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Photo: Marija Ostojic is an artist and media designer whose practice explores identity, migration, and social transformation across painting, film, and participatory formats. This work is part of an exploration of transformation as a complex process that unfolds both internally and externally - not linear, but chaotic, contradictory, and open. Colour carries tension as it accumulates, overlaps, and breaks apart. Transformation does not appear here as a clear before and after, but as a continuous state of becoming.

Further works can be found on Instagram: @mar.i.jaaa.

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André Baumgart

The sustainability dilemma of decarbonisation: Green extractivism and the toxicological burden of critical raw materials

Abstract *Efforts to cut emissions depend on critical raw materials for technologies like electric vehicles and wind turbines, creating a spatial disconnect where demand in high-income countries drives production in global peripheries. This green extractivism involves ever-increasing extraction and processing that release hazardous materials, contaminating soil and water. The resulting health consequences for rural and working-class communities occur via direct exposure or consumption of local food and water. On a qualitative synthesis of peer-reviewed literature, this study traces toxicological effects along the supply chain and explores circularity measures to reduce demand and toxic impact, using China as a case study.*

Keywords *green transition, critical raw materials, health hazards, ecologically unequal exchange, rare earth elements*

1. Introduction

To meet the 1.5 to 2 °C climate targets of the 2015 Paris Agreement (UNFCCC 2016), the global shift toward green energy has accelerated, fostering investments in green energy across sectors (UNEP 2024). While the energy transition is essential in reducing operational carbon emissions arising from fossil fuel combustion, it is not burden free. Transition-relevant technologies rely on particular resources, the demand for which has consequently sharply increased in recent years.

The term 'critical', used in both critical raw materials (CRM) and technology-critical elements, is ambivalent in its meaning, referring both to the crucial role of materials in novel, transition-relevant technologies, and to the vulnerability in complex international supply chains due to geopolitical relations and resource scarcity (Cobelo-García et al. 2015). CRM thus combine high economic importance, relevance for the green and digital transition, with the high risk associated with their supply (European Parliament 2024). However, criticality is not merely a matter of risk, as it is also a question of political economy. The benefits of CRM consumption accrue primarily in industrialised economies where final products containing CRM are predominantly utilised and demand is highest, while the environmental and health costs of extraction are concentrated in producing regions, often located in the Global South. CRM can be hazardous when accumulated in the environment and can both disrupt ecological processes and be dangerous to human health; however, research on toxicological effects is still emerging but has increasingly gained scientific and public attention.

As visualised in Figure 1, the risk of exposure to critical materials occurs throughout the materials' life cycle, either directly, through occupational exposure during mining, processing, and waste treatment activities, or indirectly, through the uptake of materials that have accumulated in soil and water.

2. Theoretical framework and scope

Here, the political economy of critical raw materials is examined through the lens of green extractivism and ecologically unequal exchange. Green extractivism describes the intensification of resource extraction as justified by the imperative of climate mitigation, in which the discourse of sustainability is mobilised to legitimate the socio-ecological 'sacrifices' demanded of resource-rich 'peripheries' (Bruna 2022: 841; Dunlap et al. 2024: 446). Originating in world-systems theory, ecologically unequal exchange refers to an asymmetric transfer of environmental burdens from 'core' consuming nations to peripheral producing regions where resource extraction, raw material processing and waste disposal are largely located, and consequently where health and environmental hazards accrue, while value generation occurs mostly elsewhere (Hornborg/Martinez-Alier 2016; Wallerstein 1974). As Milanez and Garcia (2023) argue in the context of

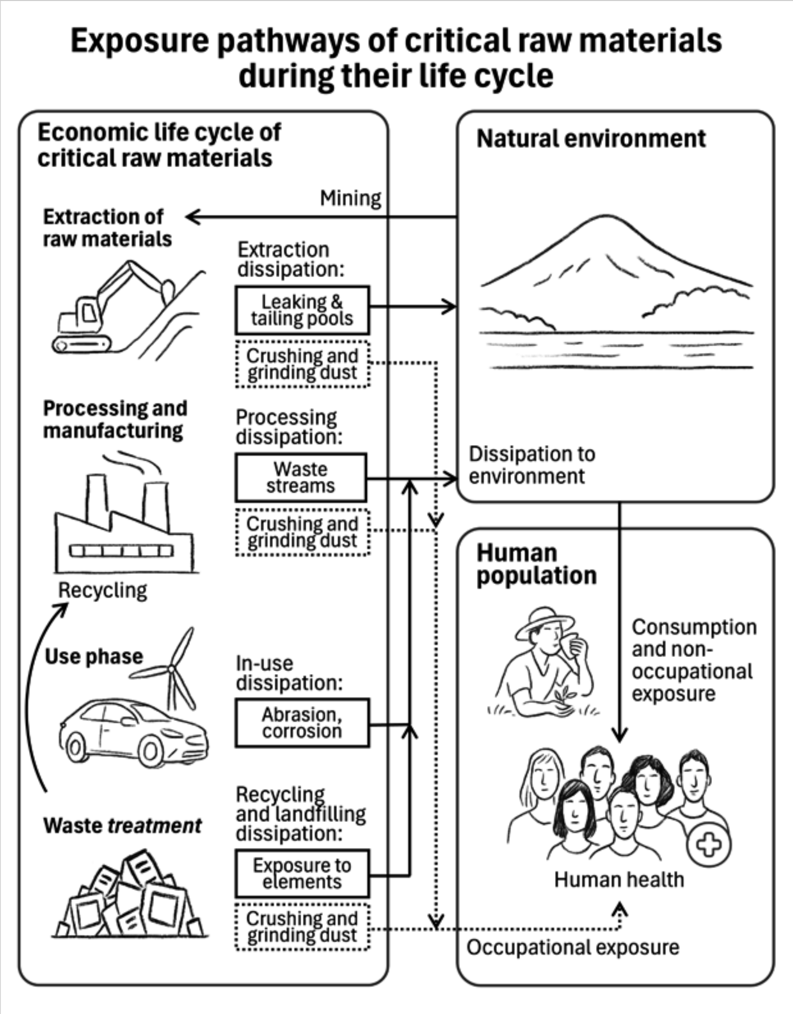

Figure 1: Schematic overview of the life cycle of transition-relevant critical materials and their dissipation pathways to the environment and human population. Source: own illustration, 2026

Latin American extractivism, the undervaluation of natural resource flows and the transfer of environmental costs from core consuming nations to peripheral producing regions grant industrialised economies a disproportionate use of ecological systems while imposing environmental damages on the Global South. This is a dynamic that mirrors, for example, the relationship between China's rare earth mining regions and the distant consumption centres that benefit from these materials.

Against this theoretical backdrop, it can be argued that the current model of CRM extraction required for the green transition reproduces neocolonial patterns in which the socio-ecological burdens of decarbonisation, i.e., the replacement of fossil fuels with renewable energy sources, are externalised to peripheries. Methodologically, this paper draws on a qualitative synthesis of peer-reviewed literature, integrating findings from across multiple disciplines, including political ecology, industrial ecology, and public health, to connect questions of future material demand, exposure pathways, toxicological effects, and inequality.

In the following, the focus is on the case of China, which represents two different nodes in the global supply chains of critical materials, namely material extraction and processing. At the same time, China is a significant driver of extraction, having high demand in CRM itself, thus representing the so-called 'semi-periphery', showing both core (e.g., higher value-added production) and periphery (e.g., material extraction, low-wage manufacturing) characteristics (Chu et al. 2025; Wallerstein 1974). China's mining industry has a significant share in the global extraction and processing of various critical raw materials, including lithium and rare earth elements (REE), also known as lanthanides, a group of elements occurring in the Earth's crust which are used in a variety of applications, ranging from the production of permanent magnets and green energy technologies, to robotics and defence applications. China is a key actor in the production of batteries and other technologies enabling the decarbonisation of mobility and electricity production on a global level. Potential public health and environmental effects of exposure and environmental contamination can, to some degree, be considered universal. Consequently, while focusing on China, selected studies that are not exclusive to China, but which demonstrate the underlying mechanisms by which CRM production is associated with hazardous materials being mobilised in producing countries of the Global South, are also drawn upon. Previous studies have examined environmental and health effects of CRM, supply chain vulnerabilities, and dissipation pathways (Ciacci et al. 2015). Others have explored future CRM demand and losses in circular economy and decarbonisation scenarios (Baumgart et al. 2024; Gaustad et al. 2018; Haas et al. 2025). Here, first, an overview of the application of selected CRM, their anticipated demand and environmental accumulation is provided. Secondly, toxicological risks associated with exposure are discussed. Third, this tension between the decarbonisation enabled by emerging technologies and the environmental, and social burdens associated with the materials they contain in the wider context of ecologically unequal exchange and green extractivism are discussed. Lastly, measures that have a potential mitigating effect on resource consumption are explored.

3. Materials in emerging technologies and their accumulation in the environment

From the decarbonisation of the vehicle fleet and of electricity production to the onset of digitalisation, and to widespread use in scientific and military equipment (USGS 2025) – CRM are a vital aspect of the transformation of material stocks required for a more sustainable future. However, the geographical distribution of this material transformation is profoundly uneven. While the demand for green technologies is concentrated primarily in the Global North, the extraction and initial processing of essential minerals are concentrated mostly in the Global South, and, particularly in the case of REE, in China. This section outlines the sectors and products driving future demand in critical materials and details how losses of material to the environment may occur during the various stages of product life cycles, with particular attention to hotspots of critical material extraction and processing in China.

3.1 Rising global demand for critical raw materials and reinforcement of core-periphery dynamics

CRM are crucial for the green energy transition. They include silicon, indium, gallium, and tellurium in silico- and thin-film photovoltaic technologies, and REE such as neodymium and dysprosium in permanent magnets for energy production and e-mobility. Global REE demand is projected to almost double to 176,000 metric tons by 2040, while the market value of transition minerals, including lithium and REE, is estimated to rise from 300 to nearly 800 billion USD. The installed capacity of photovoltaic and wind power is expected to reach 30 terawatt by 2050, while the electric car fleet may exceed 250 million vehicles by 2035 (IEA 2024b, 2025).

According to this Joint Research Centre analysis of supply chains, between 62 and 72 percent of CRM required for data transmission networks, data storage products, personal electronic devices, lithium batteries, solar photovoltaic, wind turbines, and traction motors are extracted in China, Africa, or Latin America, with China being by far the largest producer (Carrara et al. 2023: 84). This concentration reflects historical patterns of resource extraction established under colonialism and perpetuated through contemporary trade regimes. In past centuries, colonial powers structured economies in peripheral regions around the large-scale extraction and export of raw materials, while industrial production and value-added activities were concentrated in core regions, creating a core-periphery division of labour in the global economy, in which resource-rich regions were integrated as suppliers of primary material commodities rather than as sites of diversified industrial development (Hornborg/Martinez-Alier 2016).

Below, the focus is on the light REE neodymium, praseodymium, dysprosium and lanthanum, as well as tellurium and lithium, all of which are central to e-mobility and renewable energy. The former three are found in permanent magnets used in electric vehicle drivetrains, wind turbines, and various electronics. Tellurium is key for cadmium-telluride thin-film photovoltaic panels, currently constituting seven percent of the solar market, with an expected growth trend (Nuss 2019), while lithium is currently indispensable for lithium-ion batteries and energy storage. Supply of these CRM is highly concentrated, with neodymium and tellurium mainly extracted and processed in China, with market shares between 60 to 70 percent (Hoenderdaal et al. 2013: 349; USGS 2024b: 179). Dysprosium is virtually exclusively mined in China. While lithium production has for a while been dominated by Australia and Chile, China currently produces around a fifth of global lithium, thus ranking second (USGS 2024a).

3.2 Material dissipation during production

Growing demand for green technologies increases CRM extraction and processing, leading to material losses throughout their life cycles. Such losses can occur during mining, processing, product use, or disposal, and may dissipate through leaching, abrasion, or corrosion. Contaminated wastewater can infiltrate soils and waterways, while fine particles disperse through air and rainfall, spreading material into surrounding environments. Improper handling or weathering of products, such as damaged photovoltaic panels, can further release CRM during use or at end-of-life.

Dissipation during material extraction

In China, the mining of CRM is associated with significant losses of material to the environment. In REE mining, topsoil is removed and leaching pools are established where chemical processes isolate extracted minerals from soils. In these ponds, material from ore or tailings can leak and contaminate water and soils (Cho 2023). REE mining produces large amounts of tailings – waste by-products of ore processing, which may contain REE, radioactive material such as thorium and uranium, salts, and chemicals, stored in tailing ponds that further contaminate soils and groundwater (Bai et al. 2022; Cho 2023). Abandoned tailings in soils around mining sites can contain significant REE and other CRM, as shown in Shuimochong in Anhui, China, where average observed tellurium concentrations were three orders of magnitude above average crustal tellurium abundance (Qiao et al. 2025: 10). It is estimated that around 90 percent of tellurium is lost to tailings, which, if abandoned to weathering, can release tellurium to the environment. For example, lakes around copper mining sites also show increased concentrations (Nuss 2019: 246). REE pollution in Jiangxi Province, China, was found not only in tailing soils but also in stream waters, sediments, and farmland soils. Strong leaching and transport were linked to heavy rainfall and poor soil water retention, with particularly high mobility for light REE such as neodymium, praseodymium, and lanthanum (Liu et al. 2019).

Dissipation during material processing and manufacturing

During post-mining mechanical and chemical processing, fine-particle CRM dust can form. Ores are crushed and ground to fine particles, with magnetic and electrostatic separation further reducing particle size and liberating airborne REE minerals. At Baotou in Inner Mongolia, China, the largest REE processing site, portable particle sampling showed REE concentrations, including neodymium and praseodymium, 100 to 400 times higher in workers than in a control group, indicating elevated occupational exposure (Qiao et al. 2022: 3). Dissipation also occurs via waste streams with significant shares of permanent magnets containing REE being scrapped during manufacturing, often ending up in landfills, where they are exposed to weathering (Weber/Reisman 2012). Losses occur for tellurium as well, with ~18 percent not incorporated into final products or recycled scrap. Since tellurium primarily originates from anode sludge during copper refining, around 55 percent is lost in this phase, with another 10 percent lost during conversion of copper telluride into non-electronic products (Nuss 2019: 244f.).

In-use dissipation

During use, dissipation varies by material and product. In vehicles, permanent magnets in motors and components can release particles through abrasion and corrosion, leading to small REE losses from motors, autocatalytic converters, batteries, and tyres (Baumgart et al. 2024: 5; Ciacci et al. 2015; Mleczek et al. 2021). For photovoltaic panels, rainfall can mobilise small amounts of tellurium if panels are damaged or improperly assembled, affecting cadmium-telluride thin-film cells in particular (Nain/Kumar 2020; Zapf-Gottwick et al. 2015). Lithium is generally stable within lithium-ion batteries, but damaged or exposed cells may leach to the environment (Mrozik et al. 2021). Although in-use dissipation is comparably small and consequently one of the least-studied source of dissipation, it often occurs in densely populated areas, posing potential exposure risks despite limited overall material loss (Baumgart et al. 2024).

Dissipation during waste treatment

While recycling of CRM is preferable over mining due to its reduced environmental impact (Weber/Reisman 2012), material is nevertheless lost to the environment. Mechanical dismantling and shredding that occurs during the recycling of REE-containing products that have reached their end-of-life (for example, electric motors and electronics) can generate dust that may contain hazardous components (ibid.). Similarly, during lithium-ion battery production, airborne particle matter can be released during disassembly and recycling processes, with shredding identified as the main mechanical processing activity generating lithium-containing dust emissions (Mrozik et al. 2021). Due to organic degradation, landfill sites are typically highly acidic. This in turn enhances the solubility of REE and leads to the potentially high mobility of dissipated material (Gutiérrez-Gutiérrez et al. 2015). Likewise, degradation at landfills and dumpsites can also lead to lithium losses to the environment (Mrozik et al. 2021). A large percentage of waste containing CRM is currently shipped to low-income countries of the Global South, where they are often recycled using informal processes that may include manual dismantling, open burning and de-soldering, and open-vessel acid leaching. Such processes are usually uncontrolled and can have significant implications for human health and the local environment (Weber/Reisman 2012), thereby thwarting potential environmental benefits of recycling. China, once the largest importer of e-waste globally, in 2000 implemented regulations effectively banning e-waste imports due to growing concerns over environmental pollution and human health risks associated with informal recycling practices, although subsequent illegal shipments of e-waste from the European Union and other high-income regions to the e-waste recycling hubs of China have been reported (Illés/Geeraerts 2016; Palmeira et al. 2018). Even today, Guiyu in Guangdong province is one of the largest informal e-waste recycling centres in the world, with severe toxicological implications (Li et al. 2024; Xu et al. 2012).

4. The burden of the green transition: Toxicological risks of critical material accumulation in the environment

Material lost along the material life cycle eventually accumulates in the environment and is in practice lost for further socio-economic utilisation. In the environment, dissipated materials and elements were shown to have the potential to alter or disrupt ecological and biological processes. Further, direct as well as indirect exposure – the latter through uptake from plant matter and water – were shown to be potentially hazardous for human health in various regards. In the following section, these possible impacts are briefly outlined.

4.1 Toxicological impacts on ecological health

General environmental concentrations of REE are often considered too low to cause harm, but hotspots near mines or wastewater plants can reach ecotoxic levels, such as in the case of the world's second-largest light REE mining site in Maoniuping in Sichuan province, China, where significant light REE concentrations have been detected in surface water (Wang et al. 2024). Laboratory experiments showed that high REE exposure, including lanthanum, were shown to cause DNA damage, suppress repair mechanisms, and activate the cell death of zebrafish (Kang et al. 2022). Likewise, impairment to the reproduction of marine invertebrates such as Mediterranean mussels was reported (Freitas et al. 2020), while local conditions such as acidity were shown to amplify negative effects on other species (Siciliano et al. 2021; Vukov et al. 2016). Studies on aquatic flora have shown that lithium content in various fish species present around mining sites along the Jinjiang river was nearly tenfold that of fish in up- and downstream river sections (Yang et al. 2024). While research on the toxicological effect of lithium on aquatic life in China is lacking, long-term lithium exposure was shown to cause mortality and genetic damage in amphibians near Chilean mining sites (Peltzer et al. 2024). On land, REE accumulation in soils can stunt crop growth: neodymium and lanthanum, beneficial at low doses, become toxic at higher concentrations, inhibiting root development in rice (Rezaee et al. 2018; Shi et al. 2021; Sun et al. 2022). High concentrations of lithium in soil were shown to lead to metabolism depression and other toxic effects in various cultivated plants as well as in earthworms (Xu et al. 2023). Toxicological risks also stem from the co-extraction of hazardous elements. Neodymium mining often mobilises radioactive thorium and uranium (Periyapperuma et al. 2021), while lithium extraction is linked to elevated heavy metal levels, as is the case in the Jiajika mine in Sichuan province (Gao et al. 2021). Overall, CRM affect multiple ecological compartments, yet thresholds remain understudied. Without reductions in global demand for CRM and technology-critical elements, the ecological burden of CRM production is expected to further increase sharply (Langkau/Erdmann 2021)

4.2 Toxicological impacts on human health

The accumulation of CRM in the environment affects ecosystems and poses risks to human health through contaminated food, water, and air.

Beyond such indirect exposure, workers at mining, processing, and waste sites face direct risks from contact with fine particles. The highest impacts are typically found near these sites, where environmental concentrations are greatest. Although dissipation during product utilisation is less significant, it is expected to rise as more CRM-containing technologies enter widespread use.

Occupational exposure

Workers at mining, processing, and waste treatment sites that handle CRM such as REE are exposed to these materials for extended periods of time, often lacking adequate safety gear. The ways of how materials are taken up by the body and the resulting impacts vary across material types and life cycle stages. For example, CRM can be taken up by inhalation, ingestion, and dermal exposure (Gwenzi et al. 2018). As a result, workers often exhibit significantly higher levels of CRM in their bodies compared to control groups (Hong et al. 2025), as was shown in case studies at REE processing plants in Northern China (Li et al. 2018; Qiao et al. 2022). Workers at REE mining sites are susceptible to inhaling, absorbing, and ingesting chemicals throughout the mining process (Oladipo et al. 2023). Inhalation of neodymium dust was correlated with lung embolisms and liver damage. Likewise, exposure to lanthanum can lead to pneumoconiosis (Rim et al. 2013; Zhu et al. 2025). Other studies have shown that occupational exposure to lanthanum is associated with phosphate deposition, pulmonary fibrosis, cytotoxicity, genotoxicity, lung cancer, and inflammation, as well as deposition in blood vessels, while neodymium is associated with disorders of bone metabolism, and decreased bone mineral density (Wang et al. 2024). A recent study by Hong et al. (2025) on workers in chromium-related enterprises in China found that exposure to mixed REE could lead to mitochondrial and genetic damages in workers. Long-term exposure to REE in work environments was further found to induce bone metabolism disorders and reduce bone mineral density, as shown in a study on Baiyunebo mining areas in Inner Mongolia, China (Liu et al. 2021).

Recycling of REE is comprised of multiple steps. During collection, substances can be inhaled or ingested by workers, or come into contact with skin when leaking into the atmosphere due to the manual or, in the case of a more common source of occupational exposure, the mechanical dismantling of products and separation of materials, thereby generating dust that may contain REE (Shin et al. 2019). Inhalation of neodymium can cause irritant bronchitis, chronic lung and liver damage, as well as eye and skin irritation. Likewise, Lanthanum can cause inflammatory responses and alveolar proteinosis in lungs. Dysprosium was also shown to lead to eye and skin toxicity (Rim et al. 2013; Shin et al. 2019). In the case of lithium, lithium-containing dust released during the recycling and landfilling of lithium-ion batteries can enter the respiratory system, leading to cardiovascular and respiratory diseases and carcinogenicity, and can disrupt the endocrine system, with shredding identified as the main mechanical processing activity generating dust emissions (Mrozik et al. 2021).

Non-occupational exposure

In addition to direct worker exposure, CRM pollution from mining and processing sites affects nearby environments and even distant areas through abiotic transportation. Once contaminants enter soils used for crops or local water sources, they can pose health risks to surrounding populations uninvolved in CRM industries. Bodies of water are essential in distributing dissipated heavy metals and REE through space. China's largest lithium extraction industrial area is located in the Jinjiang River basin, where lithium mining was linked to chronic health risks from contaminated water, with over 95 percent of dissolved lithium in the river downstream attributed to local industrial activities. Lithium concentrations in such waters were measured to be above 100 μg/L, far exceeding the health-based screening level of 10 μg/L for drinking water, as recommended by the United States Environmental Protection Agency (Yang et al. 2024: 11641). REE pollution also occurs downstream of industrial areas, as in the Jiulong River Basin, where increased REE levels have been detected, with light REE shown to have the highest exposure risk. Toxic effects from exposure to light REE, including neodymium and dysprosium, include risks to respiratory, cardiovascular, nervous, reproductive, skeletal, and digestive systems (Wang et al. 2024). Likewise, controlled experiments showed that REE concentration in rice was significantly correlated with that in soil, highlighting a direct consumption pathway from contaminated soils to human bodies (Zhang et al. 2022).

The Jinjiang River basin is not only home to significant lithium extraction, but is also an important agricultural area in the region. Water irrigation often uses polluted water sources, demonstrating a direct pathway from industrial pollution to locally grown food (Yang et al. 2024). Likewise, fish in the river sections closest to mining sites showed significantly elevated lithium contents (ibid.). Similarly, REE mining and processing industries can severely impact local agriculture through the transportation and use of polluted water in agricultural areas. The largest ion-absorption rare earth mining site in the world is located in Jiangxi Province, China (Liu et al. 2019). In Ganzhou, located in the same province, Zhu et al. (2025) found the REE content in vegetables to be up to three times above subclinical thresholds, with REE accumulation in edible plant parts being identified as a particular health risk. Likewise, a study by Li et al. (2013) found a significant correlation between REE concentrations in soil and the blood of local residents, showing how REE from industrial pollution are mobilized, taken up by plants, ingested by people and finally absorbed into the bloodstream. Road dust in Baotou, the world's largest REE mining and refinery hub, carries neodymium, lanthanum, and praseodymium particles, and was evaluated as being harmful to children when taken up through hand-to-mouth contact (Li et al. 2020). Waste sites represent another dissipation source, with leaching from landfills and e-waste exposing residents to lanthanum and praseodymium, among other CRM, with evidence of disruptions to hormonal balance, particularly affecting the thyroid system (Guo et al. 2020). These findings highlight REE pollution as a growing health concern.

5. Externalisation of environmental costs of decarbonisation: Green extractivism and ecologically unequal exchange

With the justification of green energy transition, large amounts of transition-relevant CRM are mostly extracted in global peripheries. This green extractivism (Dunlap et al. 2024) is neither conducted on an equal footing, with value flowing unidirectionally from peripheries to the core, thus contradicting the notion of capitalist theory that trade benefits all parties involved, nor is it burden-free in terms of impacts on the environment and human health, and therefore rather reproduces preexisting neocolonial patterns.

Accounting for roughly two thirds of total sales in 2024 (IEA 2025), China currently dominates global demand in electric light duty vehicles. However, already every fourth car sold is being used in either Europe or North America, where demand is expected to increase to two thirds of the global market by 2030 according to state policies (ibid.). Similarly, a strong increase in the installed capacity of photovoltaic and wind power is anticipated (IEA 2024a). While in the future most demand is expected to come from Europe and North America, the current extraction and production of many essential raw materials is predominantly located in China and a few regions of the Global South, such as Chile for lithium, and the Democratic Republic of Congo for cobalt. In political ecology, the concept of 'ecologically unequal exchange' is used to describe the externalisation of environmental costs of consumption in wealthier countries of the Global North to economically less developed countries of the Global South (Hornborg/Martinez-Alier 2016). This concept can be used to describe the asymmetrical relationship between regions predominantly importing and consuming CRM, and those regions extracting and processing them, while the environmental and, by extension, toxicological burden remains in the latter regions. In this regard, the opening of new mining sites for the extraction of critical raw materials can be considered a key mechanism through which this unequal exchange manifests itself and as a form of 'green grabbing', whereby land is appropriated, often accompanied by environmental degradation and the displacement or disruption of local communities (Dunlap et al. 2024). With a focus on neo-extractivism in Latin America, Bringel and Svampa (2024: 243) argue that the global imperative to combat climate change has given rise to a new 'decarbonisation consensus', which legitimises intensified resource extraction in the Global Majority under the banner of sustainability. In the context of CRM, ecologically unequal exchange is facilitated by neocolonial practices (control over mining rights, trade terms, as well as control over environmental risks), leading to the Global North capturing most of the value, with the Global South absorbing the burden of material costs and associated risks. This asymmetry between producing and consuming regions constitutes what in political ecology is termed 'ecological debt' (Avendaño

2023; Bringel/Svampa 2024: 252), whereby the environmental burden of the energy transition tends to fall upon resource-rich peripheries.

While demand for CRM from the Global North, including North America and Western Europe, is expected to sharply increase and drive material demand, the case of China, being both a primary producer and consumer of transition-relevant materials, further demonstrates the complexity of the issue. It also reveals that environmental injustice and unequal exchange can be both inter- and intranational phenomena (Tausch/Althouse 2025). The degradation of natural habitats and the contamination of vital water sources due to CRM and REE mining activities as outlined above show that the extraction of CRM tends to be at the cost of the environment and rural, often economically vulnerable communities, showing a pattern of unequal exchange also within countries (Smyer Yü 2024). The incentive for intensive mining and increased processing of REE and other CRM in China arises from both domestic and international demand, as well as from the strategic international position that the Chinese government is able to retain through control of global supply chains, providing it with international diplomatic leverage (Vekasi 2021). With Chinese authorities having become increasingly aware of the toxicological effects of REE mining, stricter controls have been enacted in recent years (Chai et al. 2020). One unfortunate side-effect of tighter regulation is that REE mining activity has reportedly been increasingly pushed into conflict zones, such as those along the Myanmar border (Thibault 2025), where environmental and work safety regulations are significantly more relaxed – a situation mirroring that of mining activities in other conflict areas such as the Democratic Republic of Congo (Williams et al. 2021).

Similar to the effects of raw material extraction, the concept of waste colonialism (Pratt 2011) is relevant when discussing the environmental and human health impact of final product waste treatment. In light of increasingly strict waste management policies, particularly in North America and Europe, international corporations can circumvent rising costs associated with the recycling and legal disposal of complex products containing potentially highly toxic materials by exporting these to countries of the Global South where environmental legislations and workers' safety protections are enforced less rigorously. However, with receiving countries not always being technologically equipped with the necessary means for the protection of workers and the environment, reports of pollution and health risks are widespread (Daum et al. 2017). In the context of this 'conflict' between producing and consuming regions, questions of responsibility and possible compensation have entered the public discourse. For example, it has been suggested that the financial burden of cleaning mining sites should fall on global companies which benefit from access to metals, instead of local institutions (Standaert 2019).

6. Mitigation measures and risks to their implementation

Circular economy measures can provide a pivotal set of tools to balance out the anticipated increases in primary material demand of CRM associated with the green transition, and to mitigate the environmental, toxicological and social impact of CRM mining, processing, and waste treatment. While these measures have a high potential to reduce demand for raw materials, their implementation is hindered by geopolitical barriers, path dependencies and various other socio-economic and technological barriers.

6.1 Demand reduction through circular economy measures

Mitigation measures can be grouped into demand-side and supply-side strategies. Supply-side measures address environmentally and socially burdensome resource procurement through increased use of recycled material in production, recovering material from mine tailings, or employing cleaner processing technologies to reduce environmental impacts. Demand-side measures aim to reduce overall resource needs, for example through lowering consumption. In Austria, the annual demand for scarce materials such as light REE in electric vehicles, photovoltaic, and wind power is projected to rise by over 50 percent from 2018 to 2040 under current trends, and by a factor of nine under the decarbonisation of mobility and electricity sectors (Haas et al. 2025: 6). At the urban level, electrification of mobility and energy alone could almost triple total demand in technology-critical elements (Baumgart et al. 2024). This illustrates that sustainability policies, such as decarbonisation, can paradoxically increase CRM demand and associated environmental pressures. Demand-side strategies are particularly effective in reducing personal transportation needs, for example by shifting to public transport, car sharing, or reducing commuting, and by lowering overall electricity demand through energy-efficient housing and e-mobility. Substituting CRM with non-CRM in key technologies such as permanent magnets (van Gaalen/Slootweg 2025) can further reduce pressure on scarce materials. Further reductions in primary raw material demand can be achieved through supply-side measures, making combinations of the two approaches most impactful. Supply-side measures focus on minimising losses across life cycles and returning waste material back into production, thereby lowering primary resource demand and reducing potential environmental and toxicological impacts, for example through recovery of material from mine tailings (Sarker et al. 2022), or via recycling from collected end-of-life waste (Omodara et al. 2019). Reducing demand also mitigates indirect pressures, including deforestation, land use, biodiversity loss, and energy and water consumption (Kaunda 2020; Luckeneder et al. 2021). Techniques such as in-situ leaching offer less environmentally damaging alternatives to conventional REE extraction (Bai et al. 2022). In the end, a holistic approach integrating both demand- and supply-side measures, as well as balancing circular economy and decarbonisation measures, is thus most effective, with responsible material use and limiting environmental harm.

6.2 Mitigation barriers and risks of implementation

The global economy is currently largely linear, meaning that resources are extracted, used to produce goods, and then discarded as waste rather than being reused or recycled. In terms of CRM, this 'take-make-dispose' approach is particularly challenging, as the current system has a low recycling capacity, with present technologies often not being able to extract CRM from waste flows in an economically feasible way. REE recycling is applied in the areas of magnets, abrasives, phosphors, and batteries, using processes such as collection, dismantling, pyrometallurgy, hydrometallurgy, electrochemical process and materialisation. However, practical cases are few due to limited government support, poor infrastructure, inefficient collection, technical challenges, and weak incentives (Shin et al. 2019). Disassembly of products is commonly a prequisite of material separation and recycling. The fact that circularity and the end-of-life stage of products have long been neglected in product design hinders an efficient recovery of CRM. Modular design considerations with material recovery in mind, including the provisioning of information on material components and disassembly instructions, could create a basis for a more economically feasible and technologically potent recycling system.

Transition technologies are relatively new, and products are therefore yet to reach their end-of-life. This limits potential material recycling to the future. Because of their harmfulness, appropriate workplace safety measures such as skin protection and dust suppression (ibid.) are essential for CRM recycling, but often lacking. Ensuring that future recycling processes are designed with strict safety protocols from the outset will be crucial to protect workers and reduce emissions to the environment. Material substitution, such as replacing REE including neodymium in permanent magnets with non-REE materials, may help to lower overall demand (van Gaalen/Slootweg 2025). Likewise, changes in technologies, such as the replacement of permanent magnet motors with induction motors could lower demand in some CRM. However, both strategies carry the risk of other materials becoming high in demand and consequently being regarded as critical. This is reflected in the dynamic and regionally varying definition of what constitutes a CRM. From a geopolitical perspective, certain conditions in producing countries counteract more sustainable raw material procurement. A main issue is political instability in many extracting economies, such as the Democratic Republic of Congo and Myanmar, where safety regulations are often ignored or difficult to implement and monitor.

7. Conclusions

While the global transition to renewable energy and decarbonised technologies is crucial for meeting the Paris Agreement climate targets, it comes with complex environmental, health, and social trade-offs linked to CRM. Critical materials such as REE, lithium, and tellurium, underpin the functionality of green technologies but also introduce significant risks throughout their life cycles. From extraction and processing to use and waste treatment, CRM dissipate into the environment, where they can contaminate soils, waters, and food chains, with toxicological effects on ecosystems and human health. Mining and recycling activities particularly expose workers and nearby communities to hazardous concentrations, amplifying risks in the Global South, where regulations are less rigorous. This reflects the fundamental dilemma of the sustainable transition: while CRM are indispensable for decarbonisation, their extraction and use simultaneously threaten both environmental integrity and social sustainability. Accurate modelling of material demand is therefore essential to anticipate future toxicological risks across global supply chains. While supply-side measures are important, they are not sufficient to address the issues faced. Overall demand-side measures are required to effectively reduce mining and mitigate environmental and social pressures. This dynamic reflects an ecologically unequal exchange in which the environmental and health burdens of CRM production are externalised to resource-rich but vulnerable regions, while the benefits accrue largely in industrialised economies.

An integrated approach, combining narrowing demand-side measures, with supply-side measures such as material substitution, foresighted design, and improved recycling, holds promise to reduce primary demand and limit environmental impacts. However, effective implementation faces technical, economic, and geopolitical barriers. To align sustainability ambitions with just and safe practices, CRM governance must integrate circular economy measures, environmental protection, global equity, and occupational safety alongside climate goals.

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Abstract *Maßnahmen zur Emissionsreduzierung sind auf kritische Rohstoffe für Technologien wie Elektrofahrzeuge und Windkrafträder angewiesen, was eine räumliche Diskrepanz erzeugt, bei der Nachfrage in wohlhabenden Ländern die Produktion in globalen Peripherien antreibt. Dieser grüne Extraktivismus geht mit stetig zunehmender Materialextraktion und -verarbeitung einher, die zur Freisetzung umweltgefährdender Stoffe führt und Böden sowie Gewässer kontaminiert. Die gesundheitlichen Folgen für die arbeitende Bevölkerung in ländlichen Regionen treten durch unmittelbare Exposition oder Konsum lokaler Lebensmittel und Grundwasser auf. Mittels qualitativer Synthese peer-reviewter Literatur verfolgt diese Studie die toxikologischen Effekte entlang der Lieferkette und untersucht Kreislaufmaßnahmen zur Nachfrage- und Belastungsreduzierung am Fallbeispiel China.*

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