the air and surrounding water bodies, with consequent negative effects on soil, wildlife, vegetation and humans (Balaram, 2019; Mirakovski et al., 2011). TCEs and other toxic compounds may be released by open burning of e-waste (Gangwar et al., 2019).

3.5 IMPACT ON CLIMATE CHANGE

TCEs are considered essential elements of the decarbonized economy, particularly in their applications in electric vehicles, wind and solar energy, and lighting (Moss et al., 2013). However, because TCEs are relatively scarce, their extraction often involves processing large amounts of material, sometimes causing environmental damage, including the emission of greenhouse gases from burning fossil fuels and large chunks of forest and from ore processing (Norgate and Haque, 2010). Minimizing the use of virgin TCEs through recycling has potential to mitigate this impact.

3.6 IMPACT ON HUMAN HEALTH

More mining of TCEs will inevitably mean more environmental degradation and human health hazards as waste disposal areas, particularly when exposed to weather, have the potential to pollute the air, soil and water (Barakos, Mischo and Gutzmer, 2015). Furthermore, some TCE minerals contain significant amounts of radioactive elements, such as uranium and thorium, which can contaminate air, water, soil and groundwater (IAEA, 2011).

Some studies indicate that the chemicals used in TCE ore processing, extraction and refining processes have resulted in health hazards to workers and local residents, as well as water pollution and destruction of farmland (Rim, Koo and Park, 2013). Exposure to rare earth metals has been reported to increase the risk of respiratory and lung-related diseases such as pneumoconiosis (Rim, Koo and Park, 2013). Exposure to selenium is also hazardous as it may cause selenosis (Cayumil et al., 2015). Cadmium is a heavy metal with potential to bioaccumulate in the human body and in the food chain, leading to acute and chronic intoxication due to biomagnification (Sharma, Rawal and Mathew, 2015). Beryllium is classified as a carcinogen as it may cause lung cancer and can be inhaled as a dust, fume or mist. Short exposure may lead to several diseases (WHO, 2001). An environmental risk assessment of TCE mining to examine processes, emissions, the spread of contaminants and exposures to humans and biota is recommended.

There are still some gaps in our understanding of the adverse effects of TCEs on human health, particularly with respect to their anthropogenic levels and fate, their biogeochemical or anthropogenic cycling, and their individual and additive toxicological effects. More studies are needed in these and related areas (Gwenzi et al., 2018).

3.7 SOCIOECONOMIC IMPACT

Recent socioenvironmental issues related to the health impacts of REE ore processing (from both radioactive and non-radioactive contamination) in areas of China have been raised as a major concern. For example, the urban street dust of Zhuzhou, an industrial city in central China, has shown very significant concentrations of REEs (suspended REEs ranged from 66.1 mg/g to 237.4 mg/g, with an average of 115.9 mg/g). This reveals the gravity of REE pollution, particularly in industrial cities (Ali, 2014; Cool Earth, 2018; Sun et al., 2017). There have also been several reports of REE occupational exposure that resulted in bioaccumulation of REEs and adverse effects to respiratory tracts (Rim, 2017; Yoon et al., 2005).

Next generation residential VRFB manufactured by StorEn Inc and recently arrived in Australia" (Courtesy: Freedom Energy Pty Ltd: 100% subsidiary of Multicom Resources Limited)

4. FRONTIER AREAS OF TCE SUPPLY FOR GEF PROJECT DEVELOPMENT

Five frontier areas that should be considered within GEF projects to reduce the environmental impact of TCE supply are introduced in this section: recycling, green mining, alternative technologies and materials, phytomining, and oceanic minerals.

4.1 RECYCLING

Building capacity to recycle metals through a range of public-private partnerships might be a key mechanism for mitigating the impact of TCE extraction on the environment. However, there are key limitations to TCE recycling at present. This section explores some of the challenges and possible solutions.

4.1.1 Circular economy

The European Commission (2015) defined the circular economy as a state in which "the value of products, materials, and resources is maintained in the economy for as long as possible, and the generation of waste is minimized". At the sixth GEF Assembly in 2018, the Council noted the importance of the circular economy in realizing global environmental benefits:

> *Circular economy is recognized as a unique opportunity for the GEF to pursue a suite of environmental benefits through public-private partnerships. The GEF's comparative advantage is its convening power and its ability to bring together all the actors in these complicated and interlinked global supply chains—including governments, industry, and the finance sector—to scale-up existing experiences with the circular economy (GEF, 2018).*

Circular economy approaches include eco-design; recycling, refurbishment and reuse; and the development of secondary sources of minerals and metals resources (figure 9). As yet, little attention

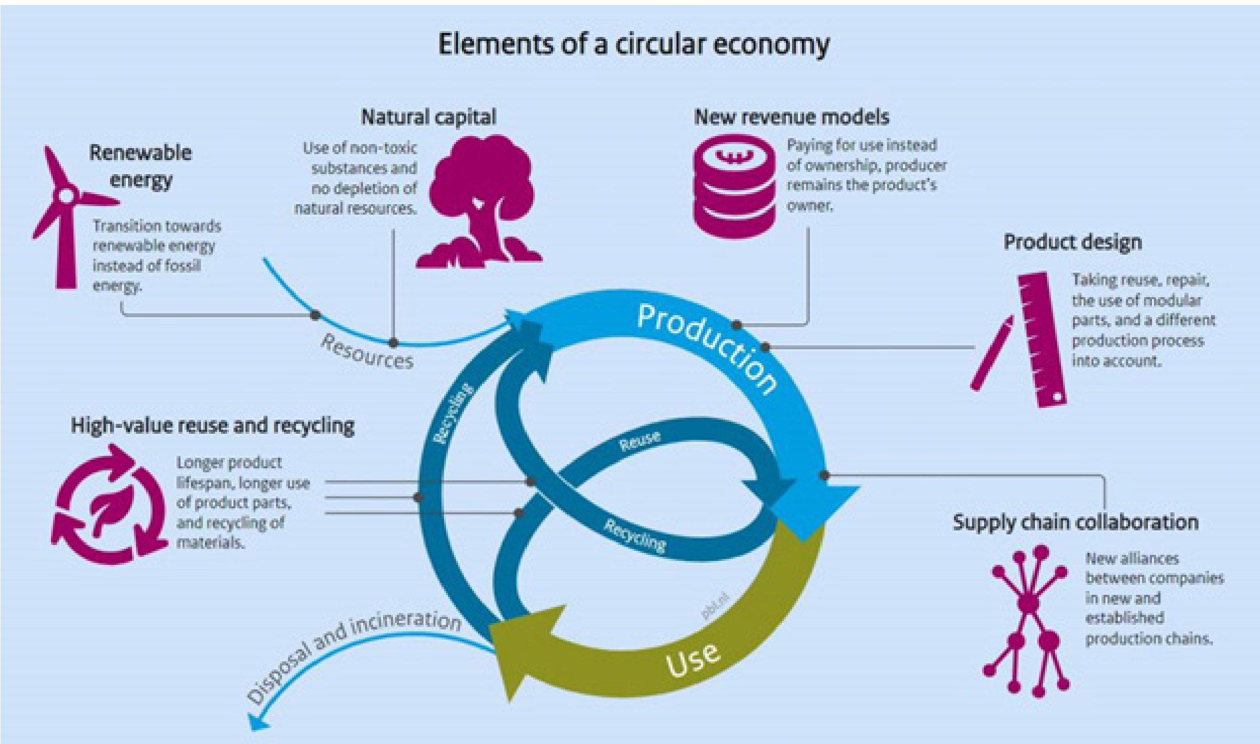


Figure 9. Elements of a circular economy. Source: PBL, 2019.

has been given in the literature to remanufacturing and reuse of TCEs, as illustrated in figure 10. The considerable potential benefits that circular economy strategies can offer to TCE production are yet to be fully explored.

Circular economy strategies that could apply to TCEs include (Hübner, 2012):

- Making products containing TCEs:
  - More durable or easily repairable
  - More energy and resource efficient
  - Able to be remanufactured or reused
- Using recycled materials and/or commonly recyclable materials in products containing TCEs
- Making it easy to separate the recyclable components of a TCE-containing product from the non-recyclable components
- Ensuring that TCE-containing products do not contain toxic or problematic components or, if they are present, that they can be easily replaced or removed before disposal

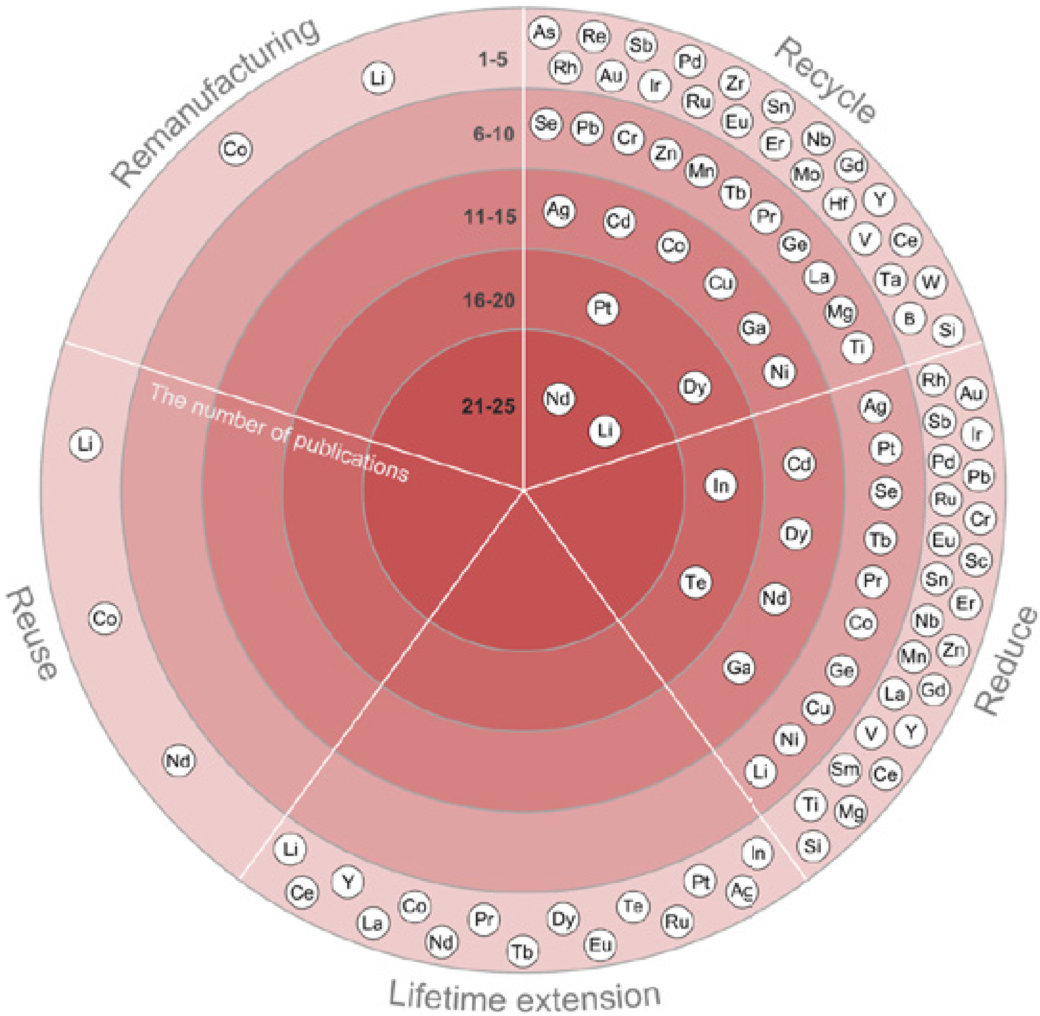


Figure 10. Number of publications covering each circular economy strategy and element. The most explored elements appear in the inner circle. Source: Watari et al., 2020.

- Using product design to provide environmental education
- Using fewer resource-inducing products (products that eliminate the need for subsequent waste)
- Reducing the need for packaging

4.1.2 Challenges to recycling of TCEs

Recycling is a well-recognized circular economy approach, and in the context of TCEs can reduce demand for virgin materials and reduce TCEs' overall environmental footprint. However, the volume of TCEs being recycled is still very low, despite the fact that the amount of some TCEs in consumer goods makes up 4–20% of the annual amount mined (Hagelüken, 2014). Table 3 shows the recycling rates of TCEs.

Increased recycling could play an important role in mitigating augmented demand for primary mineral extraction. Figure 11 highlights the impacts of recycling on mineral demand and shows how raising current recycling rates could mitigate those demands. Furthermore, since a number of TCEs are by-products or co-products of other mined materials, secondary production (e.g., through recycling) could reduce supply restraint risks by decoupling the supply of TCEs from that of the primary material (Tercero Espinoza et al., 2020).

Table 3. Recycling rates of technology critical elements

Recycling rate (%)1	Critical elements
<1	Beryllium, gallium, germanium, indium, osmium, rare earths
1–10	Antimony
>10–25	Ruthenium, tungsten
>25–50	Iridium, magnesium
>50	Chromium, cobalt, niobium, palladium, platinum, rhodium

Source: Wellmer and Hagelüken, 2015.
1. According to UNEP (2011).

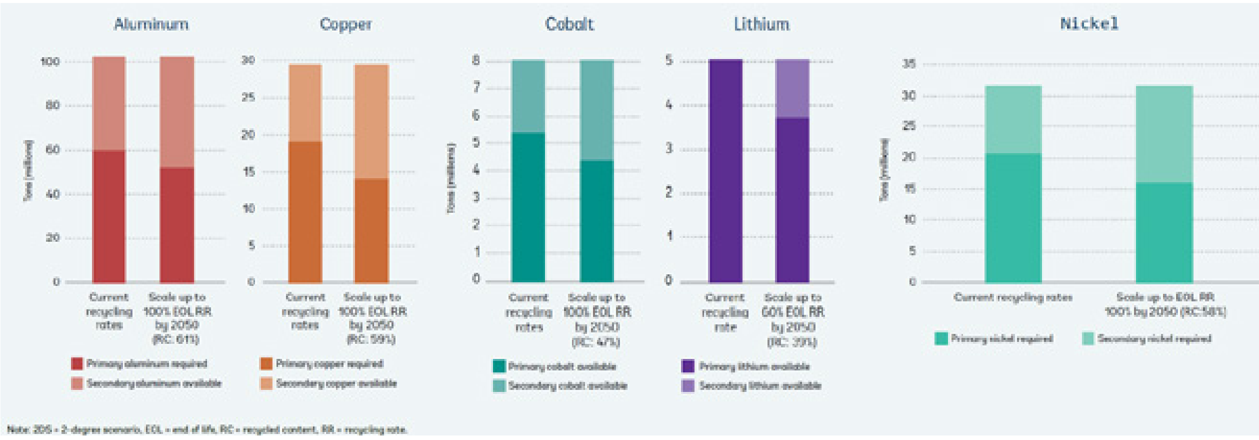


Figure 11. Impact of recycling on cumulative demand for minerals under two-degree warming scenario through 2050. Source: Hund et al., 2020.

The recycling of TCEs faces two key challenges:

- **The concentration of TCEs in materials that are to be recycled is often low (especially true for REEs).** Post-consumer recycling of TCEs may be constrained by low concentrations of TCEs in waste flows. TCEs are typically a minor part of a complex material matrix (containing many other metals, plastics, and so on), making TCE concentration in a single unit very low.

- **There is not enough stock available for recycling to meet demand.** Among other issues with stock availability, the final use of many consumer products takes place in emerging or developing countries without sufficient take-back and collection systems for secondary materials.

Because of these challenges, recycling and other circular economy approaches are often oriented to bulk materials such as cement or plastics (Tercero Espinoza et al., 2020).

Nevertheless, project design solutions, aligned with proper policy and legislation, could foster strategies to tackle current challenges in recycling TCEs. In fact, with the rapid progress and growth in TCE-dependent technologies, it is important to ensure that legislation is applicable and flexible to the rate of technological change. Example strategies related to recycling are discussed in section 4.1.3, but means to increase circularity might also include product inventory and tracing systems for monitoring and recovering consumer end-of-life items; a modular approach in product design; and artificial intelligence for material separation.

4.1.3 Recycling strategies for TCEs

Recycling of TCEs is an area where GEF projects can encourage infrastructure and project development to increase the availability of future recycling stocks. The recycling industry also has significant potential to be explored by developing countries, especially in areas where no mineral resources are available and urban mining (process of reclaiming metals from waste products, e.g., electrical and electronic equipment) can be strategically explored. Key areas to consider are highlighted below.

Batteries. There is immense potential for battery recycling as e-mobility infrastructure and vehicles gain traction worldwide (Chen et al., 2019). The World Economic Forum has launched the Global Battery Alliance to provide cleaner recycling options for the battery industry in coming years. In addition, electric vehicle battery modules can be sorted and reassembled for stationary storage. A number of projects have implemented such photovoltaic applications (Pagliaro and Meneguzzo, 2019). Developing countries could take advantage of stationary energy storage as an option to generate significant environmental and economic savings.

Figure 12 shows the recycling process for lithium-ion batteries, which contain key TCEs and are likely to be the most extensive source of recycled metals for e-mobility applications. The three forms of treatment required to harness the metals – thermal processes (pyrometallurgy), chemical processes with water (hydrometallurgy), and bacterial or phytomining mechanisms (biometallurgy) – all deserve greater attention for development. Box 2 highlights the specific potential for recycling vanadium redox flow batteries, used in energy storage.

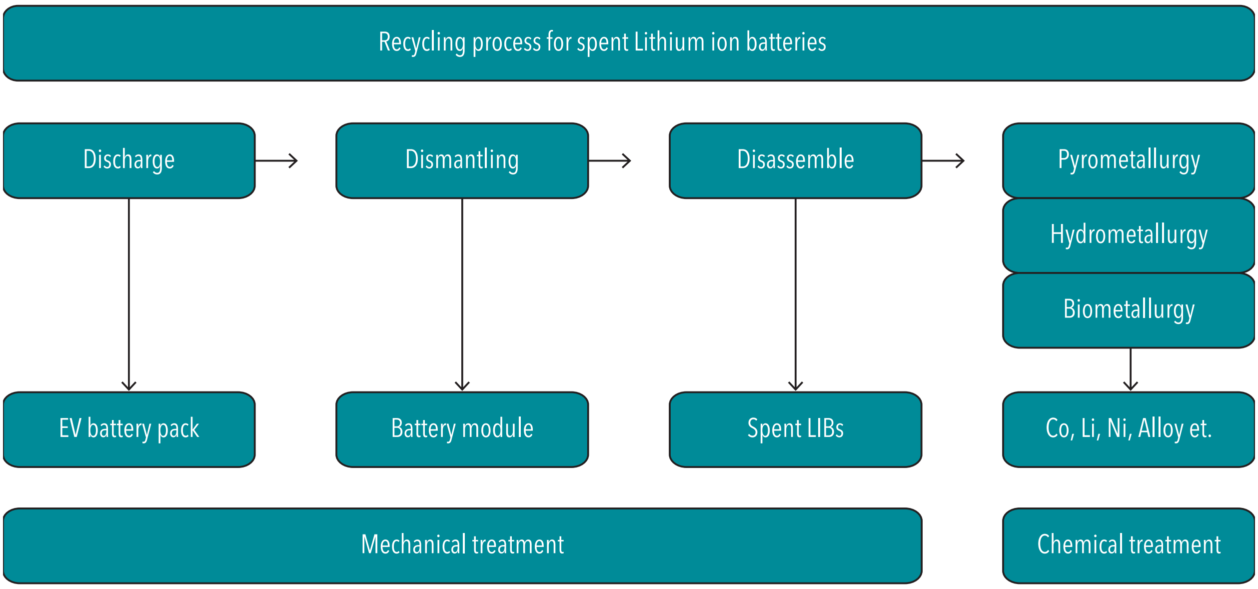


Figure 12. Recycling mechanism for lithium-ion batteries. Source: Yun et al., 2018.

BOX 2. VANADIUM REDOX FLOW BATTERIES

Vanadium redox flow batteries (VRFBs) are an energy storage technology. The batteries use vanadium in four oxidation states in a concentrated aqueous solution to store and release energy on demand. VRFBs are highly scalable, with commercial batteries sized from a few kilowatt-hours up to a few hundred megawatt-hours (Huang et al., 2019; Shigematsu, 2019). Since 2011, VRFBs have been deployed more frequently and on a larger scale, growing to average installation sizes of 19.5 MW (76.2 MWh) in 2015. In 2017, the 200 MW/800 MWh Rongke Power project in Dalian, China, significantly increased the scale of VRFB installations. In April 2019, there were 113 recorded installations globally, for a combined energy storage capacity of 209.8 MWh. Further developments in electrolytes and improvements in stability have led to significant improvements in energy density and operational stability (Cao et al., 2018; Li et al., 2011).

VRFBs belong to a larger group of flow batteries, with various chemistries, and must be chosen to fit their purpose (Easton and Maschmeyer, 2018). Unlike lithium-ion batteries, flow batteries allow for complete depth of discharge. Because they allow for the decoupling of energy storage and power delivery, VRFBs are ideal batteries for stationary applications in grids, microgrids, virtual power plants and behind-the-meter storage in homes and property developments. Their aqueous nature eliminates the fire risks typically associated with conventional lithium-ion batteries. The key detracting factor of VRFBs compared with lithium-ion batteries is their larger size, although for stationary storage this is mostly not a major constraint.

VRFBs are ideal for energy storage between 2 and 8 hours and are suitable for both storage and arbitrage in electricity grids (Akter et al., 2019). They are also ideal for stationary storage in mine electrification, and several mines have decided to go 80–90% renewable and some 100%.

BOX 2. VANADIUM REDOX FLOW BATTERIES, CONT.

The most expensive part of the VRFB is its aqueous vanadium electrolyte, whose costs are proportional to the vanadium prices of the day. The remainder of the VRFB system is essentially made of plastic equipment, storage vessels, pumps and polymer membranes.

VRFBs do not have to be recycled as entire units: While the electrolyte might deteriorate after some years, the hardware remains intact; the electrolyte can be pumped out and replenished after a few years of use, cleaned up and reused. This allows for a full circular economy on vanadium used in VRFBs (although the largest use of vanadium is still in steel). Various business models are currently being proposed, such as a model where the hardware remains with the user of the VRFB but the electrolyte is leased. This allows the reagent provided to retain stewardship of the electrolyte.

Vanadium, although a scarce metal, does not share the social, ethical and environmental issues associated with cobalt and lithium. As VRFBs do not share the environmental burden of lithium-ion batteries at the end of life (which is greater than 20 years), requiring only replacement of the liquid electrolyte (Arenas, de León and Walsh, 2019; Díaz-Ramírez et al., 2020), these batteries are ideal for deployment in islanded microgrids in developing countries in conjunction with renewable energy sources. Their modular design allows for easy scalability. In contrast to conventional batteries, VRFBs can provide multiple service functions, such as peak shaving and subsecond response for frequency and voltage regulation, for either wind or solar power generation and the power grid.

In many parts of the developing world, ageing or non-existent pole-and-wire transmission grids are becoming too expensive to install or maintain, making investment in distributed energy resources via renewable energy generation (e.g. solar photovoltaic, wind) with battery energy storage systems ideally suited to more remote towns, agricultural communities and mining operations. The inherently safe nature of VRFBs, their lack of environmental impact, their very long operating lifespans, their modular scalability and the ease of electrolyte replenishment, clean-up and reuse also make them ideal for many of the islands in the Indo-Pacific region, and the Indian Ocean Rim countries, such as the central-southern Asia region and eastern Africa. Australia, as the country that pioneered this technology, has significant vanadium resources as well as a location bordering the Indian and Pacific oceans, making it ideally positioned to design, manufacture, deploy and maintain these systems. Several Australian companies are developing supply chain capacity in this area to provide end-to-end vertical integration capability.

1. https://willigan.digital/pr/bold-editorial/vanitec/v3
This case study was contributed by Nathan Cammerman, Multicom Resources, and Jacques Eksteen, Future Battery Industry Cooperative Research Centre.

Platinum group metals. Metals such as platinum, palladium and rhodium in automotive catalysts are typically present in concentrations between 2 g and 5 g per unit (a concentration of more than 1,000 ppm – more than 100 times higher than natural ores) (GFMS, 2005), making them a good target for recycling.

Electrical and electronic equipment waste. Typical e-scrap, like circuit boards, contains a spectrum of interesting metals, such as copper, tin, cobalt, gold, silver, indium, palladium and platinum. This makes e-scrap a challenging task for recycling technologies owing to its complexity, but e-scrap recycling could result in the recovery of valuable metals. For this reason, electrical and electronic equipment was described by Umicore/Öl (2008) as a "mine above ground".

Upstream mining activities. Some upstream mining activities offer recycling opportunities. For instance, small-scale reprocessing of tailings can deliver benefits such as providing livelihood opportunities and preventing expansion of greenfield extraction. Likewise, the use of alternative chemical or leaching techniques could enhance mining waste recovery as well as reduce associated environmental impacts.

Bioleaching. The biological conversion of an insoluble metallic compound into a water-soluble form, bioleaching has attracted growing attention as a greener alternative for mineral extraction in recent years. Current large-scale operations for the primary production of elements including copper, uranium, cobalt, nickel, gold and zinc can be found in a number of countries, such as Chile, China, the Islamic Republic of Iran, and South Africa (Yin et al., 2018). Although further laboratory and field-scale development is expected with respect to TCEs for both e-waste and mining waste recovery, bioleaching is promising – particularly for use in emerging countries – owing to its simplicity, low capital cost requirement and associated economic and social benefits (Arya and Kumar, 2020; Schippers et al., 2013).

4.2 GREEN MINING

Green mining is defined as technologies, best practices and mine processes that are implemented to reduce the environmental impacts associated with the extraction and processing of metals and minerals. Green mining entails carefully balancing resources, adapting new equipment and altering the supply chain to accommodate more sustainable processes. To meet the increasing demand for TCEs, while minimizing the environmental footprint of their extraction, green mining technologies should be promoted.

The green mining mechanisms might include:

- Using carbon instruments, such as emissions trading approaches, to reduce carbon footprints
- Improving financing tools to encourage renewable energy use in upstream activities
- Assessing the geographical distribution of refining, smelting and other beneficiation projects for emissions savings in transportation

In addition to their potential to reduce greenhouse gas emissions, ecological footprint, and chemical and water use, green mining techniques can reduce operating costs. An example success story is the Green Mining Initiative's automated mine ventilation system for an underground mine in greater Sudbury, Ontario, Canada, which has reduced energy consumed by up to 40%, reduced greenhouse gas emissions, and led to cost savings of up to $4 million per year (Kirkey, 2014).

Rapid advances in technological innovation, including through automation, digitization and electrification, can move green mining forward. Such innovations include autonomous vehicles, automated drilling and tunnel boring systems, drones, and smart sensors (Bliss, 2018).

In addition to their environmental benefits, automated technologies allow companies to remove staff from dangerous working conditions. For example, it is estimated that using smart sensors could create US$34 billion in value for the mining industry by facilitating predictive maintenance, improving equipment use, reducing equipment downtime and failure, and lowering the frequency of health and safety incidents. The improved health and safety achieved through such digitization could also save an estimated 1,000 lives and eliminate an estimated 44,000 injuries (van der Voet et al., 2013).

To keep track of the mitigation of social and environmental impacts within mining operations, a comprehensive monitoring framework could be considered. For instance, biodiversity indicators (e.g. persistence of species and their habitat, environmental DNA [through water monitoring], persistence and resilience of ecosystem services) can help the extractive sector to understand its impacts and monitor its efforts, aiming towards net ecological gains or no net loss. The use of remote sensing tools can make such monitoring less invasive. Engaging the local community through a more active role in monitoring impacts (e.g. via personal smartphone monitoring apps) can increase the community's sense of ownership and stimulate environment protection.

4.2.1 Efficient use of water

The extraction of TCEs uses large quantities of water, needed particularly for ore processing, dust suppression, slurry transport and employee requirements. For every tonne of rare earth oxide extracted, up to 1,000 tonnes of water is used. In areas where water is already scarce, this heavy use of water has been a major concern for the communities living near the mining site, particularly when the mining operations pollute water sources (Banza et al., 2018).

The primary way that mines can cut back on water usage is through close-circuit approaches that maximize water conservation. Freshwater use can be further reduced by such measures as (Einhorn, 2015; van der Voet, et al., 2013):

- Water control and recycling:
  - — Adequate measurement and control of water inputs to the plant
  - — Use of high-efficiency thickeners to decrease water losses to tailings
  - — Recovery of water infiltration from tailings for use in the overall process
  - — Recycling of tailings run-off and its return to the overall process
- Water substitution: use of wastewater or grey water
- Real-time calculation to predict and manage actual water needs

4.2.2 End of the line: new methods to improve mine closures

Poorly rehabilitated mines – including those for TCEs and REEs – leave significant legacy problems for all elements of society (governments, communities and companies) and can leave the mined land in a devastated state. Mine closures should require the development of smart and effective closure and rehabilitation plans to ensure public safety and health, and environmentally stable conditions compatible with the surrounding environment. All such plans should address issues of physical and chemical stability.

In post-mining areas, sustainable land use should be given priority, particularly in ecologically sensitive areas. However, such initiatives will depend on environmental, technical, economic, social and cultural factors. Biowaste, such as manure compost, biosolids and municipal solid waste, if low in contaminants (particularly, low in heavy metal content) can be used to rehabilitate mine spoils. Rehabilitated mining sites may be used for a variety of activities, including reforestation, recreational activities and aquaculture (Kirkey, 2014; Wijesekara et al., 2016).

These closure methods may not be suitable for artisanal and small-scale mining (ASM) as, owing to its informal nature, it would be more difficult to guarantee consistent application of such practices.

4.2.3 Forest-smart mining[3]

Forest-smart mining is a concept championed by the World Bank to draw attention to the impacts of mining on forests and the opportunity for the mining sector to generate positive outcomes for forest health. Forest Smart Mining is one of 12 pillars of the World Bank's Climate Smart Mining Facility, designed to ensure that minerals for the green economy, including TCEs, are "green" in production and manufacture, as well as use and disposal, and to protect market access for TCE mines in developing nations.

At its simplest, forest-smart mining aims to protect forests and forest values. Mining can be understood as forest-smart when miners behave in ways that recognize that forests have "significance for sustaining growth across many sectors" and that "changes in forest cover affect other land uses as well as the people living in that landscape". Forest-smart mining involves "identifying opportunities for

3 This section and the accompanying case study of Coltan in the Democratic Republic of the Congo were contributed by Estelle Levin-Nally, Sebastien Pennes and Blanca Racionero Gomez, Levin Sources.

mutual benefit and creating practical solutions that can be implemented at scale" (PROFOR, 2016).

The World Bank's PROFOR (Program on Forests) trust fund commissioned three studies in 2017, which together investigated what forest-smart mining might mean, where examples of forest-smart and not-so-smart mining might be found, and what key lessons could be learned to make mining more forest smart in the future (Hund and Reed, 2019). The studies considered forest-smart mining across all scales – from artisanal mines to mega-mines – and diverse geographies: 44 case studies in 20 countries. One outcome of the work was the definition of 14 forest-smart mining principles to support the development of context-specific forest-smart mining approaches across all scales (World Bank, 2019b). A specific report on ASM clarifies those principles for ASM activities (World Bank, 2019a):

Principles for forest-smart artisanal and small-scale mining

Good governance

1. Develop and implement clear policies for land use allocation and land ownership.

2. Ensure that the regulatory environment of ASM attempts to stay ahead of the development of the sector (recognizing that this sector has commonly been neglected or overlooked to date).

3. Take special care to safeguard comparatively weaker communities/individuals and those with special rights.

4. Improve mining regulations to adopt an ASM forest-smart approach.

Improved understanding and approaches

5. Contextualize mining deforestation by taking into account other sectors.

6. Improve the understanding of where ASM is occurring and its impacts on forest landscape degradation, human health and ecosystem services as a basis for designing appropriate realistic interventions with a higher chance of success.

7. Consider all impacts of mining when considering forest-smart interventions.

8. Obtain clear understanding of the role and responsibilities of miners and regulators.

Capacity-building

9. Assist and strengthen the regulators of ASM in developing countries so that they can effectively implement forest-smart mining.

10. Assist and strengthen ASM operators in developing countries so that they can effectively implement forest-smart mining practices

Widen the participants in the pursuit of forest-smart mining

11. Consider the opportunities for positive synergy between ASM and LSM, and build cooperation and alliances to enable ASM to perform better on forest impact mitigation.

12. Work with the overall poverty reduction agenda and secure a critical level of political stability in priority countries.

13. Work with the environmental education agenda to disseminate facts related to the need to safeguard/protect forests.

14. Consider the role of protected areas and REDD+ in limiting the impacts of ASM on forest landscapes.

15. Take advantage of existing frameworks for supply chain management and due diligence and use market influence to raise the business case for forest-smart mining.

In the Democratic Republic of the Congo, the world's fourth most important country for biodiversity and a key mining destination, primary forest loss was 38% higher in 2018 than average forest loss from 2011 to 2017 (Carrington, 2019). The Democratic Republic of the Congo accounts for 70% of worldwide cobalt production, 62% of tantalum (USGS, 2020), and 4% of tin (International Tin Association, 2020). The Democratic Republic of the Congo's economy is heavily dependent on the mining sector, which in 2018 provided 29% of the country's gross domestic product, 98% of its export revenues, and 25% of employment (IMF, 2019). The ASM sector directly employs 2 million people, and 16% of the population (about 10 million people) derive their livelihoods from ASM (Megevand, 2013).

BOX 3. COLTAN MINING IN EASTERN DEMOCRATIC REPUBLIC OF THE CONGO FORESTS

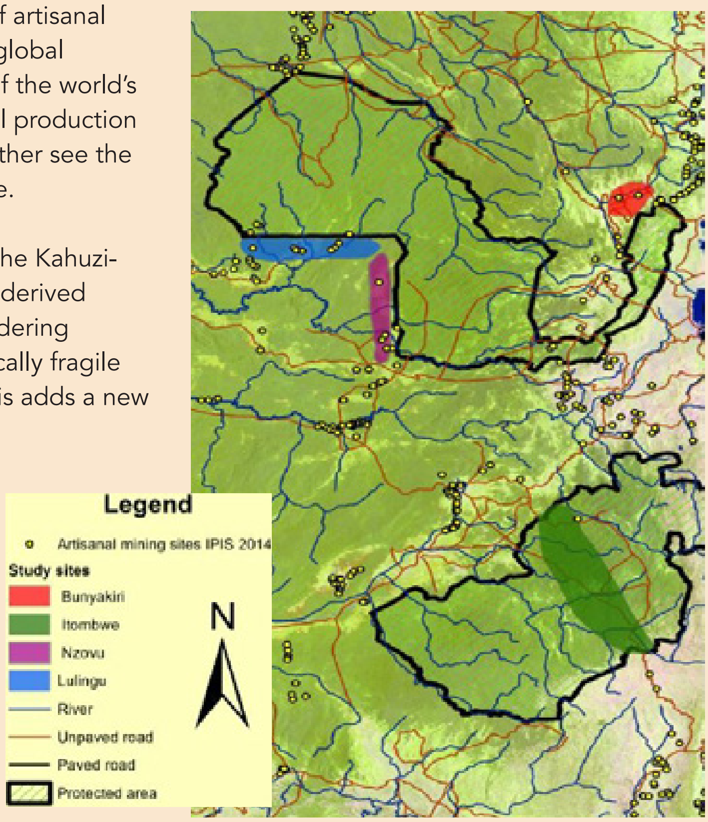
The case study illustrates the challenge of introducing forest-smart mining solutions to remote, largely self-governed, vulnerable artisanal mining communities and offers a few practical suggestions.

Columbite-tantalite ("coltan") deposits are located within and around two high biodiversity areas in South Kivu Province: the 6,000 km² Kahuzi-Biéga National Park, which is a World Heritage Site, and the 12,000 km² Itombwe Natural Reserve. The daunting loss of 95% of the elephant population and 50% of the gorilla population in the highlands of Kahuzi-Biéga in the four years of the coltan rush, from 1999 to 2003 (Tamagiwa, 2003), has been widely attributed to the skyrocketing prices of tantalum at that time (Hayes and Burge, 2003; Ostermeier, 2016; Redmond, 2001). In fact, the real driver was the economic elasticity of artisanal mining – its ability to react promptly to global demand. Since the area hosts only 9% of the world's known deposits but yields 62% of global production (BGS, 2012; USGS, 2020),[1] we should rather see the ecological cost as a global market failure.

Compliant cassiterite mining sites near the Kahuzi-Biéga National Park (certified by OECD-derived initiatives) risk becoming points for laundering non-compliant production from ecologically fragile areas into responsible supply chains. This adds a new layer of complexity for monitoring.

Practical initiatives launched to combat the negative environmental effects of artisanal coltan mining include:

- An integrated land-use planning effort, initiated with local chiefdoms and communities in the Itombwe Reserve, which delimits zones for integral conservation and



Map artisanal mines around the Kahuzi-Biega National Park and Itombwe Natural Reserve. Source: Kirby et al. 2015

BOX 3. COLTAN MINING IN EASTERN DEMOCRATIC REPUBLIC OF THE CONGO FORESTS, CONT.

for environmentally friendly economic activities (Weinberg et al., 2013). The initiative is grounded on the local assumption that ecozones will attract economic development that can compete with mining. However, the remoteness of the area makes it doubtful that ecotourism could become a viable economy there, even in the long term.

- The provision of alternative livelihoods to local miners through microfinance schemes (Kirkby et al., 2015). But with a mean monthly income of US$116 for miners against US$62 for non-miners, this initiative does not bear hopeful prospects.

Although somewhat effective, these solutions do not address the root cause of the problem: the relationship between artisanal coltan mining and deforestation. All studies agree that the direct impact of artisanal mining on forests, the removal of trees to expose the mineralized substrate, is far less damaging than the indirect impacts caused by mining-related economic activities (Megevand, 2013). These activities include bushmeat hunting to feed the miners; timbering and tree de-barking to build pans and sluices; the collection of timber and branches to build camps or to cook and provide heat; slash and burn agriculture; secondary migration; and human waste.

Ultimately, local market-driven solutions can complement the value chain requirements of OECD-derived models, land-use planning or "zoning" solutions, or community engagement schemes between large- and small-scale miners, like in the cassiterite site of Bisie (Fahey and Mutumayi, 2019), to make artisanal and small-scale mining of coltan more forest smart. In remote communities, the improvement of existing techniques will always garner more buy-in, increasing the scope for the gradual adoption of more forest-smart mining policies and practices.

Note: This case study was contributed by Estelle Levin-Nally, Sebastian Pennes and Blanca Racionero-Gomez at Levin Sources OECD = Organisation for Economic Co-operation and Development.

1 The official figure for production origin is 42%. However, most studies suspect that a lot if not all of the production declared by Rwanda (20% of global production) actually comes out of the eastern Democratic Republic of the Congo as well.

4.3 ALTERNATIVE TECHNOLOGIES AND MATERIALS

Alternative technologies are innovations that, through improved design or manufacturing processes that call for reduced or different material use, decrease demand for virgin TCEs. In doing so, they may also ensure a more secure supply of the technology that was formerly reliant on a particular TCE, result in products with increased efficiency and lower costs, and decrease the chance of future TCE crises.

One promising alternative technology, phytomining – the biometallurgical process of using hyperaccumulator vegetation not only for metal recovery of some TCEs but also for land restoration and decontamination – is discussed separately in section 4.4.

Efforts are also growing in the development of alternative materials. The Critical Materials Institute at the U.S. Department of Energy has a targeted research programme on developing substitutes to critical elements.[4] The research focuses on dematerialization of key elements with constrained supply, such as the heavy REEs used in magnets. Polymer substitutes are also being considered,

4 www.ameslab.gov/cmi/developing-substitutes.

Nanchang, Jiangxi Province, China, has been a major center for artisanal technology metals extraction and trading. Saleem H. Ali

but for synthetic materials such as these, the environmental impact of using fossil fuels versus biofuels in their production must be evaluated. For example, carbon fibres used to replace metal in aircraft chassis production are, on the one hand, lighter and can reduce operational fossil fuel usage but, on the other, require petroleum products in their production. Such trade-offs can be exemplified through life cycle assessment (see appendix 1), which may be an important tool for evaluating business partnerships in GEF projects in which material production is involved (such as eco-industrial parks).[5]

As many TCEs are co-products of other metals, the methods of processing these TCEs are reliant on the economics and technologies used in the primary metal extraction. Therefore, opportunities to improve the TCE extraction process are largely linked to improvements in the overall metal extraction process. New implementations and specific side processes – such as using less harmful solvents or reducing the number of steps in extraction – could be implemented so that TCE production could be maximized and its environmental impacts mitigated (Płotka-Wasylka et al., 2017).

4.4 PHYTOMINING[6]

Phytomining (or "agromining") entails deriving economically valuable, high-purity metals or

5 See for example, the GEF project for eco-industrial park development in Vietnam: www.thegef.org/project/implementation-eco-industrial-park-initiative-sustainable-industrial-zones-vietnam.

6 This section was authored by Amelia Corzo Remigio, Mansour Edraki, Peter D. Erskine and Antony van der Ent, Sustainable Minerals Institute, University of Queensland, Australia, and is derived from the review article, Corzo Remigio (2020).

Figure 13. Example hyperaccumulator species: (a) Pycnandra acuminata (Sapotaceae), endemic to New Caledonia, is a nickel hyperaccumulator and concentrates up to 25% nickel in its blue-green latex. Photo: Adrian L.D. Paul, Sustainable Minerals Institute, University of Queensland, Australia;(b) Neptunia amplexicaulis (Fabaceae), native to north-west Queensland, is a selenium hyperaccumulator (13,400 mg/kg biomass). Photo: Peter D. Erskine, Sustainable Minerals Institute, University of Queensland; (c) Noccaea caerulescens (Brassicaceae), distributed in Western Europe, is one of the strongest hyperaccumulator plants and can concentrate zinc (53,450 mg/kg biomass) and cadmium (3,410 mg/kg biomass). Photo: Mark Aarts, Laboratory of Genetics, Wageningen University and Research, the Netherlands; (d) Pteris vittata (Pteridaceae), a cosmopolitan fern native to China, concentrates arsenic at up to 22,630 mg/kg biomass on its fronds.

metalloids from the metal(loid)-rich biomass of plants. Hyperaccumulators are plants that accumulate metal(loid)s in their shoots in quantities hundreds, or often thousands, of times greater than other plants. A plant is considered a hyperaccumulator of metal(loids) if it meets threshold values in plant dry shoot matter of:

- 100 mg/kg biomass for cadmium, selenium or thallium
- 300 mg/kg biomass for cobalt or copper
- 1,000 mg/kg biomass for arsenic, nickel or REEs
- 3,000 mg/kg biomass for zinc
- 10,000 mg/kg biomass for manganese

There are currently 750 hyperaccumulator species known globally, of which 532 reach the threshold for nickel, 53 for copper, 45 for selenium, 42 for cobalt, 42 for manganese, 20 for zinc, 7 for cadmium, 5 for arsenic, 2 for thallium, and 2 for REEs (see figure 13 for some examples).

Hyperaccumulator plants have been used in geobotanical prospecting for ore deposits. Subsequently, Rufus L. Chaney proposed their use in the remediation of contaminated soils, a new technique called "phytoextraction". This technique involves (a) cultivating selected hyperaccumulator plants on a contaminated site and (b) removing the harvestable metal(loid)-enriched biomass to reduce the volume of plant material disposed of as hazardous waste. Phytoextraction can remove hazardous metal(loid)s from the soil in a cost-effective way and compares favourably with other available remediation techniques, such as physicochemical methods of decontamination. Phytomining – through subsequent metallurgical processes to recover valuable metal(loid) elements from the biomass (see figure 14) – can create a profit from these metal(loid)s.

Elements such as cobalt, nickel, selenium, thallium and some REEs are considered as critical owing to their limited availability and increasing demand. The high market price of these elements makes them ideal for phytomining. In the case of nickel and cobalt, phytoextraction can be applied to low-grade and agriculturally unproductive ultramafic soils, which naturally contain high concentrations

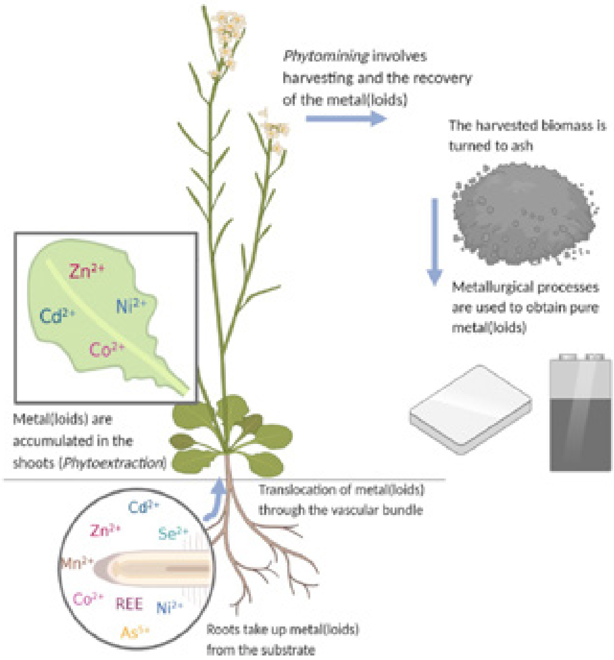


Figure 14. Main processes in phytomining. Figure created in Biorender.com and Mind the Graph platform.

of these elements and cover more than 3% of the Earth's surface. Phytomining can also be applied to seleniferous soils, where the prevailing concentration of selenium is high. These soils cover very large areas in Australia, the United States of America, and other countries. Worldwide, abandoned mining waste left without sufficient remediation could be considered a raw material for phytomining. Metal(loids) without a profitable market price (e.g. arsenic, cadmium) can also be phytoextracted from the waste to reduce toxicity, ultimately improving the soil geochemistry and allowing native plant succession and land remediation.

Cobalt is a critical commodity. Global demand for it is increasing, and the highest-grade ores occur in just one geographic location: more than 50% of the world cobalt supply originates from the Democratic Republic of the Congo, an area with considerable sociopolitical instability. Cobalt is used to build lithium-ion batteries for electric cars and is most often a by-product of copper and nickel mining. Phytomining of cobalt from current and abandoned mine would offer an alternative approach to obtaining the element. For example, the large-scale laterite nickel-cobalt mines in

Australia (Murrin Murrin), former cobalt mines in the Democratic Republic of the Congo (owned by the mining company Gécamines) and artisanal mining activities in Katanga all produce massive volumes of waste material with a suitable cobalt content. Hyperaccumulator plants *Haumaniastrum robertii* and *Berkheya coddii* are potentially good candidates for phytomining in these scenarios. The biomass yield of *H. robertii* is estimated to be up to 5 tonnes per hectare per year, containing cobalt on average at 5,000 mg/kg biomass, for an annual cobalt yield of 25 kg, which is worth US$1,350 (excluding production and processing costs).

REEs comprise 17 metallic elements (15 lanthanides, plus yttrium and scandium) which are widely distributed throughout the Earth's crust. Cerium, lanthanide, neodymium and yttrium are the most abundant. Recently, these elements have been used in a myriad of applications, such as green technologies, medical instruments and microfertilizers. The increasing demand for REEs has resulted in their limited future availability, and their potential future release to the environment poses a risk to numerous ecosystems. Phytoextraction can remove these elements from polluted soils, and phytomining can commercially produce high-value REEs.

The market price for REEs in the oxide form depends on the element and its purity. For example, cerium and lanthanide have low prices (~US$5/kg), whereas terbium and dysprosium are currently valued at more than US$200/kg. *Dicranopteris linearis* is a hyperaccumulator fern that can concentrate REEs at up to 3,358 mg/kg biomass in its fronds; however, it contains 47.5% lanthanide and just 6% dysprosium. Even though REE yields of up to 300 kg per hectare have been estimated for *D. linearis* (based on 15 tonnes of biomass containing REEs at 2,000 mg/kg biomass), REE phytoextraction using this particular hyperaccumulator is not currently economically feasible owing to the low price of lanthanide and cerium.

The use of hyperaccumulator plants for phytoextraction and phytomining offers a series of benefits, such as the natural concentration of the desired elements and the exclusion of unwanted elements. The economic feasibility of phytomining, however, depends on the ability to recover the metal(loid)s of interest from the harvested biomass. In most cases, the harvested biomass is incinerated to ash to obtain "bio-ore", which greatly increases the metal(loid) concentration. Most work has focused on nickel recovery, in particular from *Odontarrhena muralis, Rinorea bengalensis* and *Phyllanthus rufuschaneyi*, using either ashing or leaching of dry biomass followed by further refining to obtain pure metal, salts or nickel catalysts. *O. muralis* contains nickel at 20,000 mg/kg biomass, translating to 32 wt% nickel in the ash. *P. rufuschaneyi* has very low concentrations (0.1 wt%) of unwanted contaminants such as iron, chromium, silica and manganese. Recovery of REEs from *D. linearis* biomass has also been studied, including leaching processes and purification using ion exchange resins or selective precipitation. To date, no work has been undertaken to recover cobalt or thallium from hyperaccumulator biomass.

Phytomining is a unique and relevant technology that pairs resource acquisition with environmental remediation and low-waste resources. The many abandoned mine waste and metal(loid)-enriched soil localities globally may be strong candidate sites for the installation of hyperaccumulator plants. Phytoextraction and phytomining have been trialled in experimental settings; however, they require testing at field scale to assess their broad-scale commercial potential.

As these practices continue to grow in technical importance and require greater donor interest for upscaling, phytoextraction and phytomining may be important avenues for encouraging investment within the innovation aspects of GEF proposals. The cultivation of specific kinds of plants that are well suited for phytomining could be supported through GEF projects both for ecologically sensitive land restoration as well as for boutique commercial extraction of key metals for green technologies.

4.5 OCEANIC MINERALS

Given the rapid rise in demand for minerals and the declining ore reserves on land, attention is turning to potential extraction of marine mineral deposits. While coastal marine mining for diamonds and for mineral sands has been undertaken for some decades, deep sea mining is still in the early stages of development. The Law of the Sea Convention established the International Seabed Authority to issue licences for mineral exploration. A key requirement of these licences – and of specific relevance to GEF projects – is that all private ventures (contractors) must partner with a country that is a party to the Law of the Sea Convention. In some cases, the countries are small island developing States, such as Nauru, which have established their regulatory bodies and, in some cases, invested in exploration companies.

However, the environmental impact of oceanic mining remains widely contested,[7] and as the process of environmental regulation is formulated by the International Seabed Authority in coming years, attention will need to be paid to the following key issues:

- Sediment dislocation and plumes being generated by mining activity
- Impact of mining activity and noise on biodiversity
- Potential release of deep-sea carbon through extractive activity
- Impact of mining on fisheries and resultant livelihoods

Oceanic mineral extraction, however, does have technical advantages over terrestrial mining: reduced waste and water usage for processing; lower carbon footprint for processing; and much less social impact on communities in terms of physical displacement and adverse effects on local livelihoods (Paulikas et al., 2020).

Three main kinds of oceanic mineral deposit are being considered for extraction owing to their comparative ease of extraction and given their economic-ecological cost balance: (a) polymetallic nodules, (b) cobalt-rich crusts (which occur on some, but not all, seamounts) and (c) sea floor massive sulfides (which are sulfide deposits from extinct hydrothermal vents). Much of the International Seabed Authority interest is currently focused on polymetallic nodules in the Pacific Ocean, details regarding which are provided in figure 15.

Preliminary comparative analysis of the carbon footprint of terrestrial and oceanic mineral processing, as well as the waste generation and water generation potential calculated by contractors approved by the International Seabed Authority, is provided in figure 16. Scaling the as-is per-kilogram global warming potential results to the total metal needed for one billion electric vehicles yields a total static global warming potential scenario value for each source: 1,749 metric Mt CO_2-equivalent for metals produced from land ores, versus 445 metric Mt CO_2-equivalent from nodules.

As concerns mount about ocean governance and protection of the high seas, the GEF may well be called on to consider the intersectionality of its conservation activities with such extractive industries. Furthermore, GEF projects in small island developing States may need to consider oceanic minerals, as many small island developing States have very large exclusive economic zones and are trying to balance extraction revenues in these areas with conservation efforts. Projects that include environmental monitoring to help realize any win-win opportunities in these areas may be plausible within the next decade.

7 For a recent summary of the environmental concerns related to deep sea mining, refer to the High Level Panel for a Sustainable Ocean Economy's Blue Paper, released in June 2020: Haugan et al. (2020).

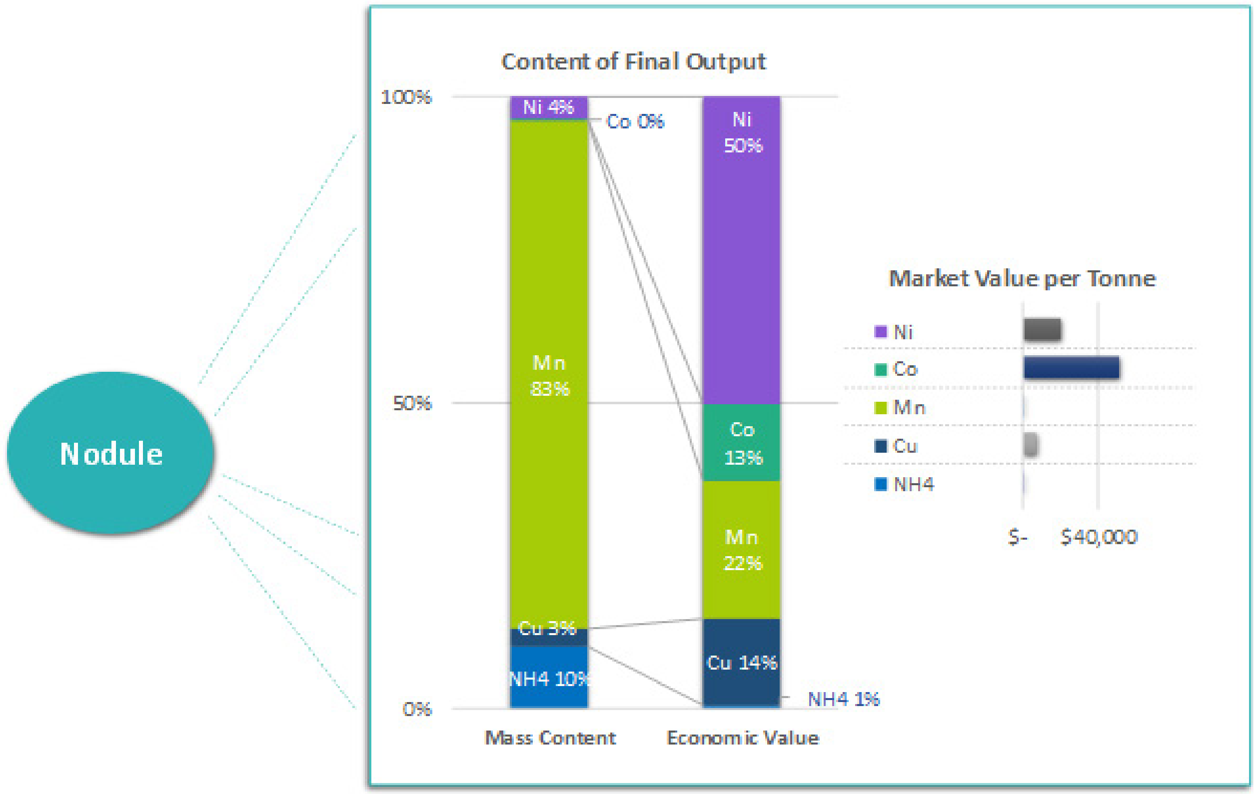


Figure 15. Approximate critical metal content of oceanic nodules from Clarion-Clipperton zone. (Source Paulikas et al, 2020)

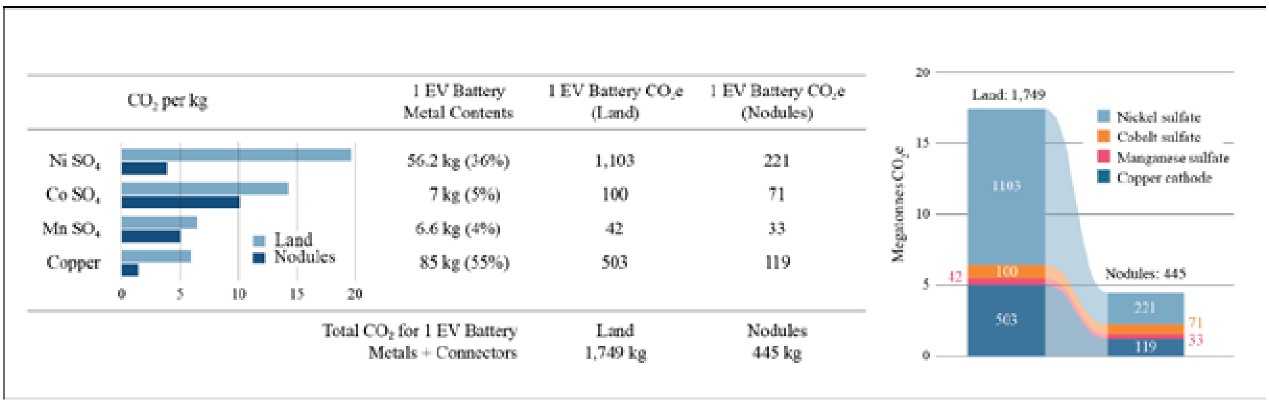


Figure 16. Per unit comparison of carbon dioxide emissions for electric vehicle battery production from land and seabed sources (left) and aggregate emissions comparison for 1 billion electric vehicle forecasts (right). Source: Paulikas et al., 2020).

Mary Kathleen Mine in Queensland. Dr. Antony van der Ent

5. CONCLUSION AND RECOMMENDATIONS

A review of past and current GEF projects (see Appendix 4 for information on the review process) reveals that much of the interface with metal extraction and its environmental impact has been in projects under the Minamata Convention related to cleaner techniques for gold ASM, which has used mercury for amalgamation purposes. There are over US$50 million of country-level capacity-building projects in this arena, spanning several countries.

The fieldwork capacity being developed in gold ASM by GEF Member States and implementing agencies could also be applied to TCE ASM projects in countries such as the Plurinational State of Bolivia, Brazil, the Democratic Republic of the Congo, Peru and Rwanda (some of the key countries where TCE small-scale mining is continuing at a high rate). The GEF's basin-wide programmes in the Congo and the Amazon also intersect with numerous TCE extraction sites and regions.

Furthermore, the following GEF programmes and concepts have potential to link with the TCE sector:

- Global Programme to Support Countries with the Shift to Electric Mobility (with particular reference to battery recycling interface and infrastructure to improve the circular economy of metals)
- Strengthening of the blue economy (with particular reference to the impacts and benefits of exploring oceanic minerals)
- Global Cleantech Innovation Programme (GCIP) to accelerate the uptake and investments in innovative cleantech solutions (with potential focus on cleaner metal sourcing and processing for green renewable energy infrastructure)

5.1 GOVERNANCE REFORM: INTERNATIONAL PROTOCOL BETWEEN TREATIES ON MINERAL GOVERNANCE

The extractive sector has potential to act as a catalyst for development in mineral-rich countries, but many challenges prevent this potential from being fully realized. Relevant challenges to governance include illicit financial flows; lack of transparency and accountability and the associated risk of corruption; political instability; global asymmetries of power and conflicting stakeholder interests leading to social conflict; and conflict between formal and informal mining activities (UNEP, 2019).

Key governance gaps include unintended consequences of governance instruments that undermine the sustainability of mining; lack of buy-in to existing instruments; lack of compliance with existing instruments; uneven focus of current instruments relative to the broad range of issues confronting the extractive sector as a whole; proliferation of standards concerning different aspects of mining sustainability; and the lack of a coherent and collective theory of change (UNEP, 2019).

To bridge those gaps, the United Nations Environment Programme (2019) advocates for the development of a new governance framework that involves all actors in the extractive sector and whose implementation is a shared responsibility by host and home countries along the extractive value chain. The framework should integrate all pillars of sustainable development – people, planet, prosperity, peace and partnership – and set out principles, policy options and good practices for enhancing the extractive sector's contribution to achieving the Sustainable Development Goals. According to the United Nations Environment Programme, the new framework should embrace a holistic approach to decouple mining from environmental and social impacts; aim to protect human rights to minimize impacts, allow greater engagement of the home country, promote responsible business practices, balance security of supply concerns, promote access to data, and ensure that information and knowledge is available transparently to all stakeholders to encourage trust.

At the next United Nations Environment Assembly in 2021, mineral governance is on the agenda for action, as a consultation process is currently under way following the passage of a resolution introduced by Mexico at the 2018 Assembly. Follow-up activity from this should be monitored as it may provide direct opportunities for the GEF to incorporate project activities related to TCE supply chains. The STAP sees new scientific advancements in the extraction, recycling and processing of TCEs as an important area of inquiry ensuing from our earlier work on novel entities of relevance to the GEF, and we will endeavour to keep the Council and the Secretariat duly apprised in this regard.

5.2 EMERGING TRENDS

Fast emerging technologies that use TCEs, such as electric car batteries, solar panels, wind turbines, communication devices and military applications, are expected to drive tremendous growth and demand for these metals in near future. While efforts are being made to search for new TCE resources not only on land but also in ocean bottom sediments, there is a great need to develop, and meticulously follow, sustainable exploitation schemes for all kinds of TCE ore deposits. Ecosystems damaged and degraded by TCE extraction will take a long time and cost a great deal of money to restore. Therefore – as part of the sustainable development of the TCE industry – life cycle assessment should be employed to ensure that the actual environmental footprint of TCE processing is known and mitigation measures are developed.

Circular economy principles such as eco-design; recycling, refurbishment and reuse; and development of secondary sources of minerals and metals are considered promising options for the near-future TCE supply. The amount of TCEs recycled from e-waste is not yet significant, attributable to low critical element concentrations in waste flows, dissipative applications, and the critical element being a minor composition in a complex material matrix, among other factors. Although several studies have been initiated to find good substitutes for TCEs in different technologies, more emphasis should be placed on these research and development efforts to draw away from total reliance on TCEs.

The widespread application of TCEs in different industries as well as agriculture is expected to increase the concentrations of these elements in the environment, which would disturb not only aquatic systems but also plant and soil ecosystems, leading to a range of human health issues. Close monitoring, therefore, is needed at places where phosphate-based fertilizers are used, in areas where soil conditions are favourable to TCE mobility, where there is availability and uptake by plants, and at e-waste dump sites where surface run-off could contaminate the local environment. Extensive use of TCEs in day-to-day life requires the development of human, as well as technical, capacity to undertake toxicological assessment of these elements from a human health perspective.

5.3 RECOMMENDATIONS

The world depends on TCEs for many technologies that are beneficial to the development of humankind. However, many TCE-containing products, such as electric cars, wind turbines and solar cells, contribute to climate change mitigation. The mining and processing of TCEs, as well as the disposal of TCE products, could negatively impact the GEF's work in the areas of biodiversity, land, forest, international water and food security. Since the GEF is funding projects that use TCEs, a possible role for the GEF could be to help direct the course of the technology used in such projects to ensure that it does not result in negative environmental impacts. In addition, the GEF could play following roles:

- Supporting policies and actions that promote the sustainable extraction of TCEs, including through developing alternative or substitute technologies that reduce the environmental damage from mining, refining and recycling TCEs, or that lessen overall dependence on TCEs.

- Facilitating the improved design of TCE products so that they more effectively use the elements.

- Improving the process of recycling component TCEs, in part by promoting circular economy approaches and life cycle assessments.

- Supporting efforts to quantify the demand for, the material and energy needs of, and the environmental implications of emerging applications that could increase global dependence on TCEs, such as magnetic refrigerators or next-generation LED lighting.

- Raising awareness of the possible environmental and health impacts of continued unsustainable production and consumption of TCEs.

- Collaborating with and supporting partnerships aimed at ensuring sustainable TCE production and consumption, including public-private cooperation.

Furthermore, the GEF should consider the following recommendations:

- Given the ability of some plants to adapt to high-metal soils and hence be used for metal extraction and land restoration, GEF projects should consider conservation of such plants as well as afforestation of these plants in degraded soils. Encouraging investment in phytomining may be important as the practice grows in technical importance and requires greater donor interest for upscaling.

- Given the criticality of TCEs, GEF projects should consider encouraging infrastructure and project development to facilitate future recycling of TCE stocks.

- The GEF may also encourage the application circular economy approaches; for example, where recycled TCEs are preferred over virgin TCEs, where smaller quantities of TCEs are used in technologies, and/or where TCE-containing products have prolonged life.

- GEF projects in small island developing States may need to consider oceanic minerals as many such States have very large exclusive economic zones and are trying to balance extraction revenues in these areas with conservation efforts. Green mining approaches should be promoted.

- GEF projects in climate change mitigation and adaptation, food security and e-mobility should employ life cycle assessment to identify the impacts of TCE extraction, use and disposal and develop mitigation measures. Life cycle assessments are distinct from risk assessments and require different expertise and metrics.

- GEF projects should be encouraged to conduct environmental risk assessments to identify and minimize impacts on human health.

- The GEF should consider uncertainties associated with the scarcity of TCEs, through supply chain risk assessment, as this could impact the durability of GEF-funded project activities such as renewable energy, e-mobility and food security.

- TCE mining activities embedded in GEF projects should be subject to responsible mining methods and to comprehensive socioecological assessments that ensure local biodiversity and social impacts from their operations are considered and improved.

These recommendations are based on a consultative process conducted with a range of stakeholders (see Appendix 5 for a list of participants). Given the context of the COVID-19 pandemic, other areas of technology metal needs and constraints will require further study. For example the resilience in livelihoods provided by widespread internet telecommuting requires substantial material infrastructure such as underwater cables across the oceans and energy-intensive server farms. As the next phase of GEF funding matures, there will undoubtedly be a need to keep track of our growing material needs for such elements.

Electric vehicle charging station.
3D rendering. Nerthuz

Solar power plant aerial drone photo. Sebastian Noethlichs

APPENDIX 1. LIFE CYCLE ASSESSMENT OF TCEs

TCEs continue to gain importance in many new energy technologies and systems, and with the drive to reduce greenhouse gas emissions, the demand for TCEs will keep increasing. The production of TCEs is energy and material intensive and heavily polluting. A comprehensive understanding of the environmental impacts of TCE production is needed. Life cycle assessment is the most widely used method for evaluating environmental sustainability. However, very few life cycle assessment studies have been conducted on TCEs (Awuah-Offei and Adekpedjou, 2011; Navarro and Zhao, 2014). This may be attributed to lack of knowledge and data on many factors, for example human toxicity, ecotoxity and freshwater aquatic ecotoxicology of TCEs (Nuss and Eckelman, 2014; van der Voet et al., 2013). In addition, the fate of TCEs in the environment and their impacts are generally site specific and can therefore be difficult to quantify using generic fate-transport models (Goedkoop et al., 2009; Rosenbaum et al., 2008).

Further studies on life cycle assessment and life cycle inventory are needed to better understand the environmental footprint of TCEs. A comprehensive and transparent life cycle assessment database would support efforts on greening TCE extraction and inform policymaking on how to minimize the environmental impacts of TCEs throughout their life cycle.

APPENDIX 2. RISK ASSESSMENT OF TCEs

In addition to life cycle assessment, two other types of assessment may be of interest to the GEF: supply chain risk assessment and environmental risk assessment.

As global TCE demand is increasing at a fast rate, the risks to supply chain disruptions are high. For example, the cobalt market is highly concentrated, with more than half of all cobalt being mined in the Democratic Republic of the Congo and almost half of all cobalt being refined in China. Almost all cobalt is mined as a by-product of copper and nickel, and political stability in production countries is considered to be medium to very weak (van den Brink et al., 2020). Carrying out risk assessment on the supply chain of TCEs is vital to ensure the durability of those GEF projects that depend on the availability of TCEs and REEs.

Environmental risk assessments examine processes, emissions, the spread of contaminants and the potential exposure of humans and biota to those contaminants, among other factors. As shown in section 3.6, exposure to REEs and TCEs may negatively impact human health. Environmental risk assessments, in addition to identifying risk to the environment, are therefore important in identifying human health risks associated with the extraction, processing and use of TCEs.

Haut-Uélé in Congo. Sebastian Pennes

APPENDIX 3. TAILINGS, ACID MINE DRAINAGE AND RADIATION MANAGEMENT

TAILINGS MANAGEMENT

Tailings may cause different environmental footprints, both spatially (storage area) and temporally (long timescales over which tailings must be managed and rehabilitated) (DITR, 2007). Collapses of tailings or waste-rock management facilities can cause severe environmental damage – and even loss of human lives (Diamond, 2005). Tailings ponds can also be a source of acid drainage.

The most common methods of managing tailings include discarding slurried tailings into ponds (European Union, 2009); backfilling tailings or waste-rock into underground mines or open pits or using them for the construction of tailings dams; dumping waste-rock or dry tailings onto heaps or hill-sides; using the tailings and waste-rock as a product for land use (e.g. as aggregates or for restoration); dry-stacking thickened tailings; and discarding tailings into surface water (e.g. seas, lakes, rivers) or groundwater.

Promoting a transformative change in the mining industry aimed at including circular economy practices in waste management could reduce liability and increase the economic value of waste materials generated by these activities. One example of a project in operation is that of New Century Resources, which has developed an economic rehabilitation plan in Queensland, Australia, that integrates mined land rehabilitation and tailings reprocessing for zinc recovery (Tayebi-Khorami et al., 2019).

ACID MINE DRAINAGE

There are two types of acid mine drainage treatment technology: active treatment and passive treatment. Active treatment technologies require the input of energy and chemicals, for example the addition of limestone (calcium carbonate), hydrated lime or quicklime addition of caustic soda for Acid Rock Drainage with a high manganese content. Passive treatment uses only natural processes, such as gravity, microorganisms and/or plants in a system; for example, in constructed wetlands, open limestone channels or anoxic limestone can drain diversion wells. Passive treatment systems are a long-term solution after the decommissioning of a site, but only when used as a polishing step combined with other (preventive) measures (Skousen, Hilton and Faulkner, 2011).

RADIATION MANAGEMENT

Some TCE minerals contain significant amounts of radioactive elements, such as uranium and thorium, which can contaminate air, water, soil and groundwater (IAEA, 2011). It is necessary to manage radioactive waste to protect human health. The ultimate goal of radioactive waste management is the restraint and seclusion of waste from the human environment for a period of time and under conditions such that any release of radionuclides does not pose unacceptable radiological risks to people or the environment (Valdovinos, Monroy-Guzman and Bustos, 2014). For waste materials that contain radioactive or toxic constituents, three basic options are available: permanent disposal, unconditional reuse and conditional reuse. Each of these options requires a specific approach (Öko-Institut, 2013).

However, where waste contains short-lived radionuclides in small concentrations within prescribed limits, the waste should be diluted with other mined material before it is disposed of to ensure that in the long term the use of the disposal site is not restricted (Government of Western Australia, 2010; India, Atomic Energy Regulatory Board, 2007).


TCE ore processing sluice in Uganda. Alex Tyson

APPENDIX 4. PROCESS FOR THE REVIEW OF CURRENT AND PAST GEF PROJECTS RELATED TO TCEs

A total of 98 GEF projects were identified as relevant to TCEs, with 37 of them being completed projects, 28 being under implementation and the remaining 33 being under approval stages. From the total number of projects, the great majority corresponded to the Climate Change focal area and then in a smaller number to the Chemicals and Waste area, with only very few under biodiversity, MFA or "POPs" categories.

These projects were then classified into three larger categories: Electric mobility, Solar and Wind Energy, and Mining. Within the latter of the categories, all 17 projects included in it, are focused on gold mining and control of mercury release whether it is from a biodiversity, international waters or multi-focal area approach. The Minamata Convention was mentioned in all of them as this agreement focuses precisely on eliminating human-related releases and emissions of mercury. Regarding the first two categories the Minamata Convention was not highlighted or mentioned as a reference agreement. Most of these projects linked more to barrier removal and/or implementation rather than to mining or element extraction.

By the GEF's 6th Replenishment Period a 141 million resource envelope was made available under the Minamata Convention, enabling countries to have rapid access to two forms of important support: the Minamata Convention Initial Assessments (MIA) and the National Action Plans (NAPs) to enable developing countries to prepare to meet their obligations with regard to artisanal and small-scale gold mining (1). In February of 2019, the GEF-backed Global Opportunities for the Long-term Development of the ASGM Sector (GEF GOLD) Programme was launched spanning to eight countries as a five-year programme. The GEF has presented three reports to the Conference of the Parties to the Minamata Convention reporting its mercury-related activities and funded projects (2,3).

1. https://www.thegef.org/news/minamata-convention-mercury-and-global-environmental-facility-partners-start

2. https://www.thegef.org/news/minamata-convention-meeting-focuses-ways-makemercuryhistory

3. https://www.thegef.org/sites/default/files/documents/GEF%20Report%20to%20Minamata%20COP%203%20Final%20Sept%205%202019.pdf

APPENDIX 5. STAP'S TECHNOLOGY CRITICAL ELEMENTS VIRTUAL WORKSHOP PARTICIPANTS; 29-30 APRIL 2020

The Scientific and Technical Advisory Panel appreciates the contribution to this report provided through the Technology Critical Elements Workshop by the following participants:

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Estelle Levin-Nally	Levin Sources
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Takuma Watari	NIES
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Daniele La Porta	World Bank
John Drexhage	World Bank
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Barbara Reck	Yale University

Acacia sp. growing in tailings of tungsten and molybdenum in north Queensland, Australia. Amelia Corzo Remigio

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