Critical Minerals - Vital Ingredients and Huge Challenge to Energy Transition

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Abstract: As mankind engages on yet another bold development cycle, all the newly-designed high technologies for a more sustainable future, primarily the technologies required by the energy transition, depend, inevitably, in terms of their implementation, on the mineral resources that our planet can provide. Especially the minerals deemed critical. This article looks at the impact that the switch to a new paradigm in the way we produce and consume energy is inflicting on the global demand for critical minerals, at the challenges and risks posed by this unavoidable process, as well as at the opportunities and the positive spillovers brought by it, providing relevant examples and data from the industries involved. Throughout this analysis, the conventional fossil fuels-based energy system and the renewable energy-based new system are compared from different angles, both in terms of their impact on the industries and markets of critical minerals, and of their strong influence on the socio-economic environment, on the international relations between states and the strategic and geopolitical interplay between the most important global technological powers of our time.

Keywords: critical minerals, high technologies, energy transition, electric cars, EV, rechargeable batteries, photovoltaic panels, PV, wind turbines, renewable energy

JEL Classification: N70, O13, Q40, Q42

1. A new paradigm in energy production and use

Humankind has developed and kept progressing by using both our planet's natural resources and human resources of smartness and creativity. Mankind exists and thrives thanks to humans' ability to harness not only our planet's flora, fauna and soil, but also the metallic and non-metallic minerals, the chemical elements and their compounds, as well as the fossil fuels that form deposits in the earth's crust.

As an expression of the utmost importance that mineral resources had in our evolution, the very first stages of human existence were identified in history as time-frames in which early collectivities made their main discoveries on how to extract, transform and use the planet crust's resources, naming these stages accordingly: as the first humans used minimally and rudimentary finished rocks to serve as tools or weapons, this evolutionary stage in their existence was named *the stone age*; later on, as they have gradually discovered and learned how to extract and process certain metals for their needs, the successive development stages of mankind were named after the metal predominantly used, *the bronze age* and then *the iron age*. Gold and silver, some of the first metals processed by man, have initially been used to create adornments, but later, with the advent and fillip of trade, they were also processed into coins, becoming payment instruments in commercial exchanges and giving a huge boost to development. Similarly, every other mineral, metal or source of energy discovered, processed and used along millennia contributed to the economic, technological and social progress of mankind, sometimes acting even as triggers of deeply transformative industrial revolutions.

As, on the one hand, they are essential to meeting peoples' primary needs (heating, light, cooked food) and, on the other hand, they are indispensable to the great majority of manufacturing and transport activities, *fossil fuels energy resources* (coal, oil, natural gas) were, and they still are, the pivot around which the world economy is organized and functions, having a huge impact on both the economic progress, the living standards, the national security of states and on their place in the world economy and hierarchies. Also – as the recent history shows – they can become potent geopolitical and geostrategic instruments of coercion of the states that are short of such resources, by the states that control them (see OPEC or Russia's oil and gas policies, for instance).

For centuries *fossil fuels* have been the premises of progress, richness and power, but also, as we more recently realize, they have been one of the main root-causes of the current environmental damage through land, water and air pollution, greenhouse effect and global warming that lead to climate change and extreme phenomena (floods, hurricanes, drought, wildfires etc.) which not only make havoc and victims increasingly often in various parts of the world, but they also gradually transform the geography itself (by desertification, glaciers and polar ice cap melting, sinking islands and ocean shores etc.) and deplete Earth's flora and fauna.

Life on Earth is seriously endangered. Therefore, it has become increasingly clear and accepted that the ***fossil fuel energy resources have neared the end of their pivotal role in the economic development of nations and in the economic, commercial, political and geostrategic relations between states.*** In terms of energy needs, nations must completely rethink both how they obtain and how they consume energy. In fact, the current industrial revolution envisages what life itself imposes on us with a high degree of emergency: a worldwide switch from fossil fuels used as source of energy, to new technologies that harness only clean and preferably renewable energy sources, doubled by a steady focus on drastically reducing pollution, wastage and the carbon content in the atmosphere, as well as a greater concern for recycling and efficient waste management. In a nutshell, we need to completely change the way in which we live, work, travel and produce goods and services.

In the new rationale of decarbonisation, the vehicles propelled by internal combustion engines and powered by fuels of fossil origin are already being replaced by new transport means - electric vehicles (EV) - equipped with electric engines powered by rechargeable electric batteries. In its turn, the electricity these batteries are stocking, or that which is used for heating, productive activities and everywhere else, should come either from the well-established technology of hydropower stations, or from solar parks, land and sea wind farms, geothermal installations and other new types of power producing units that harness clean and renewable energy from the water and air kinetics, solar radiation, or the Earth's inside heat.

The technologies and part of the new equipment and installations needed by this transition exist, are in production and some are already in use in sufficiently large numbers to reach the necessary economies of scale that make prices plunge and become accessible to customers while they are still profitable for producers, with no further need for subsidization.

Still, adopting the new paradigm of clean energy and of the world economy "turning green", brings important new challenges. They are primarily connected with the raw materials needed (i) to build the new types of power producing equipment – such as the photovoltaic panels (PV) for solar parks, or the turbines for wind farms –, (ii) to manufacture the devices that can efficiently stock and provide electricity according to needs (EV batteries, but also larger energy storage devices to be integral parts of the power grid systems) and (iii) to produce and use extensively new, non-polluting means of transport by land, water and air. All of these require both much larger quantities and a broader range of different raw materials, some of them quasi-ignored, hardly used and even thrown away in the past, but essential and irreplaceable when implementing these new technologies. As the minerals they are extracted from are either found in insufficient quantities and sometimes in just a few places on Earth, as they are often very difficult and polluting to extract and to process, as they may be subject to a (quasi)monopolistic regime or may be located in politically and economically unstable countries, they a prone to often disrupt the value chains of all the new high tech products and revolutionary technologies that depend on them and, as such, providing enough of them will be a great challenge for the global energy transition. That is why they are now considered *critical mineral resources* (CMR).

The most technologically developed countries of our time – US, EU, Japan, South Korea, Canada, Australia – have put together national lists of the minerals that are deemed critical from their specific point of view, lists which they periodically revise and upgrade with the purpose of better monitoring CMRs' availability and of devising the proper strategies to ensure that their high tech industries are not hampered by insufficient access to these inputs. Nevertheless, their totally justified alertness is late, as most of these critical mineral resources many of the raw materials and even the final products that are processed from them are currently controlled by China, a country known for its long-term approach in its strategies, that has already envisaged the issue and is decades ahead in implementing policies that placed itself in this favorable position, to the disadvantage of the other actors in the global markets, who are now dependent on China and quite vulnerable. Besides CMRs scarcity, access control by China is another big challenge that the other countries have to face during the energy transition and, in the case of some, primarily the US, in their technology war with China.

2. Energy transition and the demand for critical minerals

As mankind engages on yet another bold development cycle, all the newly-designed high technologies for a more sustainable future, primarily the technologies required by the energy transition, depend, inevitably, in terms of their implementation, on the mineral resources that our planet can provide. Especially the minerals deemed critical.

According to current knowledge on global mineral deposits, many critical minerals are scarce, either geographically concentrated in a few countries, or extremely dispersed all over the globe, so that they are rarely found in sufficient volumes to be mined at a profit. Additionally, they are difficult and very polluting to extract and process, and are often under the control of only a few actors, either their source-countries, or, most often, China. That is why procurement is and will continue to be difficult and value chains are and will continue to be easily disrupted.

On the other hand, CMRs are vital for the new technologies in general and specifically for the energy transition, many of them having unique qualities that render them irreplaceable, at least at this stage of technological development. As such, in the foreseeable future, demand will be on the rise and countries will have to fiercely compete for these resources. That will further trigger price upswings, but it might also encourage investors to reopen former inefficient mines and new explorations might be decided and financed. Still, new mines often need long time-frames, sometimes more than a decade, to become operational and, therefore, their positive impact on the market is most probably going to be felt with a considerable delay.

Energy transition and the ambitious plans of many countries regarding the *green revolution* have already triggered a considerable upswing in critical minerals demand and prices. In fact, ***the most active part of the critical minerals demand comes from the key industries involved in the low-carbon emissions crusade waged as part of the energy transition process*** – the manufacturers of electric vehicles (EV), photovoltaic panels (PV), wind turbines, batteries and other equipment that can store electricity etc. – ***as well as from their subcontractors*** – the producers of various types of semiconductors, electric batteries, permanent magnets, alloys, oxides and other secondary processing commodities etc. Hence, ***clean energy transition turned the energy sector into a major force in the minerals' global markets, where it had been an insignificant presence before 2015, but afterwards it started playing an increasingly important role.*** In the synoptic table hereunder one can see the most significant metals involved in the current energy transition – including those processed from critical minerals –, along with the final products and technologies which require them.

Table 1: Critical mineral inputs for the transition to new energy technologies

Critical minerals	Electric engines	Concentrating solar power	Energy Storage	Carbon capture and Storage	Electric Vehicles (EV)	Nuclear electricity generation	Photovoltaic panels (PV)	Light emitting diodes	Wind Turbines
Aluminum	■	■	■	■			■	■	■
Chromium				■		■		■	■
Cobalt			■	■	■	■			
Copper	■			■	■	■	■	■	■
Indium					■	■	■	■	
Iron(cast)		■	■					■	■
Iron(magnet)	■								■
Lead						■	■	■	■
Lithium			■		■				
Manganese			■	■	■				■
Molybdenum				■		■	■	■	■
Neodymium*					■				■

Nickel			■	■	■	■	■	■	■
Silver		■			■	■	■	■	
Steel									■
Zinc							■	■	

Note: *A proxy for rare earths (REE).
Source: World Bank (2017).

The newly developed technologies for the energy transition and the materials they use are creating the prospect of a swift increase in the demand for minerals that used to be produced only in comparative small quantities not long ago. This is, for instance, the case of *lithium, cobalt* or *nickel,* needed for the *rechargeable batteries* that equip the EVs, or of the *rare earths elements* (REEs), which are now indispensable for the *fluorescent bulbs* production and, more importantly, for the manufacturing of the *permanent magnets* that are vital for wind turbines and electric vehicles, or it is the case of elements such as *cadmium, tellurium, indium*, needed to produce the *photovoltaic cells* (Eggert, 2010; IEA, 2020). Hereunder we exemplify in more concrete terms how the critical minerals demand is propelled by the pressure exerted by the downstream industries involved in the energy transition.

Example no. 1: electric vehicles and batteries

There were 11.2 million electric cars in use in 2020, but according to IEA[1], if governments intensify their efforts to reach the energy transition and climate goals, the global EV number is expected to reach 145 million units by the end of this decade and 230 million units by 2050. A single EV needs on average 1 kg of REEs to produce the permanent magnets that make a vital part of its electric engine, therefore, such an upswing in expected EV production will be reflected in a similarly abrupt growth of REE demand. Another important and at the same time the most expensive component of any EV is its rechargeable battery and again when the EV global fleet is expected to register such a growth, the demand for electric batteries is of course expected to increase accordingly. This upswing will further trigger a considerable increase in the global demand for *lithium, cobalt, nickel, graphite* and the other metals and materials used in the electric battery production.

To give a rough idea on the critical minerals growing needs under the circumstances, Table 2 presents the mineral mix in an average electric Li-ion battery, while Table 3 provides a relevant comparison between the usual lead-acid battery technology for an internal combustion car, and the new technology of the Li-ion battery for EVs, in terms of the metals they require: while the older technology needs only lead and steel, the second one, for EVs, needs six different metals, at least four of them included in the critical minerals listings of all the technologically developed countries. Also, as Table 2 reveals, not only the diversity of metals required by the newer technology, as seen in Table 3, but also the quantities of metals needed for an average Li-ion battery that propels electric vehicles, critical ones included, are quite impressive.

Table 2: The metals and minerals[2] mix in an average Li-ion battery for EV (60KWh), 2020

Minerals used in a 60KWh Li-ion battery	The components in which they are used	Total quantity per average battery (kg)	Percentage of the battery weight (%)	Notes*
1. Graphite	Anode	52	28.1	Abundant, cheap resource, with a long life cycle.
2. Aluminum	Cathode, case, electricity collectors	35	18.9	

[1] IEA = International Energy Agency
[2] The materials used in the electrolytes, glues, separators and cases are not included.

3. Nickel	Cathode	29	15.7	It is used to increase the energy density
4. Copper	Electricity collectors	20	10.8	It has the highest electric conductivity
5. Steel	Case	20	10.8	
6. Manganese	Cathode	10	5.4	It is a stabilizer, it increases safety
7. Cobalt	Cathode	8	4.3	It is a stabilizer, it increases safety
8. Lithium	Cathode	6	3.2	
9. Iron	Cathode	5	2.7	
TOTAL		185 Kg	100%	

Note: *Based on the general literature in the field.
Source: Bhutada (2022).

Table 3: Comparison of the metal content in lead-acid and Li-ion batteries

Metals required	Energy storage batteries	
	Lead-acid	Lithium-ion
Aluminum		▪
Cobalt		▪
Lead	▪	
Lithium		▪
Manganese		▪
Nickel		▪
Steel	▪	▪

Source: World Bank (2017).

Moreover, keeping in mind the expected up-swing in EV production and considering the data in Table 4, which provides another relevant comparison, this time between the metals needed for the manufacturing of an electric car, versus those necessary for building a conventional one, we can get a pretty good idea on the huge size that demand for critical minerals might come to reach by 2030 and further on by 2050 and on the pressure that EV manufacturing might inflict on the critical mineral resources, on their exploration, mining, processing, pricing, competition and trade between firms and between countries.

Table 4: Metal demand – comparison: electric car vs. conventional car

Kg/car	Copper	Lithium	Nickel	Manganese	Cobalt	Graphite	Zinc	REE
Electric car	53.2	8.9	39.9	24.5	13.3	66.3	0.1	0.5
Conventional car	22.3	-	-	11.2	-	-	0.1	-

Source: IEA (2020; 2021).

Manufacturing more electric vehicles is going to push up the extension of production capacities for electric batteries. In 2020, the global production capacity of rechargeable electric batteries cumulated 755 GWh, but in the project and building phases there were additional capacities of other 3792 GWh (or 3.8TWh) by 2030, accounting for a 402% capacity increase in the 2020-2030 time-frame. Out of the entire 2030 global production capacity, 70% is projected to be built in China, 16% in Europe and 11% in North America. Against this background, *lithium* demand is estimated to jump from 300,000 m.t.[3] in 2020, to 1 million m.t. in 2025 and to 2 million tons in 2030 (Palandrani, 2021). Due to its central role in replacing fossil fuels with EVs in transports, *lithium* is considered the „oil of the future" (Durkin, 2021).

According to the EU forecasts, *cobalt* demand is going to increase 5 times by 2030 while *lithium* demand will grow 18 times by 2030 and 60 times by 2050 (Eggert, 2010; IEA, 2020; Wrede, 2022). Also, in one of its studies IEA (2021) forecasted a 50 times larger demand for *lithium* and 30 times larger for *cobalt* and *graphite* in 2040, as compared to their levels of 2020.

According to market analysts, the world's largest auto-makers plan to spend nearly USD1.2 trillion in order to develop and manufacture millions of electric vehicles, batteries and raw materials for these (Barrera, 2023). The impact of the global automotive industry's growing demand for the critical minerals needed in the EV production is already being felt, pushing raw materials prices up, and this trend is going to continue.

Example no. 2: wind turbines

In 2020, the size of the global market for wind turbines was evaluated at USD 54.3 billion and forecasted to reach USD 98.4 billion in 2030, at a compound annual growth rate (CAGR), going to become, as such, one of the most dynamic energy sector.

According to IREA[4], to reach carbon emissions neutrality by the middle of this century, the global cumulated capacity of land wind turbines should triple by 2030 (up to 1787 GW) and to increase nine times by 2050 (up to 5044 GW) relative to the 2018 level, when the global installed capacity totaled 542 GW. With such a fillip of wind turbines installations, the need for permanent magnets and implicitly for the heavy rare earths (HREE) they are made from (neodymium, praseodymium, dysprosium, and terbium) is expected to grow explosively. Considering that just one terrestrial wind turbine needs to be equipped with permanent magnets that require 600 kg of heavy rare earths to be produced, it is obviously anticipated that the pressure on REE mining and refining will become huge, the more so as HREEs normally make only one third of the total REE volumes extracted (Mitchel, 2022)[5].

Permanent magnets are used not only in wind turbines production, but also in the manufacturing of electric engines for EVs. For 2021-2030, *Adams Intelligence* consultancy predicts a jump at 9.7% CAGR in the world demand of REE oxides for permanent magnets (mainly for neodymium, praseodymium and didymium) estimating that the global shortfall for these oxides will reach 16000t in 2030. This is expected to further generate an annual 48000t deficit in the global offer of neodymium-iron-boron powder and alloy by 2030, which is the necessary quantity to produce 25-30 millions electric engines for EVs (Mitchel, 2022).

Growing demand for HREEs already pushes prices up and the trend will certainly go on.

Example no. 3: photovoltaic panels

Similarly, photovoltaic panels demand is expected to rapidly grow, as the electricity from solar source has already become the cheapest electricity ever produced by mankind. Also, one can expect a swift surge in global photovoltaic panels demand considering IEA's predictions that, as compared to 2019 when solar energy met only 2% of global electricity demand, by 2050 the photovoltaic parks' production will come to cover about one third of the world's electricity demand (Watson, 2022).

Investors feel encouraged to massively finance solar parks installation. Only China, the largest world manufacturer of PVs and leader of this upward trend, plans to increase its installed solar capacities by 25 GW annually by 2030, an endeavor that will determine that one third of the worldwide solar capacity installed between 2019 and 2030 to be in this country. Obviously, such an upswing in demand for PV production and installations will generate a huge demand for the necessary critical minerals, especially for *gallium, cadmium, tellurium, indium,* but also for *aluminum* (Umar, 2019).

[3] m.t. = metric tons

[4] IREA = International Renewable Energy Agency

[5] There are 17 different elements included in the group called rare earths/rare metals (REEs), some of them light (LREEs), some heavy (HREEs). They have very different features, but are to be found mixed together in common ore deposits, which makes industrial separation a complex, difficult and highly polluting process. For high tech industries the heavy rare earths are of interest, but these normally make only one third of the mixed ores extracted, therefore to get the necessary quantities it must be roughly mined and refined a three times bigger quantity of REE ore. This has obviously an impact on costs, prices and the necessary time to produce the required HREE volumes.

Example no 4: semiconductors

The most advanced technologies of present and future, including the fundamental ones for the energy transition, depend on the capacity of humankind to manufacture increasingly sophisticated and advanced semiconductors[6] (e.g. *leading-node logic chips,* the most advanced semiconductors that are essential for the on-coming quantum computing, artificial intelligence, robotics, advanced wireless networks and all the other daring technologies of the future). At the very least, manufacturing any logic semiconductors requires over 300 different materials (i.e. minerals, industrial gases and chemicals, with very specific and sometimes unique features that render them irreplaceable).

Almost a decade ago, the American chip-maker *Intel* stated – and it was later on confirmed by the evaluations of the *UK Office of Science and Technology* -, that if in the 1980s production of semiconductors for computers used raw materials derived from 11 chemical elements and in the 1990s there were used to the same purpose 10-15 elements, by 2020 microchip manufacturing was already using 60 elements from the Periodical Table. Altogether, in 2020 the minerals' and metals' usage rate increase triggered by the down-stream industries demand reached 80% of the global production of *REEs, indium, gallium*, and of all the metals in the *platinum group*, relative to the situation in 1980 (Eggert, 2010; Umar, 2019).

Minerals are crucial for semiconductor industry, some of the most used of them including *silicon, gallium arsenide, REEs and cobalt.* As semiconductors are required in more and more diverse and sophisticated applications, their demand has soared in terms of both quality (speed, safety of operation etc.) and quantity, generating in recent years a steep surge in the demand for the critical minerals and metals that they use. For instance, *cobalt* demand has grown by 30% during the short 2019-2020 time-frame, while the demand for *ruthenium* and *iridium* increased by triple digits between early 2020 and early 2022 and *silicon* demand jumped by 300% in less than a year, between August and December 2021 (Dwivedi & Wischer, 2022). Such abrupt surges in demand almost always determine significant supply shortages and prices up-swings, and the more so this happens in the case of the minerals deemed critical.

To better understand the impact that the shortage of critical minerals might inflict on the semiconductor industry, the US case - the country where this technology was born and which still remains one of the few major chipmakers in the world -, seems to be most telling: in 2018 the US Geological Survey identified and listed 35 minerals as *"... critical to the economic and national security of the United States"*. Out of the 35 critical minerals, not less than 30 have a direct impact on chip production, for 23 of these 30 minerals, the US import reliance goes beyond 75%, and for 12 of the 23, there is an import reliance of 100% on a single source, and that source is China (Dwivedi & Wischer, 2022). Obviously US microchip production influences global demand for most of the critical minerals in the US list (30 of the total 35!) and insufficient supply of any of the 30 minerals, which in their great majority are imported, have a considerable potential to disrupt US semiconductor supply chains and production. As China is dominant in both the mining and refining of most of the critical minerals included in the highly developed countries' lists, not only the US, but also the EU, Japan, South Korea and probably others are in different degrees vulnerable, risking supply disruptions, price manipulation and even geo-political pressure and blackmail.

3. Energy transition and the critical minerals' challenges

Energy transition is not an easy or quick process. On the contrary, switching to a completely new paradigm in energy production and consumption, replacing fossil fuels with renewable and non-polluting energy sources and completely reforming and reorganizing the functioning of our future world around a new pivot, the critical mineral resources are very complex, lengthy and challenging transformations, both on the demand and supply side. At the same time is unavoidable.

3.1 Demand-side challenges

As already demonstrated, ***energy transition is intensive in critical mineral resources***, leading as such to a strong surge in critical minerals demand. The energy systems resting on technologies that harness clean and renewable energy resources differ profoundly from the conventional ones still in operation, which rely on burning fossil fuels. Building photovoltaic parks, wind farms or electric vehicles, as the new paradigm requires, consumes

[6] Semiconductors, integrated circuits, (micro)chips are notions roughly equivalent and are generally, as well as in this article, used interchangeably.

considerable more mineral resources than the power stations that produce electricity or the installations that provide heating by simply burning coal, natural gas or oil-based products (IEA, 2021).

Building a land wind farm needs 9 times more mineral resources than building a gas power station, while an average electric car needs 6 times more mineral inputs than a conventional one equipped with an internal combustion engine. In Table 5 we have a comparative illustration of the critical minerals needs for building green or conventional energy producing installations.

Table 5: Needed mineral quantities for energy-producing installations, by energy source

Energy type Kg/MW	Copper	Nickel	Manganese	Cobalt	Chromium	Molybdenum	Zinc	REE
Offshore wind	8000	240	790	-	525	109	5500	239
Onshore wind	2900	404	780	-	470	99	5500	14
Solar PV	2822	1,3	-	-	-	-	30	-
Nuclear	1473	1297	148	-	2190	70	-	0,5
Coal	1150	721	4,6	201	308	66	-	-
Natural gas	1100	16	-	1,8	48,3	-	-	-

Source: IEA (2021).

The critical minerals required by energy transition and the markets' dynamics differ according to technology (IEA, 2021):

- *Lithium, nickel, cobalt, manganese* and *graphite* resources are crucial for the technical performance, recharging speed, energy density, longevity and safety of the electric batteries for EV. In these minerals' markets, demand will follow the evolution of the EV demand.
- *REE* resources are essential for manufacturing permanent magnets which, in their turn, are vital for wind turbines and electric engines production, but are also important for making other car devices, that improve comfort, as for instance the automatic adjustment of mirrors, windows and seats. In the HREE market demand will be strongly influenced by the evolution of wind turbines and EVs markets, but the LREE demand, which is not influenced by the energy transition, demand will stay stable.
- *Copper* and *aluminum* resources are needed in high quantities for the extension of power grids. In their case, demand will be influenced by the compounded impulses coming from the numerous down-stream industries that use them.

3.2 Supply-side challenges

Still, for the great majority of critical resources the main concerns are not demand-side focused, but connected with supply-side issues: the available quantities of critical minerals are increasing much slower than their demand does, both for technical reasons and, more worryingly, because of the insufficient quantities existing on our planet. Under the circumstances, competition flares up, prices soar and at least a part of the green energy cheapening, which was obtained due to economies of scale, is risking to be lost. At the same time, as quite many critical resource markets are (quasi)monopolized, the risk of price manipulation, or that of turning resources into means of coercion of the dependent and vulnerable countries by the ones that detain control over these resources and/or over their refining capacities and technologies, are significant.

To increase critical minerals supply, large investments in exploration and mining are needed. According to estimations by *Wood Mackenzie* consultancy, in the next 15 years the global mining industry needs additional investments of USD 1700 billion in order to be able to provide the mineral supply asked for by the renewable energy technologies (LePan, 2021). However, new mines often need 7 to 15 years to become fully operational and the return to investments come similarly late, acting as such as a discouraging factor for investors.

In the meantime, under additional the impact of the COVID-19 pandemic and of the war waged by Russia in Ukraine, the critical minerals demand/supply gap kept getting larger, pushing prices up. For the great majority of the resources that are vital for the energy transition the 2021- Q1/2022 price increases exceeded by far their largest upsurge in the 2010s. From solar and wind farms to batteries, the steady downward trend of production costs registered in the preceding decades was almost reversed as a result of the 2021 price surge in critical minerals: the estimated price of the wind turbines mounted by 9%, that of the photovoltaic modules by 16% and for Li-ion rechargeable batteries by 5% (Kim, 2022).

An important peculiarity of the critical minerals production and refining is their high geographic concentration. For instance, just one country, D.R. Congo, mines 80% of the *cobalt* produced yearly on the planet, China produces 70% of the *REEs,* Australia 52% of *lithium,* Indonesia 33% of *nickel*, while Chile, Argentina, R.D. Congo and Peru provide together the largest part of the annual global *copper* supply (Klare, 2021). Geographic concentration takes a toll on the accessibility to critical minerals, on the safe functioning of their global value chains and it creates vulnerabilities and relations of dependency between states.

Increasing mining in order to push up production of critical minerals rises many specific problems too, as for instance:

- *The decreasing quality of deposits.* For instance, the average quality of the copper ore in Chile has decreased by 30% in the last 15 years;
- *The production of critical minerals that are secondary products to other minerals' mining depends on how the demand for the main mineral evolves;*
- *The most promising deposits of some minerals are located in economically and politically unstable countries;*
- *The high costs and risks of investments in new mining projects vs. much delayed returns dampen investors;*
- *The highly polluting effect of some of the minerals' mining or refining processes that determine the communities' refuse to accept new mining projects* (e.g. the rejected lithium mining projects in Ireland, Greenland or Serbia).

Besides the geographic concentration of mining, which is the result of natural distribution of global resources, there is also a geographic concentration of the industrial separation and refining processes, which is often the result of deliberate policies that decide if a country is ready to assume the risk of inducing high pollution in its territory, or it would rather prefer to simply import the raw materials that are obtained through very polluting secondary processing.

China accepted a few decades ago to carry out and develop these highly polluting activities and at present is separating and processing 87% of the rare earths, 90% of the heavy rare earths (dysprosium and neodymium used for permanent magnets fabrication), 65% of the cobalt, 58% of the lithium, 40% of the copper, 35% of the nickel etc., produced yearly in the world (Edward, 2022; Venditti, 2022; Klare, 2021; Umar, 2019). Altogether, China refines 45% of all the critical resources mined annually worldwide, ranking first, while the other 10 big providers that follow in the top cover together 35% of the total global supply.

Chinese domination in the global value chains of green energy technologies developed for a low carbon future is overwhelming, extending also to links responsible for key components and even to complete final products as shown in Table 6.

Table 6: Top 3 manufacturing regions of green tech by shares in global wind, solar and EV capacity, 2021

Green Technology	Main links in GVCs	Country/Region ranking 1st by capacity share	Country/Region ranking 2nd by capacity share	Country/Region ranking 3rd by capacity share	Total global capacity
Offshore wind	tower	China: 53%	Europe: 41%	Asia-Pacific*: 6%	18 GW
	nacelle	China: 73%	Europe: 26%	Asia-Pacific : 1%	26 GW
	blades	China: 84%	Europe: 12%	Asia-Pacific : 4%	25 GW
Onshore wind	tower	China: 55%	Europe: 16%	Asia-Pacific : 12%	88 GW
	nacelle	China: 62%	Europe: 10%	Asia-Pacific : 13%	100 GW
	blades	China: 61%	Europe: 18%	Asia-Pacific : 6%	98 GW
Solar	wafers	China: 96%	Asia-Pacific: 3%	-	367 GW
	cells	China: 85%	Asia-Pacific:13%	Europe: 2%	409 GW
	modules	China: 75%	Asia-Pacific:18%	Europe: 3%	461 GW
Electric vehicle	cathodes	China: 68%	Asia-Pacific: 26%	Europe: 2%	1.4 mil.t.
	anodes	China: 86%	Asia-Pacific: 12%	N. America: 1%	0.8 mil.t.
	batteries	China: 75%	Asia-Pacific: 11%	Europe: 8%	899 GWh
	Electric cars	China: 54%	Europe: 27%	Asia-Pacific: 10%	7 mil. cars

Source: Processed after Oguz & Parker (2023).

4. A few final thoughts on the future

Although the difficulties and hurdles that might impede energy transition are quite numerous and hard to settle, the new exploration and mining investments in critical minerals are very costly, risky and long-taking before bearing any fruit and although the international context might be quite unfavorable, ***mankind has no other solution but to get through this transition in order to mitigate climate change, create a low-carbon environment and, ultimately, avoid life extinction on Earth and allow for a clean technology-driven new beginning***.

Energy transition will most probably take quite long, both because of the techno-economic and geo-political reasons mentioned here, and given that no country will be able to abruptly give up fossil fuels, but it will have to transit gradually to using clean energy only, in step with the extent of its accomplishments in new green technologies implementation in its economy, while keeping its national energy system balanced.

To this end, research, development and innovation (RDI) activities will have to play an essential role in (i) finding new and more sustainable solutions of mining and processing ores, (ii) efficiently capitalizing on the secondary minerals in mine debris, (iii) treating polluted land and waters, (iv) capturing and stocking the excessive CO_2 in the atmosphere, (v) recycling used critical metals and materials, (vi) discovering substitutes for rare chemical elements, and much more.

On the other hand, given the extended control and market domination exerted by China on many of the critical resources' mining and processing activities, as well as on the manufacturing of some key parts and components (e.g. permanent magnets, rechargeable batteries, cathodes, electric engines, wafers, solar cells etc.) and even of entire final products, vital for the global energy transition (e.g. electric vehicles, photovoltaic panels), ***no country in the world will be able to successfully complete this transition in the absence of an acceptably good economic relationship with China.*** Irrespective of any efforts the advanced economies would be ready to make in order to mitigate their excessive dependency on imports from China, an honest evaluation of the current status would show that there are no short-term or medium-term realistic prospects to totally eliminate this vulnerability. That is why, especially the US, with its Trumpist decoupling policy, but also the EU, which used to be moderate and more nuanced in its policies, but is now in a cool relationship with China, as well as the other economies worldwide will have no choice but to re-evaluate to what extent maximizing the distance and inflexibility towards this country would allow them to complete their energy transition and succeed in building a low-carbon future, based on renewable clean energy, digitization and high technologies.

It is very important to note here that ***once the energy transition advances significantly more, and especially once it nears completion, the surge in the critical minerals' demand, and prices, determined by the huge needs of the green technologies' implementation process, might soften and, ceteris paribus, also China's power of influence in these markets might start fading***, for a simple reason: unlike fossil resources, critical minerals are not fuels, they are not burnt to obtain energy, they are not consumed in the process of energy production – as coal, oil and natural gas are – and, therefore, they don't require to be continually replaced. Critical minerals are used to build equipment, installations and power grids that harness renewable sources of clean energy (primarily sunlight, wind and water natural kinetics), an energy which is endless and bears no intrinsic costs. ***Moreover, the equipment used to capture, transform into electricity, store and transport renewable energy can be used continually for extended periods of time and the critical materials they include can be recycled once this equipment becomes obsolete or physically worn.*** Critical metals can be recycled over and over again, without losing their qualities. Copper, for instance, can be recycled endlessly in proportion of 100% without losing its exceptional conductivity quality. As such, in the future, besides the critical metals and materials processed after mining, another important source of global supply will be a secondary market of recycled critical metals inputs, which will be easier to re-process and therefore cheaper, while preserving the same qualities. This will most probably be another factor that will push prices down, will diminish the geographic concentration of supply (as recycling, just like renewable energy production, will be developed all around the planet), will help subdue the risks of value chain disruptions and will dent China's market dominance.

Another positive fact regarding critical minerals is that in their industry the ownership structure is totally different from the one dominant in the hydrocarbons' sector: ***while in the oil and gas industry, between 75% and 80% of the oil and gas reserves are controlled by national state companies which typically disregard market signals and act as if they are extensions of their governments' interests, in the critical minerals sector the largest part of the natural reserves and of production is in private ownership and under the control of shareholders, therefore companies act to their owners' best interests, in response to market forces and without willfully distorting market mechanisms.*** More specifically, for instance, none of the first six largest *lithium* producers in the world, covering 66% of the global market, is a state company. Also none of the first five largest *cobalt* producers in the world, covering 50% of the world's cobalt needs, is a state company. In this latter case thou, a question mark still remains, as these firms are from China, a country where the dividing line between the two major ownership types – state or private – is blurred and difficult to establish. Anyway, until now, companies in the critical minerals field did not significantly behave as if they were implementing their national states' directives (Hendrix, 2022).

Even if now, at the beginning of the energy transition, market tensions, competition and the evolution of prices tend to become explosive, they will not necessarily reach the stage of a major crisis or of an economic war, if, understanding the crucial importance of a smooth switch to a new energy paradigm, countries will develop and manage wisely their trade, investment and cooperation relations, doing their best to succeed together in this transition and not each one against the others. Those actors in the global markets that are controlling the deposits, production and refining capacities of critical resources will still gain important profits, without using their market power as a weapon against competitors, impairing their energy transition.

However, even now, and the more so later on, when the energy transition will have advanced towards its completion, any temporary crises that might still ignite in these markets will never have the economic destruction power that the oil and gas crises had so many times. A temporary supply shortage – be it in the lithium, cobalt or some of the most important REE markets – will generate consequences only in, arguably, a limited number of industries – as for instance in the rechargeable batteries manufacturing and further on in the production of new EVs –, but it will never have the potential that oil or gas supply crises had and still have, of swiftly spreading across continents, across activities and in every aspect of human existence, causing huge economic damages, denting living standards, plunging entire populations in darkness and cold, and impoverishing them by triggering inflation flare-ups.

During a potential temporary supply shortage in one or more of the critical minerals' markets, the installed photovoltaic parks, the wind farms, the hydropower stations and all the other power units that generate green, clean and cheap energy, will continue to do that, uninterrupted, all over the world; power grids will keep on transporting electricity everywhere, people will go on driving their electric vehicles, factories will keep functioning, houses will still have functional lighting and heating and all their electric and electronic devices working, while collectivities will continue to be well supplied with all the goods and services they might need.

REEs, lithium, cobalt and other critical minerals will be, indeed*, *"the oil and gas" of the future, they will turn the former "irreplaceable" fossil fuels into totally replaceable resources for the world's energy needs. But, at the same time, they will be fundamentally different, at least because, from a longer-term perspective, critical minerals won't be equally dangerous for the natural environment and for life on Earth as the fossil fuels have become, and, also as, once in a supply shortage, their crises won't impact the global economic environment as comprehensively and dangerously as the fossil fuels often did.

In a world powered by renewable energy coming from multiple producers spread across the globe, price manipulation and deliberate market distortion induced designed to increase the profits and power of a few big producers, as well as the economic blackmail and the decisions with geopolitical and strategic significance forcefully imposed on others (practices that have long been instrumented by the oil and gas largest global producers acting as extensions of their national states), will no longer be the norm, but at most the exception, and, in case they happen, they will no longer have the same reach and force of impact as fossil fuels did. Still, for that world to come to exist in the future, how energy transition advances globally from now on becomes crucial.

References:

[1] Barrera, P. (2023). *EV market forecasts 2023: Top trends that will affect EVs in 2023*, February, 1, https://investingnews.com/electric-vehicle-forecast/**.**

[2] Bhutada (2022). *The Key minerals in an EV battery*, May, 2, https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/;

[3] Durkin, A. (2021). *Lithium is „the new oil" as EV market expands*, September, 21, https://www.hinrichfoundation.com/research/article/sustainable/lithium-new-oil-as-electric-vehicle-market-expands/

[4] Dwivedi, Sh., Wischer, G. D., (2022). *Critical materials can make or break America's semiconductor supply chains,* The National Interest, May, 10, https://nationalinterest.org/blog/techland-when-great-power-competition-meets-digital-world/critical-materials-can-make-or-break

[5] Edward, J. (2022). *China's critical minerals strategy*, August, 16, https://skillings.net/chinas-critical-minerals-strategy/;

[6] Eggert, R. (2010). *Critical minerals and emerging technologies*, Science and Technology, Vol. XXVI, No. 4, Summer, https://issues.org/eggert/ ;

[7] Hendrix, C. (2022). *How to avoid a new cold war over critical minerals*, November, 22, https://foreignpolicy.com/2022/11/22/critical-minerals-resources-us-china-competition-cold-war-supply-chains/ ;
[8] IEA, (2020). *Clean energy progress after COVID-19 crisis will need reliable supplies of critical materials,* May, 6, https://www.iea.org/articles/clean-energy-progress-after-the-covid-19-crisis-will-need-reliable-supplies-of-critical-minerals?utm_content=bufferee9c0&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer
[9] IEA, (2021). *The Role of Critical minerals in clean energy,* May, revised March, 2022, https://iea.blob.core.windows.net/assets/ffd2a83b-8c30-4e9d-980a-52b6d9a86fdc/TheRoleofCriticalMineralsinCleanEnergyTransitions.pdf ;
[10] Kim, T-Y, (2022). *Critical minerals threaten decades-long trend of cost declines for clean energy technologies,* May, 18, https://www.iea.org/commentaries/critical-minerals-threaten-a-decades-long-trend-of-cost-declines-for-clean-energy-technologies ;
[11] Klare, M. (2021). *Will there be resource wars in a renewable future?*, May, 25, https://scheerpost.com/2021/05/25/will-there-be-resource-wars-in-a-renewable-future/ ;
[12] LePan, N. (2021). *All the metals for renewable tech*, May, 27, https://elements.visualcapitalist.com/all-the-metals-for-renewable-tech/ ;
[13] Mitchel, J. (2022). *Can the West break China s stranglehold on rare earth supply chains?,* October, 12, https://www.investmentmonitor.ai/sectors/extractive-industries/china-rare-earths-supply-chain-west ;
[14] Oguz, S., Parker, S (2023). *Where are clean-energy technologies manufactured?,* March, 28, https://elements.visualcapitalist.com/where-are-clean-energy-technologies-manufactured/
[15] Palandrani, P. (2021). *All EV roads lead to lithium miners and battery producers*, June, 14, https://globalxetfs.eu/content/files/All-EV-Roads-Lead-to-Lithium-Miners-Battery-Producers.pdf#:~:text=All%20EV%20Roads%20Lead%20to%20Lithium%20Miners%20%26,internal%20combustion%20engines%20%28ICEs%29%20and%20towards%20battery-powered%20vehicles.
[16] Umar, A. (2019). *How dependant is the UK on critical minerals?,* December, https://mine.nridigital.com/mine_dec19/how_dependant_is_the_uk_on_critical_minerals;
[17] USDI / US Department of the Interior, (2022). *US Geological Survey Mineral Commodities Summaries* 2022, January, 31, https://www.sciencebase.gov/catalog/item/6197ccbed34eb622f692ee1c#:~:text=National%20Minerals%20Information%20Center%2C%202022%2C%20Mineral%20commodity%20summaries,production%20statistics%20for%20over%2088%20nonfuel%20mineral%20commodities ;
[18] Venditti, B. (2022). Vizualizing China's dominance in clean energy metals, January, 23, https://www.visualcapitalist.com/chinas-dominance-in-clean-energy-metals/ ;
[19] Watson, C. (2022). *The world's massive need for more solar panels has one shiny catch*, January, 21, https://www.sciencealert.com/solar-panel-boom-s-demand-for-aluminium-is-a-big-carbon-problem ;
[20] World Bank (2017), *The growing role of minerals and metals for a low carbon future,* June, 15 https://documents1.worldbank.org/curated/en/207371500386458722/pdf/117581-WP-P159838-PUBLIC-ClimateSmartMiningJuly.pdf ;
[21] Wrede, I. (2022). *Can EU do without metals from China?,* April, 15, https://www.dw.com/en/the-eus-risky-dependency-on-critical-chinese-metals/a-61462687.