

REVIEW ARTICLE

Summary and critical review of the International Energy Agency's special report: The role of critical minerals in clean energy transitions

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ABSTRACT: This paper makes a critical review of the IEA's report entitled The Role of Critical Minerals in Clean Energy Transitions. The main goal of this report is to identify key minerals and metals that could generate supply problems and bottlenecks in a clean energy transition. The IEA establishes a series of key recommendations towards mineral security, analysing the amount of different materials used in certain technologies (electric cars, solar PV, onshore and offshore wind, nuclear, coal, and natural gas). Such recommendations include, among others, ensuring adequate investment in diversified sources of new supply, the promotion of technology innovation or strategic stockpiling. This report is an essential step towards awareness rising about this issue, because until recently it had not received the attention it deserved. However, it falls short on the impact that mineral scarcity can have on the development of economies and the planet. For this reason, we analyse section by section the report and provide some additional comments on aspects that could be further addressed to avoid replacing fossil fuel addiction with raw materials dependence.

KEYWORDS: Critical review; Energy transition; IEA; Raw materials; Supply risks

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RESUMEN: *Resumen y análisis crítico del informe especial de la Agencia Internacional de la Energía: El Rol de los minerales críticos en la transición hacia energías limpias.* Este artículo hace una revisión crítica del informe de la AIE titulado El rol de los minerales críticos en la transición hacia energías limpias. El objetivo principal de este informe es identificar los minerales y metales clave que podrían generar problemas de suministro y cuellos de botella en una transición energética limpia. La AIE establece una serie de recomendaciones clave para la seguridad de los minerales, analizando la cantidad de diferentes materiales utilizados en determinadas tecnologías

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(coches eléctricos, energía solar fotovoltaica, eólica terrestre y marina, nuclear, carbón y gas natural). Dichas recomendaciones incluyen, entre otras, garantizar una inversión adecuada en fuentes diversificadas de nuevo suministro, el fomento de la innovación tecnológica o el almacenamiento estratégico. Este informe es un paso esencial para aumentar la concienciación sobre este tema, que hasta hace poco no había recibido la atención que merecía. Sin embargo, se queda corto en cuanto al impacto que la escasez de minerales puede tener en el desarrollo de las economías y del planeta. Por ello, analizamos el informe sección por sección y aportamos algunos comentarios adicionales sobre aspectos que podrían abordarse más a fondo para evitar sustituir la adición a los combustibles fósiles por la dependencia de las materias primas.

PALABRAS CLAVE: AIE; Análisis crítico; Materias primas; Riesgos de suministro; Transición energética

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1. INTRODUCTION

On 7 May 2021, the International Energy Agency presented its report: *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021a). This document can be considered a milestone. Finally, such an internationally relevant organisation has acknowledged a new “inconvenient truth”: the energy transition is at serious risk due to the lack of supply of essential raw materials. The report is a comprehensive and up-to-date compilation of a large number of studies that scholars and institutions have been developing. Indeed, for more than a decade now, scholars have been warning about the accelerated extraction of more and more minerals and the severe problems associated with it. However, it is not only the quantity extracted that is increasing, also the variety, and the problem is exacerbated by the new material requirements of the transition towards a green, climate neutral and digital world.

The first question we might ask ourselves is why the IEA is developing a report on an aspect that seems alien to the field of energy at first sight. To understand this, it is worth noting that shortly after this report, the same agency presented another one: *Net Zero by 2050. A Roadmap for the Global Energy Sector*, which presents a comprehensive energy transformation plan to achieve the Paris agreements (IEA, 2021b).

The Roadmap sets out more than 400 milestones to guide the global journey to net zero by 2050. These include, from today, no investment in new fossil fuel supply projects and no further final investment decisions for new unabated coal plants. As a result, by 2035, there will be no sales of new internal combustion engine passenger cars, and by 2040, the global electricity sector would have already reached net-zero emissions. This plan should ensure stable and affordable energy supplies, provide universal energy access, and enable robust economic growth.

Undertaking this ambitious plan means increasing current mineral consumption by at least four times (six times in a net-zero by 2050 scenario), which according to the IEA raises serious concerns about price volatility and security of supply of raw materials.

This concern is visible in several strong statements by the IEA, moving away from the agency’s neutral style in its reports and making it clear that the looming

problem is no small matter. Thus, in the presentation of the report, IEA executive director Fatih Birol said the “World faces ‘looming mismatch’ between energy transition and critical mineral supply”. The report also includes statements such as:

“The prospect of a rapid increase in demand for critical minerals – well above anything seen previously in most cases – raises huge questions about the availability and reliability of supply”

“Given the urgency of reducing emissions, this is a possibility that the world can ill afford.”, referring to the fact that there have been supply problems in the past which have led to price increases.

Let us now review the IEA’s critical minerals report, based on the studies that we have published on the subject within the CIRCE institute in recent years. We will differentiate the pure summary of the report from our comments, highlighted in italics.

2. SCOPE

The study is based on two scenarios developed by the IEA. The Sustainable Development Scenario (SDS) and the Stated Policies Scenario (STEPS). The first charts a pathway that fully meets the world’s goals to tackle climate change in line with the Paris Agreement; while the latter indicates where today’s policy measures and plans might lead the energy sector. Worth mentioning is that according to the IEA, the STEPS scenario falls far short of the world’s Paris Agreements.

The analysis is focused on a limited range of clean energy technologies: solar photovoltaic, on-shore and offshore wind, concentrating solar power, hydro, geothermal and biomass, nuclear power, electricity networks (transmission and distribution), electric vehicles (EV), battery storage and hydrogen (electrolysers and fuels), which are the majority of the technologies deployed in the SDS.

The report comprehensively reviews the technologies mentioned above, analysing future deployment, types, expected technological development, and material needs for each alternative. For example, for solar PV it takes into account conventional crystalline silicon and amorphous modules, but it also explores thin film technologies including CdTe, GaAs, CIGS,

and also perovskite solar cells. For wind energy, four main types of turbines are considered: gearbox double-fed induction; gearbox permanent magnet synchronous generator, direct drive permanent magnet synchronous generator and direct-drive electrically excited synchronous generator. Two main types of CSP technology are considered: parabolic troughs and central towers. Similarly, the two most common electric motor technologies for plug-in EV are considered: permanent-magnet and asynchronous induction motors. The report makes an extensive analysis of battery types: NCA, NCA+, NMC (111, 333, 532, and 811), LFP, LMO, solid-state batteries, and even flow batteries.

Demand from other sectors was considered only for five focus minerals. Moreover, the analysis focuses on the requirements for building a plant and not on operational equipment. Finally, not all minerals used in the mentioned technologies are considered. The five focus minerals are cobalt, copper, lithium, nickel and rare earth elements. Other elements considered are: As, B, Cd, Ga, Ge, graphite, Hf, In, Ir, Pb, Mg, Mn, Mo, Nb, Pt, Se, Si, Ag, Ta, Te, Sn, Ti, W, V, Zn and Zr. For example, steel is not covered, as it is considered abundant, and neither is Al (although aluminium demand is assessed for electricity networks jointly with copper). Industrial minerals are also out of scope.

3. MINERAL REQUIREMENTS FOR CLEAN ENERGY TRANSITIONS

Considering this scope, the IEA predicts that total mineral demand from clean energy technologies is set to double in the STEPS scenario and quadruple in the SDS by 2040 (see Fig. 1). In this respect, the IEA recognises that projected mineral demand is subject to considerable uncertainties, highly dependent on climate policies and technological innovation. This is why 11 alternative cases were built under both scenarios.

EVs and battery storage are the most demanding ones from all clean technologies, accounting for about half of the mineral demand growth over the next two decades. EVs and battery storage grow about tenfold in the STEPS and around 30 times in the SDS by 2040. Coupled with the expected increase in demand, according to the IEA's report, EVs use around six times more minerals than conventional vehicles (minerals included here are Cu, Li, Ni, Mn, Co, graphite and REEs).

In this respect, an in-depth study performed for different types of vehicles determined that an EV has a metal content that is around 33% greater than an ICEV (internal combustion engine vehicle) (Iglesias-Émbil et al., 2020). This discrepancy with the IEA study is because all metals were considered by Iglesias-Émbil et al. (2020), with steel and aluminium being the major metals. While iron is not of concern because of its abundance, the alloying metals of steel or aluminium, including Nb, V, W, Mo, and others, are scarce (Ortego et al., 2020). Moreover, these alloying elements will become more important in new electric vehicles, which are looking for strong, lightweight materials to compensate for the extra weight of the batteries. Furthermore, other essential metals in electronic components such as Ag, In, Ta or La (Andersson et al., 2017), whose presence is increasing exponentially in all types of vehicles, should not be forgotten. The shortage of semiconductors has already caused severe economic consequences in the automotive sector and digital technologies in the post-Covid period. These tensions can be expected to become more pronounced due to the increasing scarcity of materials.

Back to the IEA report, electricity networks closely follow EVs and battery storage. They currently account for 70% of today's mineral demand from energy technologies, although their share will fall as mainly EVs and battery storage grow. Wind power tops the list in the most mineral demanding solutions from all low carbon power generation

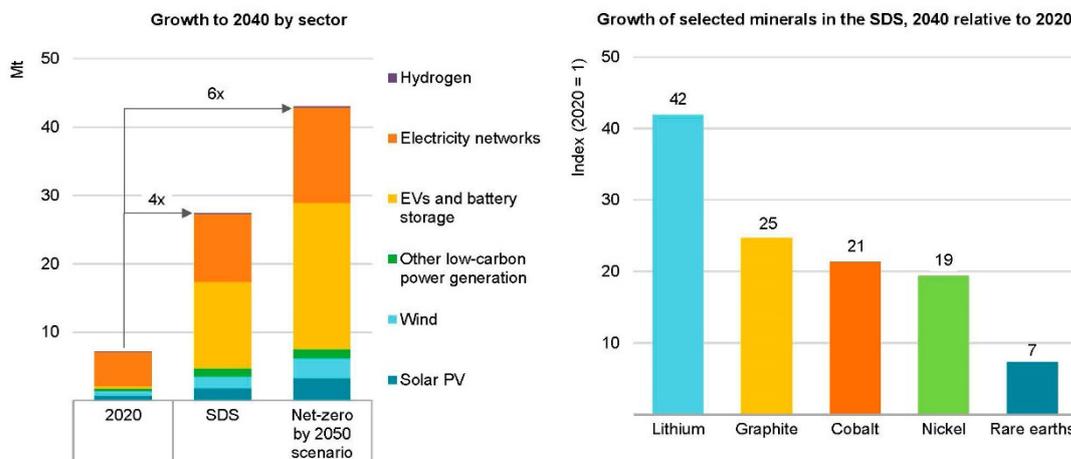


FIGURE 1. Mineral demand for clean energy technologies by scenario. Steel and aluminium not included. Source: IEA (2021a). The Role of Critical Minerals in the Energy Transition. All rights reserved.

technologies due to a combination of large-scale capacity additions and higher mineral intensity, especially coming from offshore wind. Without considering steel, aluminium, or concrete, the IEA reports that wind energy requires about nine times more mineral resources than a gas-fired power plant, as shown in Fig. 2 (*25 times more if all raw materials are accounted for, according to Valero et al. (2018b)*).

Solar PV follows closely, while hydropower, biomass, nuclear and hydrogen-based technologies make only minor contributions given their comparatively low mineral requirements and modest capacity. Clean energy technologies will monopolise the demand for various minerals, including copper and REE, with a share of 40% and 60-70% for nickel and cobalt and almost 90% for lithium by 2040 in the SDS (see Fig. 2).

Copper, graphite, and nickel dominate mineral demand by weight. Yet lithium will experience the most significant growth in demand with respect to today's levels. In the SDS scenario, lithium might increase its demand forty times, graphite, cobalt, and nickel between twenty and twenty-five times, copper twenty times, and rare earths seven times (see Fig. 1).

That said, demand projections are subject to large variations depending on how technologies evolve. This uncertainty is especially significant when it comes to mineral demand for the future mix of EV battery chemistries. For instance, lithium demand by 2040 might be “only” 13 times higher if vanadium redox flow batteries rapidly penetrate the market in the STEPS, or 51 times higher if all solid-state batteries commercialise faster than expected in the SDS.

All in all, and despite considering an increase in the capacity factor and a likely reduction in material use for all clean technologies, there will be an unprecedented increase of raw material use in the coming decades. This, in turn, could lead to higher

mineral prices and become a serious obstacle in the deployment of clean technologies. The report shows an example of this effect: “a doubling of lithium or nickel prices would induce a 6% increase in battery costs, what would eat up the anticipated learning effects associated with a doubling capacity” and “the continued cost decline of batteries at a pace observed during the past decade cannot be taken for granted without a further acceleration in technology innovation”.

4. RAW MATERIALS SUPPLY RISKS

From the supply side, the IEA evaluates whether the expected growth in raw material demand (in most cases well above the historical pace), can be satisfied reliably and sustainably. The analysis has been focused on only five minerals: copper, lithium, nickel, cobalt, and rare earths. According to the report, some elements such as lithium and cobalt are expected to be in surplus in the near term. However, some of their refined products such as lithium hydroxide, battery-grade nickel, and neodymium or dysprosium might face supply bottlenecks in the coming years as demand rises. That said, projected demand surpasses the expected supply in the medium term from existing mines and projects under construction for most minerals. This means that meeting primary demand implies strong growth in investment to bring new supply sources over the next decade. In this respect, several risks need to be taken into account: 1) higher geographical concentration of production; 2) a mismatch between the pace of change in demand and the typical project development timeline; 3) the effects of declining resource quality; 4) growing scrutiny of environmental and social performance of production and 5) higher exposure to climate risk such as water stress, among others.

The first risk, which is usually considered in the

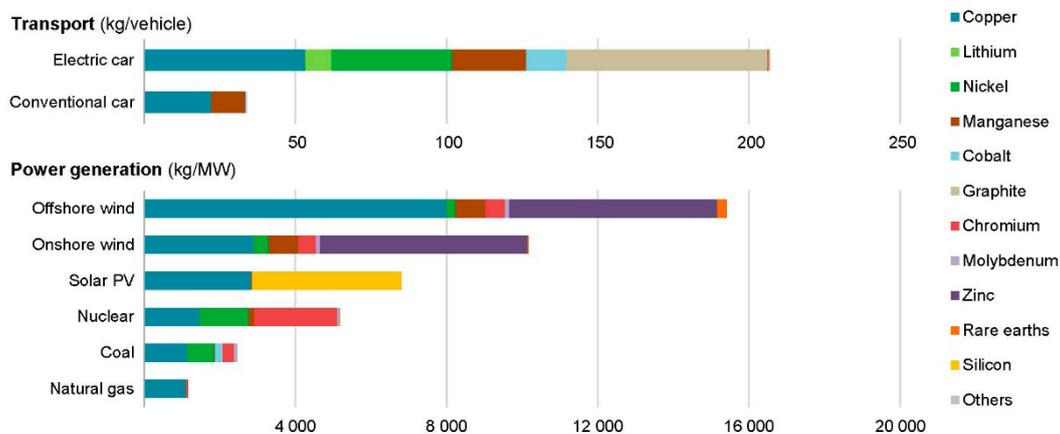


FIGURE 2. Minerals used in selected clean energy technologies. Steel and aluminium not included. Source: IEA (2021a). The Role of Critical Minerals in the Energy Transition. All rights reserved.

elaboration of critical raw material lists by governments, recognises that a few countries control the production of key elements in the clean energy transition, which is unlikely to change in the near term. For example, three-quarters of the world's production of Li, Co, and REE are controlled by only three countries (see Fig. 3). The Democratic Republic of the Congo (DRC) and China were responsible for some 70% and 60% of global production of cobalt and rare earth elements, respectively, in 2019. Moreover, China not only concentrates the extraction of key raw materials, but it also leads the processing of these minerals (i.e., providing nearly 90% of rare earth elements, 70% of Co or 60% of Li). China is also investing in overseas assets in Australia, Chile, the DRC or Indonesia, as part of its "Made in China 2025" initiative. For example, Chinese strategic investment overseas includes near 24% of the Chilean company SQM or 51% of Australia's Greenbushes lithium mine. This issue makes the system vulnerable to political instability, geopolitical risks and possible export restrictions. Notable cases of this vulnerability were experienced with the Chinese REE export embargo in 2010 or, more recently, Indonesia's ban on nickel ore exports in January 2020. Hence, there is an urgent need to diversify the extraction and further processing of essential raw materials.

However, to develop projects from discovery to first production takes over 16 years on average, which exacerbates the risk of a mismatch in timing between demand and the industry's ability to bring on new projects.

Another key question is whether there are enough resources in the crust to satisfy this increasing demand. According to the IEA, economically viable reserves have been increasing for many energy transition minerals. Among others, this has been the case for lithium reserves, which increased by 30% in the last ten years. IEA's concerns about resources relate

then to quality rather than quantity. For example, the average copper ore grade in Chile decreased by 30% over the last 15 years.

Lower ore grades imply more energy, waste rock produced and more emissions. This issue was pointed out by several studies such as Calvo et al. (2016) and Mudd (2007) already alerting about the expected exponential energy and waste rock increase in mining operations. Technological improvement that allows the exploitation of lower-grade deposits might partially offset these higher costs. However, as stated by Domínguez and Valero (2013), where historical data sets of 17 major gold producing countries were analysed, although progress in technology has been made, in most cases, energy requirements are increasing because the primary variable is the ore grade. Hence, if extractive industries continue relying on fossil fuels, it is not clear that decarbonisation will occur at the pace it is expected since this issue has not been sufficiently addressed in current energy transition scenarios.

The IEA also warns about the production peak of current mines, specifically for copper, due to declining ore quality and reserves exhaustion. *In our view, concerns should not only relate to quality, which is justified, but also to quantity. In Calvo et al. (2017), we demonstrated that the peak of a dozen commodities based on resources data (i.e., most optimistic values regarding mineral availability) might be reached before 2050. Using lithium as a case study, the influence on the fluctuations on extractable resources was analysed, stating that the peak is only delayed less than two decades even if the most optimistic resources values are doubled.*

Deep-sea mining could be developed as a response to declining high-grade deposits on land. However, there are economic, technical, and environmental hurdles, such as seafloor disturbance or sediment plumes which irreversibly affect ecosystems. According to the IEA, proper regulatory measures for

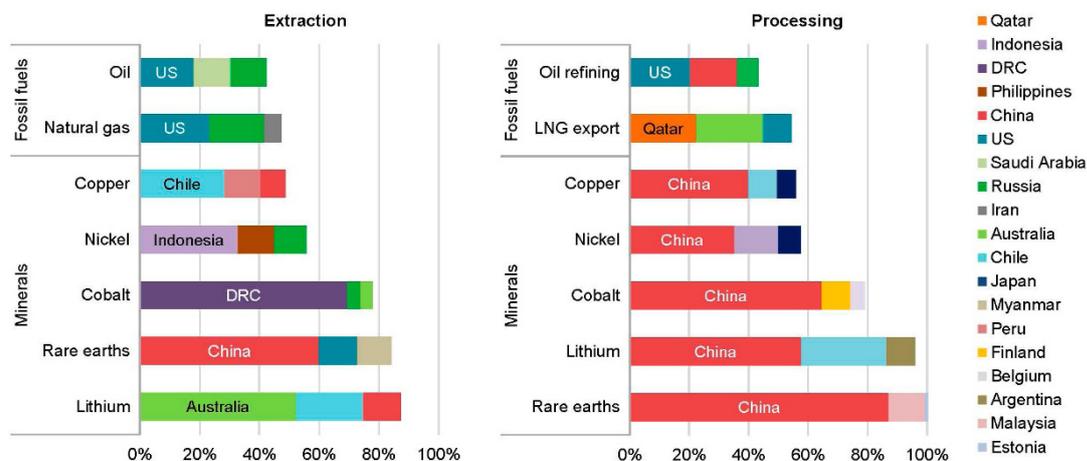


FIGURE 3. Share of top three producing countries in production of selected minerals and fossil fuels (2019). Source: IEA (2021a). The Role of Critical Minerals in the Energy Transition. All rights reserved.

deep-sea mining should be put into place after more rigorous impact assessments.

The growing scrutiny of environmental, social and governance (ESG) issues is, in fact, another risk in the supply of essential mineral resources. Mineral extraction affects the local and regional environment because it implies land use change, large volumes of water, waste generation, air pollution from particulate matter, gaseous emissions, and noise pollution. For example, over 10 square kilometres of Bayan Obo, a mining town in China, and the soil surrounding it is highly enriched with heavy metals. Effective waste management policies can reduce the risks to the environment and public health. Such is the case of the European Union's Directive on Management of Waste from Extractive Industries, 2006/21EC, which requires the use of the best available techniques to reduce the volume of extractive waste. In the same line, the "Initiative for Responsible Mining Assurance" outlines requirements related to the management of air contaminants.

The report does not hide the worrying social impacts of mining and that there are many causes for this so-called "resource curse". Corruption and misuse of government resources (almost 20% of bribery cases occurred in the extractive sector), fatalities and injuries to workers and members of the public, human rights abuses including child labour and unequal impacts on women and rights are also risks that may lead to supply disruption and could slow the pace of clean energy transitions. Artisanal and small-scale mining (ASM) is of particular concern, with cobalt especially vulnerable. ASM is often unregulated and might imply unsafe conditions for workers and the presence of child labour. According to a survey of cobalt ASM workers in the Democratic Republic of Congo, only 2 of 58 sites used protective equipment for workers and only in 2019, 60 fatal accidents and over 100 accidents involving injury were registered.

Therefore, it is not surprising that a growing number of consumers and investors are requesting companies to disclose targets and action plans. The Extractive Industries Transparency Initiative (EITI) is an example to support the development of transparency practices. Yet tightening scrutiny of ESG issues might have an impact on costs and supply prospects. Moreover, adopting transparency processes may not necessarily reduce corruption because information should also reach the public and sanction corrupt conduct. This is not a minor issue, as, for example, around 10-15% of Cu, Li, and Co-production and almost 50% of nickel in 2019 came from regions with low governance scores and high emissions intensity.

The so-called Nimby effect (Not in my backyard) reflects the growing scrutiny of ESG issues. This is notably relevant for most countries in Europe. There is much

rejection of the opening of new mines because of the environmental and social effects they cause. However, Europe is highly dependent on external mining supplies, and one of its strategies is to invest in domestic extraction. In Spain, for example, there is strong opposition to the opening of Li mines in Cáceres or rare earth mines in Ciudad Real because the deposits are located in places of high ecological value or close to urban centres. Moreover, as stated by the IEA, processing REE often generates toxic and radioactive materials, which could eventually leak into groundwater, causing major health and safety issues.

The last risk pointed out by the report is exposure to climate risks. Mining activity is also affected by climate change. Water stress combined with a higher water intensity in ore processing has brought the critical importance of sustainable water sourcing to attention. Copper and lithium are particularly vulnerable as they are mined in areas with high water stress (i.e., 80% of copper output in Chile is produced in arid areas). Additionally, mining activity is exposed to other forms of climate risk, including extreme heat and flooding, which pose challenges to ensuring reliable and sustainable supplies. It is well known that flooding can lead to spills of hazardous waste and tailings dam failure. For example, tailings storage facility at Vale's mine in Brumadinho, Brazil, led to mining waste surging across the surrounding areas and the death of over 270 people. Brazil had already experienced the collapse of the Fundão dam, which released 43 million cubic metres of iron ore tailings, polluting 668 km of watercourses from the Doce River to the Atlantic Ocean. To avoid such catastrophes, the so-called "Global Industry Standard on Tailings Management" was established.

5. CLIMATE ADVANTAGES OF CLEAN ENERGY TECHNOLOGIES

According to the IEA, emissions from minerals development do not negate the climate advantages of clean energy technologies. The IEA supports this statement through a comparative life-cycle GHG emissions assessment of a mid-size battery electric vehicle - BEV (NMC 622 – 0.19 kWh/km) with respect to an internal combustion engine car - ICE (6.8 Lge/100 km). The study assumes two scenarios, with different GHG emissions intensity for battery minerals (70 kg/CO₂-eq/kWh vs 35 kg CO₂-eq/kWh). The analysis considers today's manufacturing lines assuming dynamic global average grid carbon intensity in the SDS. As can be seen in Fig. 4, for a life cycle of 200.000 km, CO₂ emissions for the ICE almost double those by BEV in both scenarios. In a high-carbon electricity mix (800 g CO₂-eq/kWh), BEV's emissions are still under those from ICE.

That said, the IEA also recognises that energy transition minerals involve higher GHG emission

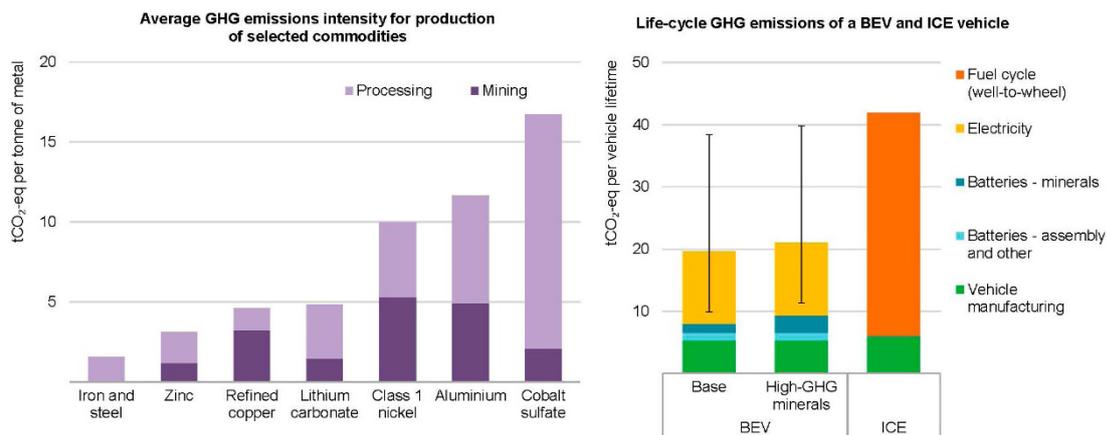


FIGURE 4. Average GHG emissions for certain commodities and life-cycle GHG emissions of a BEV (battery electric vehicle) and ICE (internal combustion engine) vehicle. Source: IEA (2021a). The Role of Critical Minerals in the Energy Transition. All rights reserved.

intensities. For example, producing neodymium oxide implies near 80 t CO₂-eq/ton, for cobalt sulphate over 15, whereas for iron and steel about 2 t CO₂-eq/ton (see Fig. 4). Moreover, as demand for energy transition minerals spirals up, new resources and processing routes with higher GHG emissions intensities will increase their share. For example, more and more nickel will need to be produced from laterites instead of from sulphide ores. Depending on the processing route (matte via nickel pig iron or high-pressure acid leaching), emissions increase between 1.5 and 5 times respectively, when compared to nickel production from sulphides. In the same way, producing lithium hydroxide or carbonate from hardrock implies that the emissions intensity triples with respect to producing them from brines.

Considering the vehicle as a proxy for not negating the climate advantage of clean energy technologies might seem to be a bold simplification. However, according to our studies, the vehicle is actually the clean technology that is most dependent on materials, both in quantity and variety (Ortego et al., 2020). Therefore, although it is a very reductionist approach, it may be valid, considering that all other technologies consume comparatively less resources, especially accounting for their whole life cycle. However, there is one aspect that is not being taken into account in IEA's report. If mines continue to be depleted, which is highlighted in the study itself, the energy associated with the mining of metals in vehicles can be expected to increase considerably. Moreover, the new generations of vehicles (BEV and ICEV) incorporate more electronics and therefore many other materials in addition to those included in batteries. This is why the overall emissions balance will have to be recalculated taking these facts into account. Several methodologies, including the thermodynamic rarity approach as proposed by the authors, could be eventually used to consider resource depletion (Sonderegger et al., 2020).

Therefore, it becomes essential that extractive processes urgently reduce their carbon footprint because "minerals are needed for clean energy transitions, and sustainable mineral development need energy". The carbon footprint of the electricity mix has a significant impact on mineral production, as an important part of the energy demand is in the form of electricity (i.e. comminution consumes about 3% of the electricity consumed in the world). Hence low-carbon electricity but also fuel switching, and energy efficiency will reduce GHG emissions associated with mineral production in the near term. According to the report, shifting all fuels to natural gas would bring emissions down by 10%, while using renewable-based electricity reduces CO₂ intensity by about two-thirds.

Net CO₂ emission reduction pledges for top 20 mining companies (accounting for 25% of cobalt and less than 20% for copper and nickel) are in the range of 30% by 2030. Yet, many more companies need to come on board to follow a sustainable development path.

6. IS RECYCLING THE SOLUTION?

Metal recycling is also considered a source of secondary supply. However, IEA's report does not go into much detail on this topic. Instead, it very much focuses on battery recycling and dedicates a small section to grid recycling.

The main conclusion drawn from the analysis for battery recycling is that recycling from Li-ion batteries can relieve a proportion of the burden from mining them from virgin ores. However, this does not eliminate the need for continued investment in primary supply of minerals. Secondary production from recycled minerals would account for up to 12% of total supply requirements for cobalt, 7% for nickel, and 5% for lithium and copper, in a scenario

where the collection rate increases to 80% by 2040 gradually. Reused batteries would contribute to a reduction of only 1-2% of total supply requirements by 2040. There are still many technological and commercial challenges to overcome. Li-ion battery recycling has yet to reach maturity.

Technology bottlenecks include, among others, the lack of standardisation of design, with vehicle manufacturing adopting different battery chemistries without disclosing information of their cell designs. In addition, there are no specific guidelines or regulations for discharging, disassembling, and storing spent batteries. Transport logistics is another challenge, and more stringent safety measures to handle and transport batteries are required. The report cites the European Union Global Battery Alliance in 2017 as an example. The proposal sets out minimum levels of recycled content of 12% Co, 4% Li, 4% Ni by 2030, as for material recovery, 90% for Co, Cu, and Ni, and 35% for Li by 2026. In addition, batteries sold in the European Union will carry a carbon intensity performance label and comply with carbon footprint thresholds.

In Valero et al. (2018a), we evaluated the recycling rates needed to avoid identified material constraints (i.e. where annual demand is expected to exceed production). Our results showed that the recycling rate of all lithium in the technosphere (not only that included in batteries) should increase to 4,8% by 2050, which is probably feasible. However, in the case of Co and Ni, it should reach 59% and 41%, respectively.

In addition to batteries and grid recycling, potential secondary sources include tailings from processing, scrap used in manufacturing and fabrication, and other end-of-life products. Enhanced metals recovery from mining and processing waste is seen as a clear opportunity to increase supply. Moreover, this would also reduce the risk of hazardous materials entering the environment. The Kiruna iron ore mine tailings in Sweden could constitute an essential source of REEs for the European Union. The Boron mine in the United States could become an eventual source of lithium from waste rock. Bauxite residue is also a potential source of REEs, titanium and vanadium. In contrast, fine-grained landfilled sludges, iron-rich sludges from metal production (from Zn production) and fayalitic slag (mostly from Cu production) could yield additional volumes of Zn, Ni, Cu, Co and others.

As mentioned, the opening of new mines in Europe will face strong opposition. Yet, it has been proven that mine tailings from existing or abandoned mines could become a valuable source of essential minerals. This is the case, for instance, of the old Zinc Penouta mine in Spain, which tailings are now a source of niobium and tantalum (Rodríguez et al., 2020)

Recycling end-of-life products still face many challenges that prevent it from being a significant

source of raw materials. Barriers include competition from primary supply, information deficits and limited waste collection. Physical collection is a primary limiting factor. Bulk products and materials including aluminium, iron, nickel or copper have traditionally achieved high rates of recycling and have a higher potential for maintaining global stock. That said, many new products such as personal electronics or alloyed materials make physical and metallurgical separation difficult. For instance, new iron and copper alloys may require the physical, chemical and metallurgical separation of over 50 materials with different thermodynamic and metallurgical considerations from a single product. An additional challenge is that minerals that enter stock today may not be recoverable for decades. Moreover, most critical minerals lack information and description of stock. Technologies must therefore adapt to the stock life and the nature of the stock's evolving thermodynamic and metallurgical properties.

At this point, the IEA report acknowledges the problem that some of us thermodynamicists have pointed out: metal mixology implies irrecoverable losses at the End of Life (Reuter et al., 2006; Valero, and Valero, 2019). This challenge is essential because recoverability depends on how the metals are mixed, alloyed, etc. According to the second law of thermodynamics, the greater the degree of material mixing in a product, the larger the irreversibility and thus the losses generated at the end-of-life. That is why it would be more rigorous to speak of a "spiral economy" rather than a "circular economy". One hundred percent recycling is impossible from a second law point of view (circles can never be closed). Yet losses can be minimised through eco-design and appropriate technologies.

Policy intervention may be necessary to build demand for secondary supply. In this respect, many countries have already set recycling rate targets for consumer products (notably for end-of-life-vehicles and electronic waste). However, as these are mostly based on weight and volume metrics, companies will likely focus on high-volume materials more readily recyclable than those found in small quantities.

Indeed, this is an issue stated, for instance, in cars. As we pointed out in Ortego et al. (2018) in the European Union, from 2015, the total mass percentage of materials reused and recovered with respect to the average car's weight must be equal to 95%, and 85% must come from reuse and recycling. However, End-of-Life Vehicles (ELV) recycling operations mainly focus on recycling major metals such as steel and aluminium alloys, with many other metals not functionally recycled (Ortego et al., 2018). Moreover, all types of steel are mixed and smelted, the result being low-quality steel. Consequently, not insignificant quantities of virgin materials need to be added to obtain the desired quality of steel. Hence, even though part of these scarce materials may be recycled eventu-

ally, only a tiny proportion is recycled back into cars. Ortego *et al.* (2018) calculated that from four recycled ELV, the metals of one become effectively lost, if metal loss is assessed in terms of a physical parameter that accounts for scarcity and energy intensities required to mine and refine the metals.

Other important measures to revitalise the secondary supply of raw materials include: supporting the development of collection and sorting programmes (such as deposit-refund schemes already in place in Denmark for nickel-cadmium batteries); developing knowledge of global and regional stocks; market incentives; collaboration, often beyond country borders; to encourage secondary market development; and incentivising manufacturers to develop products that are easier to recycle. Another option is implementing extended producer responsibility, where the manufacturer is made responsible for the treatment or disposal of post-consumer products.

*We find this last point particularly key for increasing not only recycling rates but also reuse rates. If this measure is effectively implemented, manufacturers would be encouraged to eco-design products to facilitate recycling. The aim would be to develop long-lasting and robust products with a modular design and avoiding the use of scarce materials. This would also encourage final users to maximise the useful life of products and discard them only when necessary and not just thinking about what is fashionable. Furthermore, Incentivising users through eco-credits and similar campaigns could benefit society and the system (Valero *et al.*, 2021).*

For packaging, European companies usually join integrated waste management systems transferring the problem to third parties. However, such systems that have shown weaknesses for packaging recycling in some instances, will be less suitable for recovering minor but valuable metals, if producers are not effectively engaged. Moreover, there are very few facilities in the world able to recover such minor metals. For example, Europe, which presumably is very well positioned in the global recycling ranking, does not even have one facility per country. The result is that e-waste needs to be exported to other countries, and a not-insignificant quantity arrives in China.

7. IEA'S SIX PILLARS OF A COMPREHENSIVE APPROACH TO MINERAL SECURITY

The report identifies six pillars to minerals security: 1) ensuring adequate investment in diversified sources of new supply; 2) promoting technology innovation at all points along the value chain; 3) scaling up recycling; 4) enhancing supply chain resilience and market transparency; 5) mainstreaming higher environmental and social standards; and 6) strengthening international collaboration between

producers and consumers.

The IEA states that the foremost action to ensure adequacy of supply is to provide clear and strong signals about energy transitions because the largest uncertainty around demand comes from questions about countries' real commitments to their climate ambitions. Companies will not invest in new projects if they do not have confidence in countries' climate ambitions, what could create bottlenecks, given the long lead times for new projects. Additional mentioned measures include strengthening national geological surveys, streamlining permitting procedures to shorten lead times, providing financing support to de-risk certain strategic projects or support enhanced metals recovery from low-grade ores, waste streams or abandoned mines. Moreover, governments can work to improve data availability and comparability across regions while raising public acceptance.

The second pillar is related to innovation in demand-side technology as it could mitigate upward cost pressure of clean technologies. The report shows as an example the reductions achieved in silver and silicon use for solar cells or technology advances in aluminium to help ease strains on copper and later on tin supply. Innovation in production and processing technologies are also important to unlock sizeable amounts of new supplies. For example, direct lithium extraction or enhanced metal recovery from waste streams or low-grade ores could increase supply volumes. Technologies can also help reduce energy and water consumption, while bringing environmental and operational benefits.

Scaling up recycling is the third pillar. The IEA states that it can reduce primary supply requirements and alleviate the environmental burdens associated with mineral supply. Yet recycling must be incentivised by governments, supporting collection and sorting activities and funding R&D into new recycling technologies.

Enhancing supply chain resilience and market transparency is recognised to be the fourth pillar. Indeed, a bottleneck in processing capacity could elevate prices for refined products, while a higher degree of concentration of production implies that disruption can have wider ripple impacts on the entire value chain. The IEA suggests making periodic stress-tests and emergency response exercises to identify points of potential weakness and devise required actions to mitigate such risks. Strategic stockpiling is also identified as a potential measure to enhance supply chain resilience. In addition, the establishment of reliable price benchmarks through a standardised methodology could increase market transparency. This is especially important for minor but essential minerals (such as lithium or cobalt) usually traded on a bilateral basis, with low pricing transparency and liquidity.

As previously explained, poor environmental and social performance can also lead to supply disruption. Therefore, the following coordinated policy efforts will need to be put in place: i) provide technical and political support to countries seeking to improve legal and regulatory practices; ii) to incentivise producers to adopt more sustainable operational practices (and so new entrants will have an incentive to develop new approaches to mitigate such risks); and (iii) to ensure that companies across the supply chain undertake due diligence to identify, assess and mitigate these risks.

The last pillar involves strengthening international cooperation, since given the complexity of the mineral supply chains, no individual country will be able to drive the required changes on its own. As of yet, there is no overarching international governance framework for critical minerals and coordinated policy action is lacking. A multilateral framework could: ensure reliable and sustainable mineral supply by providing clear market signals on decarbonisation targets; facilitate dialogue between producers and consumers; mobilise public funds to accelerate R&D efforts for innovation; conduct assessments of potential vulnerabilities across the supply chains and discuss collective action to respond to potential disruption; promote knowledge and capacity transfer to spread sustainable and responsible development practices; strengthen environmental and social performance standards; coordinate diplomatic efforts to prevent restrictive export policies; and collect reliable data for informed decision-making.

8. CONCLUSIONS

- In our view, while comprehensively summarising and revealing uncomfortable truths about raw material production and availability, the report falls short on the impact that mineral scarcity can have on the development of economies and the planet. Dependence on critical raw materials and their primary extraction in mines could jeopardise the future of the energy transition. Europe and the developed world will not avoid the effects of climate change by wanting to produce all their energy in a clean way unless a hard look at their dependence on critical raw materials is taken. Consequently, the criticality of raw materials must be put on the agenda of all institutions, as there will be no energy transition if there is no material transition. Therefore, the energy transition must necessarily go hand in hand with the circular – rather spiral- economy.
- Countries should promote companies that effectively recover raw materials and reintroduce them into the system. Particular attention should be paid to rare materials and with

identified supply risks. Governments should establish legal mechanisms to make producers responsible for recycling their products, avoid planned obsolescence and favour the repair of products. Cities should selectively collect waste of electrical and electronic equipment (including that in cars), batteries, and obsolete renewable technologies.

- However, as discussed above, at the current rate of mineral consumption, even if recycling rates of critical minerals significantly improve, the economy will still rely on mining. Therefore, society must be informed of the gravity of this problem, but at the same time, the populations affected by new mines must be respected and adequately compensated with an intergenerational vision.
- The six pillars proposed in the IEA report for securing mineral supply imply a green-tinted “business as usual” economy. As the IEA points out, there is no energy transition without minerals, but without energy, there are no minerals. This problem is compounded by the severe social and environmental problems that mining often entails and the enormous complexity and opacity of highly globalised raw material supply chains. For example, we are currently seeing problems of shortages of semiconductors made up of some of these elements that have disrupted or slowed down the production of cars and household appliances. The social result is that many workers may lose their jobs.
- The measures proposed in the report are necessary, although some of them, such as strategic stockpiling, are debatable as they could stress inequalities between countries and cause socio-political tensions. Arguably, the solutions proposed by the IEA, if successfully implemented, will postpone by a few decades what is already an open secret: an exponential increase in resource extraction is incompatible with a finite planet. This is the big message missing from the report. Curbing the accelerated degradation of resources by drastically reducing consumption should be the first pillar to avoid any future material disruptions and, most importantly, further damage to the Earth.

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