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► **To cite this version:**

Sophie Cerf, Adrien Luxey-Bitri, Clément Quinton, Romain Rouvoy, Thibault Simon, et al.. Untangling the Critical Minerals Knot: when ICT hits the Energy Transitions. 2023. hal-04709741

**HAL Id: hal-04709741**

**<https://inria.hal.science/hal-04709741v1>**

Preprint submitted on 25 Sep 2024

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# Untangling the Critical Minerals Knot: when ICT hits the Energy Transitions

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Dec. 2023

## Abstract

*Information & Communication Technology* (ICT) has insatiable needs for minerals, both in quantity and diversity. One should note that most of those elements are also required for the sector of energy transitions resulting from the net-zero greenhouse gas emission goals, hence adding up to the demand. Nations regularly evaluate minerals for their criticality regarding energy production. Such critical minerals can exhibit a high risk of supply disruption for geological, political or technical reasons. At the same time, global availability of minerals is a pressing challenge, due to multiple factors, such as recycling limitations and mines' grade degradation.

Unfortunately, research communities are still missing adequate analysis tools and metrics to properly evaluate and mitigate the mineral footprint of ICT, which is intrinsically multidimensional. This article aims to shed light upon the community's need to consider computing within mineral limits.

## 1 Introduction

To stabilize global warming, we ought to limit greenhouse gas emissions. In particular, reducing *greenhouse gases* (GHGs) emissions to net-zero by 2050 [1] notably requires moving away from fossil fuel, such that most energy sources become electrical. Until 2030, this implies a massive ramp-up of *critical mineral immobilization* to shift our energy infrastructure, including renewable production facilities (e.g. solar farms and wind turbines), stationary storage, and non-carbonated transportation. To steer this increasing electrical production and consumption, *Information & Communication Technology* (ICT) has a central role to play in the landscape of energy transitions. However, contrary to popular belief—that considers it as immaterial—ICT contributes to critical mineral immobilization for its extensive materiality through

the spread of data centers, network infrastructures, and devices. It thus draws on the same pool of finite resources that are needed for the energy transitions. This article is a first attempt to untangle the critical mineral knots that both ICT and energy transition sectors need to untie.

For several decades, numerous studies [2–5] have examined the interdependence of the energy transitions to mineral resources of primary and secondary origins—obtained from mining and recycling [6], respectively. However, the short-term availability of critical minerals may jeopardize the necessary manufacture of electricity plants, storage infrastructures, and electrical vehicles [7]. More specifically, all the infrastructures supporting this energy transition cannot be sourced from recycled materials for the time being, due to the extent and quality of required minerals. For the next two decades, our society therefore massively depends on resources of *primary* origin [4]. This means that, if the risks of critical minerals depletion are not addressed quickly, global progress towards net-zero will be hampered [8].

In this context, given the consensual objective of limiting GHG emissions [9] and the acknowledged limited availability of mineral resources, what are the constraints to be imposed on the development of the ICT sector? How can we objectively quantify the impact of ICT on the immobilization of critical minerals, accounting not only for device manufacturing and their associated infrastructures but also their massive need for electricity? We claim that answering these questions is a *sine qua non* step to shed light on the effective environmental impact of the digital sector, notably through the race for minerals. In particular, we believe that enabling sound public policing, individual usage shifts and pragmatic industrial adaptation requires thorough scientific analyses, comparisons, and projections.

## 2 The staggering growth of the digital sector

Our societies' unrelenting appetite for Internet access has caused an accelerating penetration rate of digital equipment in the population, accompanied by the growth of the backbone infrastructure. According to ITU's 2022 measurements [10], 5.3 billion people had access to the Internet in 2022 (66% of the population). That same year, 73% of the population aged 10 and over possessed a mobile phone. To cope with this rising demand, the volume of data exchanged over the Internet has grown by 33% every year since 2017, on average. The digital transformation of our societies requires the multiplication of devices, the expansion of network boundaries & throughput, but also the construction of more data centers to deliver the associated services.

## 3 Carbon-free considerations are not enough

A popular opinion sees the proliferation of devices, servers, and infrastructures—pictured in the idea of a "smart" society—as a necessary condition to reduce global GHG emissions and limit global climate change. With this in mind, some cloud providers set GHG-related goals for themselves, based on the "avoid, reduce, compensate" sequence. Google, for instance, announced that it offset its GHG emissions since 2007, and that it aims to go beyond and completely avoid any such emissions by 2027.<sup>1</sup> Nevertheless, carbon-free energy is not enough to solve the environmental equation. Firstly, focusing on the electrical footprint at usage time omits the hardware production's environmental impact, which can be much larger [11]. Producing the infrastructure for the massive amounts of carbon-free electricity that data centers need is also a titanic endeavor. Secondly, the environmental footprint of these infrastructures should absolutely not only be reduced to climate change. Other environmental impact categories must also be taken into account, such as resource depletion (including water), human & ecological toxicity, and land use, among others.<sup>2</sup> Accounting for the diversity of targets to preserve, such as ecosystems, human health, and natural resources, imposes to consider a more holistic range of impact categories. Such diverse criteria should thus be considered when evaluating current and future ICT prospects.

In this domain, while *Life Cycle Assessments* (LCA) are dedicated tools to “*study of the environmental impacts' contribution of a product or service across its entire life cycle*”,<sup>3</sup> we observe that thorough analyses are still publicly scarce and that the resulting data quality greatly varies. When openly available, their scope and system boundaries are not always explicitly stated and similar to other studies [12], and the uncertainty of the

results is almost never quantified [13]. For modular products (such as servers), hardware configurations can have huge consequences on the asset's environmental impact. In such a case, LCA can suffer from an *empty-shell bias*, where only unrealistically low-end configuration modelings are published. We, therefore, deem it crucial for such evaluations to be systematic, realistic, and openly available. Only then will it be possible to judge prospective ICT predictions in the light of their global environmental impact.

## 4 Our digital practices are deeply material

One of the most overlooked environmental impacts of the ICT sector is natural resource depletion. The digital sector's growth implies significant dependency on natural resources, including critical minerals. Many studies on critical minerals supply chains do not take into account the impact of ICT's constant growth, which has remained a blind spot in the forward-looking transition studies [2]. Yet, our surrounding digital devices (workstations, screens, tablets, smartphones, desktops, laptops, and even data centers) are made from critical minerals [4]. Emsbo et al. even claim that manufacturing a smartphone requires minerals covering up to two-thirds of the periodic table [2].

A mineral is considered *critical* when it serves an essential role for energy production, distribution and storage, and when geological, political, or technical reasons may hinder its supply chain. Lists of critical minerals are drawn up by nations and may differ according to their access to the resources or the technologies at their disposal. What is not considered a critical mineral today may be so tomorrow, and *vice versa*. We reported in Figure 1 the list of raw elements that are required to produce decarbonated electricity (excluding hydrogen and helium), energy storage and ICT (devices, infrastructure and data centers). With an orange background are displayed the 43 elements that appear in at least one of the following critical minerals lists: USA [14], Australia [15], Canada [16] and the European Union [17]. Only two elements (Oxygen and Iron) do not have criticality issue.

*By-products*, contrarily to main or co-products, result from smelting & refining and generate less than 1% of a mine's revenue. Their concentration and, therefore, their economic reality for mining investors, is only known once the mine is in operation and its smelting & refining infrastructure is running [3]. Figure 2 depicts the origins

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1. <https://cloud.google.com/blog/topics/inside-google-cloud/announcing-round-the-clock-clean-energy-for-cloud>. Last visited 05/11/2023

2. European Platform on LCA (EPLCA) <https://eplca.jrc.ec.europa.eu/lifecycleassessment.html>. Last visited 05/11/2023.

3. ISO 14040

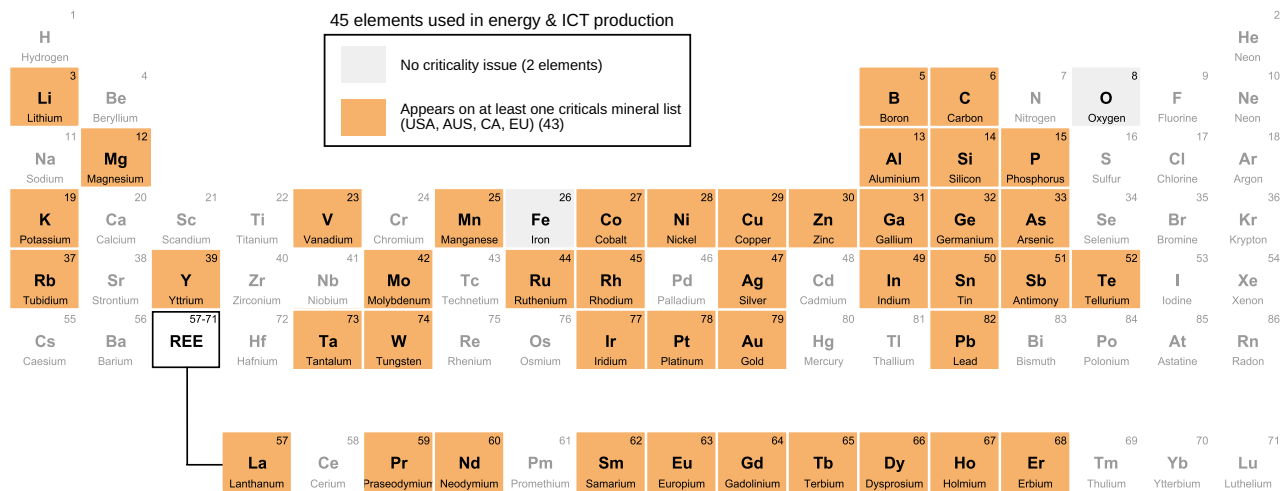


Figure 1: Criticality of the 45 elements of the periodic table immobilized for decarbonated electricity production (excluding hydrogen and helium), energy storage and ICT (devices, infrastructure and data centers). In gray, only two elements (Oxygen and Iron) pose no criticality issue. In orange, 43 elements appear on at least one critical minerals list, among the official lists from the USA [14], Australia [15], Canada [16] and the EU [17].

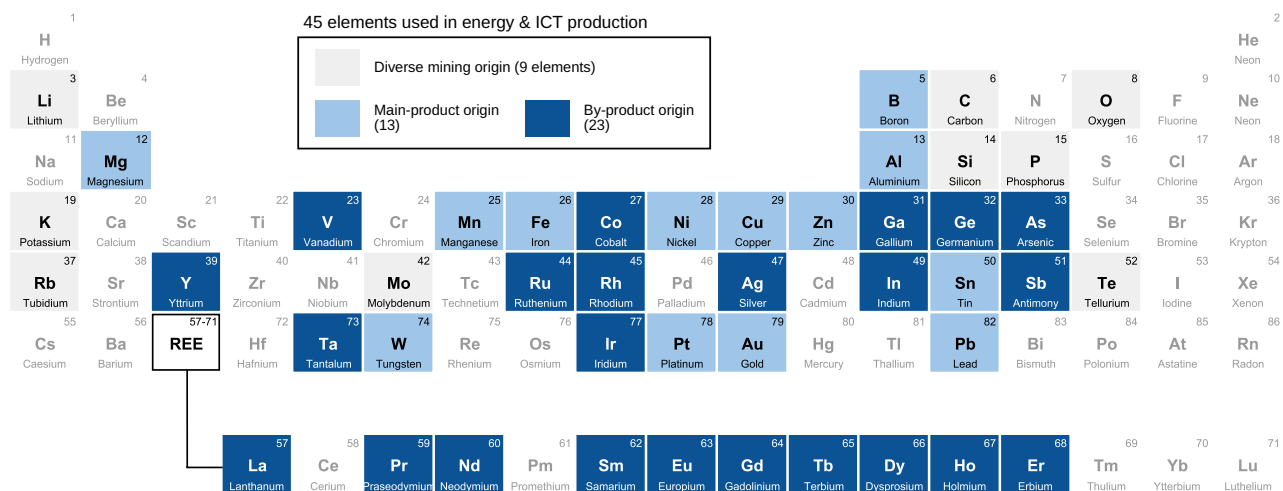


Figure 2: Mining origin of the 45 elements of the periodic table that are immobilized for decarbonated energy production, storage, and for ICT. Nine elements in gray come from diverse origins. In light blue, the 13 elements that provide a sufficient economic resource to be exploited as a mine’s main element, provided the deposit has sufficient grade content. The 23 elements in dark blue are only exploited in the form of by-products (there are generally no mines specifically exploited for them).

of elements used in the energy and ICT sectors: either diverse (9 elements), as a mine main-product (13 elements), or only available as a by-product (23 elements). It is of notable importance that all by-product minerals are labeled as critical in the previous figure. The digital sector is thus all the more vulnerable, as most of the minerals it requires are by-products [18]. The unavailability of a single one—caused by any supply issue of their main companion minerals—may, therefore, affect the sector as a whole.

The case of copper is particularly interesting, as it is not currently considered as critical in most critical min-

erals lists,<sup>4</sup> despite alarming signals [2, 5]. Firstly, its demand is exploding to support energy and digital transitions. Secondly, no significant copper deposit has been found since 2008, nor has any giant deposit in the last 25 years. Thirdly, several critical minerals (notably rhenium and cobalt) are mostly produced in copper mines as by-products.

Furthermore, for the time being, recycling is a pipe

4. The USA only added copper to their critical minerals list in their July 2023 update, see: <https://www.mining.com/us-department-of-energy-adds-copper-to-critical-minerals-list/>, Last visited 30/11/2023

dream. Recycling potential depends on the considered mineral and on the complexity of the product to be recycled. Unfortunately, state-of-the-art recycling technologies fail to deliver the high-purity substances required to manufacture ICT components. ICT uses alloys containing highly diluted minerals, notably for miniaturization and short-lived devices, hence limiting their recycling potential to around 1% [4, 6]. In addition, to be recycled, the product or infrastructure must have reached its end of life and be collected (whereas the ongoing energy transitions require an important quantity of *new* infrastructure to be deployed). As a matter of example, copper is currently immobilized for 45 years, on average [5], which seriously limits its availability for recycling.

Furthermore, many of the aforementioned minerals come from countries where environmental and human rights protection is lacking. Tantalum, for example, is essential for miniature capacitors in smartphones and comes mainly from the Great Lakes region of Africa. Recycled to a very low level, this element is currently classified as a conflict mineral [19]. Beyond the challenge of knowing the country of supply of primary metals, influencing working conditions, and environmental and social impacts will require further efforts. However, initiatives to trace resources and improve the ethics of the mining profession are emerging, raising hopes of a beneficial structuring of the sector.<sup>5</sup>

## 5 Conclusion & Call to action

Let us recap. On the one hand, our societies are ramping up the construction of carbon-neutral energy production infrastructures to alleviate climate change. During this intense phase, daunting amounts of minerals have to be extracted, “*equivalent or exceed[ing] the cumulative amount produced from Antiquity to the present*” [4], while mines are becoming scarce. Moreover, until the end-of-life of these infrastructures, these materials will be immobilized and hence unavailable for recycling. On the other hand, the digital sector (including its usages necessary for energy transitions) also immobilizes critical minerals for end devices, network infrastructures, and data centers. If the ICT sector continues on its current trend, will there be enough critical minerals for everyone?

Sustainable futures for ICT can—and must—be drawn. Only a combination of governance policies, industrial adaptation, and public awareness can achieve macroscopic change in due time. These political, industrial, and societal shifts must be strategically thought upon, through comparisons of alternatives, and prospective reasoning. Only thorough, unbiased, and publicly available scientific analyses will allow the instruction of public decisions. It is thus the scientific community’s role to survey the entire environmental impact of ICT (as is already done in other industrial sectors) and to imagine ways to reduce it.

Mineral impacts are multi-faceted and need metrics shared among several domains to be understood and collectively acted upon. The assessment of mineral impacts cannot be correctly captured by a single indicator, as the CO<sub>2</sub> equivalent captures climate ones. Indeed, available resources widely differ per host mineral, as do financial, environmental & social mining costs. Depending on its criticality, a single mineral can block the whole ICT supply chain, even if used only in limited quantity. All the more, sourcing by-products aggravates supply difficulties. Given the high dependency of ICT on critical minerals, it is thus high time that ICT academics precisely evaluate and carefully monitor the sector’s materiality.

Thankfully, many levers can be pulled to pilot the digital sector towards viable trajectories [20]: hardware repairability, reusability & recyclability; software configurations, update cycles & footprint; infrastructural deployments & maintenance; etc. The ICT community needs to explore the ways to do computing within limits, notably mineral ones.

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<sup>5</sup> See, for example, the work of Fairphone on building ethical mobile phones: <https://www.fairphone.com/en/category/fair-materials/>. Last visited 05/11/2023.

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