AMBIENTE & SOCIEDADE 25 anos años years

# Energy Security Transition: clean energy, critical minerals, and new dependencies

**Victor Gaspar Filho** [I]
**Thauan Santos** [II]

[I] *Núcleo de Avaliação da Conjuntura, Brazilian Naval War College. Rio de Janeiro, RJ, Brazil and Brazil-European Union Institute (FECAP). São Paulo, SP, Brazil.*

[II] *Graduate Program in Maritime Studies – Brazilian Naval War College (PPGEM/EGN) and Ocean Economy Group (GEM). Rio de Janeiro, RJ, Brazil..*

***Abstract:*** Different dynamics can be observed between the renewable and fossil energy markets, suggesting the need for different approaches in the theoretical and practical field of energy security. However, in the context of the current energy transition, there is a geographic concentration of production chains of new clean energy-generating equipment, which creates new dependencies for inputs and commercial partners. Consequently, energy security is affected by the relationship with non-fuel inputs such as critical minerals. In this work, we seek to engage in documentary research followed by a quantitative analysis of data provided by the United States Geological Survey. After the presentation of the theoretical discussion about energy security, energy transition and critical minerals, we analyse documents from the energy and mineral sectors written in the period from 2000 to 2020. It is posited that the transition towards less polluting energy matrices can result in the creation of new dependencies and that access to non-fuel resources is a condition for the success of the energy transition.

***Keywords:*** Energy security; energy transition; energy; critical minerals; natural resources.

**São Paulo. Vol. 25, 2022**

*Original Article*

**DOI:** http://dx.doi.org/10.1590/1809-4422asoc20210179r1vu2022L4OA

**Introduction**

Energy security is essential for human security. It is not only a commodity but a precondition for all commodities: a basic factor equivalent to air, water, and land (SCHUMACHER, 1977 apud SOVACOOL; MUKHERJEE, 2011). The imperative to obtain such resources can exert significant influence on a state's foreign and security policies. Likewise, those who have energy resources needed or coveted by others can use them as national security policy tools or even as political weapons (DUFFIELD, 2010).

Based on an analysis of the literature in the fields of international security, energy security, energy transition, and critical minerals, the theoretical and conceptual contribution of this article relies on the presentation of non-fuel mineral inputs as a bottleneck for the production of clean energy generation-equipment. We suggest that new dependencies can result from the energy transition, with new impacts on the actors' energy security. Regarding the concentration of mineral production, accessing those resources becomes a key condition for the success of an energy transition that guarantees the energy security of a state. Thus, we seek to propose the existence of a nexus between non-fuel minerals and energy security, resulting in a new theoretical framework in energy security studies.

Traditionally, literature in the field of energy security focuses on fossil resources. However, the various types of equipment involved in renewable energy generation depend on the abundant supply of minerals considered critical for different actors, such as copper, lithium, cobalt, and rare-earths (IEA, 2021).

In works such as "Critical Minerals and Energy–Impacts and Limitations of Moving to Unconventional Resources" (McLELLAN et al., 2016) or "Analyses de la disponibilité économique des métaux rares dans le cadre de la transition énergétique" (FIZAINE, 2014), there are essential contributions to this article's discussion, but which focus on different stages of the nexus proposed here. Relevant previous work is brought to explain the formulation of the non-fuel minerals-energy security nexus and offer a new contribution to the field.

We used rare-earth minerals as a proxy for the discussion on critical minerals, processing the data collectively, given the recognition of the criticality of these seventeen elements, as well as their collective treatment by governments and all mineral-related works discussed herein. This proxy choice was made also due to the history of price fluctuations, market concentration, and political motivations behind government actions involved in its market. The mineral data from the United States Geological Survey (USGS) dialogues with projections taken from energy sector reports published by the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) in order to identify the relationship between the elements of the energy security-critical non-fuel minerals nexus.

This article is divided into five main sections: first, we discuss the concepts of international security and energy security from the theoretical framework of different authors such as Buzan, Sovacool, and Raphael & Stokes, in order to present the debate about the criticality of minerals. Then, we built a historical series of the international rare earth market using data from the USGS, proceeding to a discussion about the proposed nexus, comparing data from the mineral and energy sectors. Finally, we make remarks on the subject.

## Energy security and transition

The possibility of finding a single definition for energy security is remote since it is necessarily an interdisciplinary concept that dialogues with economics, geography, as well as technical areas of the energy field. Sometimes, studies are based on incomplete or inconsistent definitions of energy security focused on technical and economic aspects, such as the security of fossil fuel supply or consumer prices, excluding socio-political factors such as governance (SOVACOOL, 2013) and environment/climate issues (SANTOS, 2018).

Raphael & Stokes (2010) describe energy security as an intersection of a number of trends, such as global energy demand, fear of a declining energy supply, instability in fuel-exporting regions, and concern about resource depletion or climate change. Distinctions are found between definitions proposed by quantitative and qualitative studies. In the first case, energy security can be measured through indicators such as energy intensity or price level. In qualitative studies, factors such as geopolitics and governance are explored (ANG et al., 2015). Furthermore, we emphasize that the concept is different when analyzing developed and developing countries (SANTOS, 2018).

Pursuing the energy security of a state is a complex objective that permeates questions about how to provide fair, accessible, reliable, efficient, environmentally benign, properly governed, and socially accepted energy services (SOVACOOL; MUKHERJEE, 2011). Energy insecurity can arise from several factors, such as geopolitical instability, natural disasters, terrorism, precarious regulatory design, or lack of investment (REDGWELL, 2004 apud ÖZDAMAR, 2010). Raphael & Stokes (2010) point out that in an attempt to stabilize supply, major powers are gradually militarizing their approach to ensuring energy security.

Energy security tends to encompass five dimensions divided into 20 components to make it possible to create an index, namely: 1) energy availability, comprising the security of supply and production, dependence, and diversification; 2) affordability, comprising price stability, access and equity, decentralization and low prices; 3) technological development, consisting of innovation and research, safety and reliability, resilience, energy efficiency, and investment; 4) sustainability, based on the use of land, water, climate change, and air pollution; and 5) regulation, consisting of governance, trade, competition and knowledge (SOVACOOL; MUKHERJEE, 2011).

Four main analytical benefits would derive from the methodology proposed by the authors: the multidimensional approach is an incentive to move away from narrow descriptions such as merely the security of fossil fuel supply. Similarly, a systematization can provide data to energy policies and build institutional capacity. Verifiable indicators and metrics can be useful in ensuring analysts can find more appropriate energy solutions. They also make it possible to identify individual energy security performances over time, relating them to major events such as embargoes, military conflicts, or the introduction of disruptive technologies or policies. Furthermore, an index would help to identify trade-offs spanning different dimensions involved and areas for improvement, making it possible to increase the understanding of the complementarity between the five dimensions (SOVACOOL, 2013).

Similarly, Ang et al. (2015) listed seven main concepts found during their research, stating that the fewer indicators are used in the set chosen to measure energy security, the more the result is susceptible to variations in one of the indicators. The criteria in descending order of occurrence in the research are: 1) energy availability; 2) infrastructure; 3) price level in the energy market; 4) social effects; 5) environment; 6) governance; and 7) energy efficiency.

Regarding the energy transition, the classical understanding encompasses changes in the national energy supply or the discovery of new energy resources. Currently, transformations in the logistics of the energy market are also included, as in devices used by the final consumer, and in electrical network systems (GRUBLER et al., 2016; SOVACOOL, 2016; BAZILIAN; SOVACOOL; MOSS, 2017). It can be the consequence of technological and economic transformations, as well as political decisions (SABBATELLA; SANTOS, 2020).

In the context of a clean energy transition (SABBATELLA; SANTOS, 2020), the dynamics of energy supply also tends to change. For Arent et al. (2017), the transition to clean matrices can offer a perspective of increasing the energy security of an actor (especially in developing countries) once it is no longer dependent on fuel imports. Ladislaw, Carey & Bright (2019) point out the possibility that by 2050 there will be five times the number of installations of photovoltaic solar energy plants and three times the number of wind energy plants internationally. The International Energy Agency (IEA, 2021) estimates that by 2040 we will witness a 40% increase in the share of renewable energy used in the world.

Fouquet & Pearson (2012) describe the energy transition as a shift from an economic system dependent on one or a series of energy sources and technologies to another. The energy transition cannot be reduced to the dynamics between technologies and systems. It involves social actors that can promote or hinder the products' life-cycles. of change, considering different cultural and evaluative structures, such as socio-environmental concerns (PARKER, 2018).

While energy matrices have always been in transition, the sophistication of technological systems, the global energy trade, the large amount of sunk costs, and the urgency of climate change determine the complexity, scale, and pace of the current energy transition (SINGHA et al., 2019). Renewable sources change energy integration arenas, transforming markets and modifying trading partners and patterns of cooperation and conflict between countries (SCHOLTEN et al., 2019).

The incentive to transition to clean matrices was strengthened not only because of the benefits noted in reducing the carbon footprint but also due to the desire to reduce dependence on other countries (HENSEL, 2011). Renewable energies would guarantee fossil fuel importers a way to diversify their energy matrix and more autonomy in the face of the global energy market (SCHOLTEN et al., 2019).

Scholten et al. (2019) and Arent et al. (2017) stress that the transition towards more geographically dispersed resources suggests a shift towards a less oligopolistic global market. Most countries have certain types of renewable energy source available, placing them in a trade-off between safe domestic production or low-priced imports, eclipsing the distinction between importers and exporters (SCHOLTEN et al., 2019). Institutional innovation in the political and market fields unfolds from the decrease in the costs of low-carbon technologies, interacting with a series of actors, influencing the Political Economy of energy transitions (ARENT et al., 2017).

Many renewable energy technologies are already cost-competitive with fossil fuels. Additionally, the potential contributions to reducing pollution and the consequent slow-down of climate change would create a propensity for the global energy transition in the face of public opinion, the market, and governments (IRENA, 2019a).

Since 2010, the average cost of electricity generated by solar photovoltaic (PV) and wind power has decreased by 73% and 22%, respectively. IRENA (2019a) estimates that by 2025 the global weighted average cost of electricity could fall by 26% with onshore wind; by 35% with offshore wind energy; at least 37% with concentrated solar energy technologies; and by 59% with solar PV.

Among the limiting factors for an energy transition to clean energies, we highlight the minerals used in the infrastructure necessary for energy generation. We suggest that countries can become resource and equipment importers from external actors that, achieving a leading role in the clean energy sector, would become price makers in this technological segment.

## Critical Minerals

Currently, few clean energy production technologies do not use rare metals at some stage of their production chain (FIZAINE, 2014). As with the concepts discussed above, there is no unanimous definition or methodology for categorizing minerals as critical (JIN; KIM; GUILLAUME, 2016). Some of the criteria to designate an element as critical are physical scarcity, political centralization of supply, high prices, or economic dependence (MCLELLAN et al., 2016). Strong geographic concentration in production, little recycling of materials due to lack of incentives, small markets associated with strong volatility in production or demand, and uncertainty caused by the lack of accurate indicators on resource depletion are also criteria associated with criticality (FIZAINE, 2014). It is a relative concept capable of determining which metals are more subject to supply disruptions (JIN; KIM; GUILLAUME, 2016).

The classification of these resources is not static and tends to change as the underlying economic conditions change. Unlike other taxonomies applied to minerals, this one, due to its economic character, is subject to constant changes (FIZAINE, 2014). Mineral resources are geologically determined but socially mediated (SOVACOOL et al., 2020). For Jenkin et al. (2015), economic importance and supply risk are the main factors defining a mineral as critical. Other factors considered by the authors are the abundance of the resource in the earth's crust and social and geopolitical factors.

Most existing methodologies share the same essential feature: criticality is measured as a function of some estimate of the probability of supply disruptions and an estimate of the consequences (LØVIK; HAGELÜKEN; WÄGERA, 2018). Non-geological factors can also contribute to the improvement of the mentioned processes, such as changes in political scenarios and existing infrastructure (JENKIN et al., 2015). Although the Herfindahl-Hirschman Index (HHI) can be applied to measure the share of production of a given product by a given state in a market, further analysis must consider political risks (HESHMATI; ABOLHOSSEINE, 2017).

According to Özdemiroğlu (1993), an indicator that correctly performs its scarcity alert role requires the fulfillment of three prerequisites:

1) It should reflect the past scarcity of the resource, but above all anticipate the evolution of future scarcity and therefore be an early indicator of scarcity;

2) It must be comparable to allow assessments of the scarcity level of various replaceable resources; and

3) It must be measurable, that is, it must benefit from data collection and a simple and reliable calculation method.

The risk of mineral supply disruption is evaluated by several criteria and if it is presented as high in the same way as its essentiality to the production chain of specific essential equipment, it can be considered critical. Some authors use "critical", "strategic" or "scarce" as interchangeable terms. However, the criticality of a mineral is not defined strictly by its strategic character. The methodology for identifying critical and strategic minerals is similar, but their assessment is different. Critical minerals are essential to the value chains of a national economy, a sector, or a company and not for their military application, as commonly observed in the case of strategic minerals (FIZAINE, 2014).

The mineral resources availability issue was less prominent in the late 1980s due to a generalized drop in commodity prices. From the 2000s onwards, with the rise in the price level, the topic stood out again (FIZAINE, 2014). The collection of data about the life cycle of mineral resources would become essential for estimating the criticality of these metals as well as material flow analysis, used for long-term planning and writing of policies related to the security of mineral supply to circumvent mineral scarcity scenarios (JENKIN et al., 2015).

Lusty & Gunn (2015) point out that there is a scenario of technical scarcity in the fact that the extraction of some metals is carried out as a by-product of others. In this case, market supply and demand mechanisms may not be effective in alleviating shortages. Unconventional resources or new regions (Arctic, Antarctica, and ocean floor) are alternative sources of critical resources with the possibility of meeting the demand mainly from population growth (FIZAINE, 2014). Strategic storage, where applicable, can also help countries resist short-term supply disruptions (IEA, 2021).

For some critical metals with low abundance in the Earth's crust and used in small quantities, the discovery of new deposit types or new exploration technologies can significantly impact supply. However, despite advances in sensing technologies, the last 50 years have seen a decline in the discovery of large deposits (JENKIN et al., 2015).

Analysis of the main mines that came into operation between 2010 and 2019 shows that it took an average of 16.5 years to develop projects from discovery to production (S&P GLOBAL, 2020; apud IEA, 2021). A trade-off can be seen in the critical minerals market that concerns the balance between independence in mineral production and competitiveness. This is due to the need for significant initial capital to make certain mining, processing and refining ventures viable.

## Methodology

The article's time frame is defined between 2000 and 2020, covering reports from agencies dedicated to the energy sector such as IRENA and IEA, focusing on the elaboration of scenarios related to the renewable sector. We examined data related to the global mineral sector within the proposed cut from 20 annual reports prepared by the USGS in pdf and xls formats.

IRENA (2019a) qualifies the minerals essential for the manufacture of clean energy-generating equipment. They are:

1) Those applied to solar energy generation: bauxite and aluminium, cadmium, copper, tin, gallium, germanium, indium, iron, lead, nickel, selenium, silicon, silver, tellurium, and zinc; and

2) Those applied to wind power generation: bauxite and aluminium, chromium, cobalt, copper, iron, lead, manganese, molybdenum, rare-earths, and zinc.

From the compilation and analyses of data available in the USGS reports, we sought to recognize relevant information about reserves, production, and price levels in the rare-earths market. We identified the complementarity of the energy and mining sector, using rare-earths as a research parameter for the proposition of the energy security-critical non-fuel minerals nexus through the essentiality of mineral resources to the energy transition.

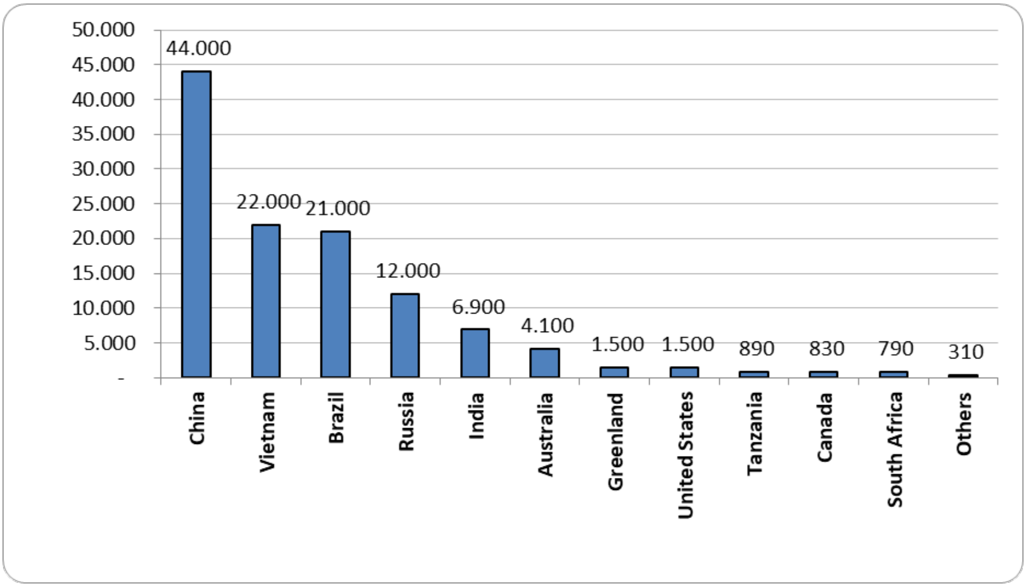
The xls files on rare-earths, more detailed than those in pdf format, were last published in 2017. We thus sought to reconcile data presented in both formats in order to bring more current and detailed analyzes and sources, although we found some limitations. With the availability of sector data, we seek to reconcile existing forecasts in the clean energy sector based on information provided by IRENA and IEA, highlighting the need for non-fuel mineral resources for the sector and existing challenges.

## Results

While each of the seventeen rare-earths has different applications, four elements - neodymium, dysprosium, praseodymium, and terbium - are of particular importance to the clean energy sector. One of the main uses is permanent magnets for motors used in wind turbines. Demand for neodymium more than doubles in the two scenarios designed by the IEA (2021), reaching 70kt/year and over 90kt by 2040, respectively. Clean energy technologies represent 15% of total neodymium demand today, and their share is expected to increase to 25% or 40% in the proposed scenarios.

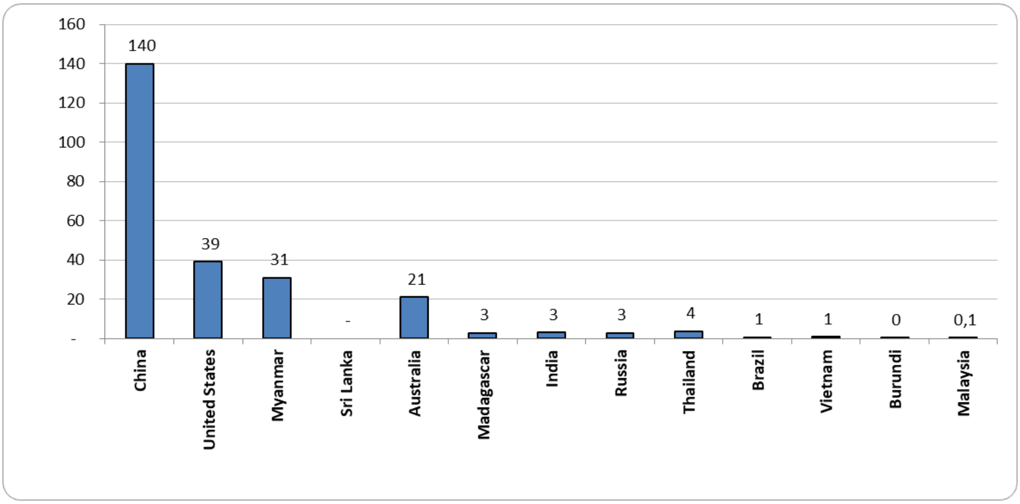
According to the USGS, international rare-earth reserves total about 120,000,000t. The five countries with the largest reserves in 2020 (Figure 1) were identified by the agency as being China, with 44,000,000t (36.7% of the international total), Vietnam, with 22,000,000t (18.3%), Brazil, with 21,000,000t (17.5%), Russia, with 12,000,000t(10.0%) and India, with 6,900,000t (5.8%) (UNITED STATES OF AMERICA, 2021). The disparity between the allocations of each country is evidenced by Figure 1: China has twice the reserves of Vietnam, the second country with the largest reserves.

**Figure 1: International rare-earth reserves in 2020 according to the USGS (in thousands of t)**




Source: Own elaboration based on USGS data (2021).

**Figure 2: International production of rare-earths in the year 2020 (in thousands of t)**




Source: Own elaboration based on USGS data (2021).

Chinese greatest concentration in the rare-earth sector happened in 2010, when its production reached 130,000t, corresponding to 97.7% of the world total (133,000t). The other countries that had produced the minerals in the same year were India, producing 2,800t (2.1% of the total), and Brazil, which produced 550t (0.4%). A price peak for all rare-earth metals in 2010 is observed during the time series (Figure 4). This year, China initiated a restriction on exports of rare earth oxides through quotas and export tariffs that caused a significant increase in the prices of the products. The government's move was motivated by the regulation of its market involving environmental guidelines (USGS, 2010). It is also attributed that the restrictions were due to a dispute between China and Japan about a territorial dispute (GASPAR FILHO, 2019).

**Figure 3: International rare-earth production from 2000 to 2020 (in t)**

| Year / country | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| China | 73.000 | 73.000 | 88.000 | 92.000 | 95.000 | 119.000 | 119.000 | 120.000 | 120.000 | 129.000 | 130.000 |
| United States | 5.000 | 5.000 | 5.000 | - | - | - | - | - | - | - | - |
| Myanmar | | | | | | | | | | | |
| Sri Lanka | 120 | 120 | 120 | | | | | | | | |
| Australia | - | - | - | - | - | - | - | - | - | - | - |
| Madagascar | | | | | | | | | | | |
| India | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.700 | 2.800 |
| Russia | | | | | | | | | | | |

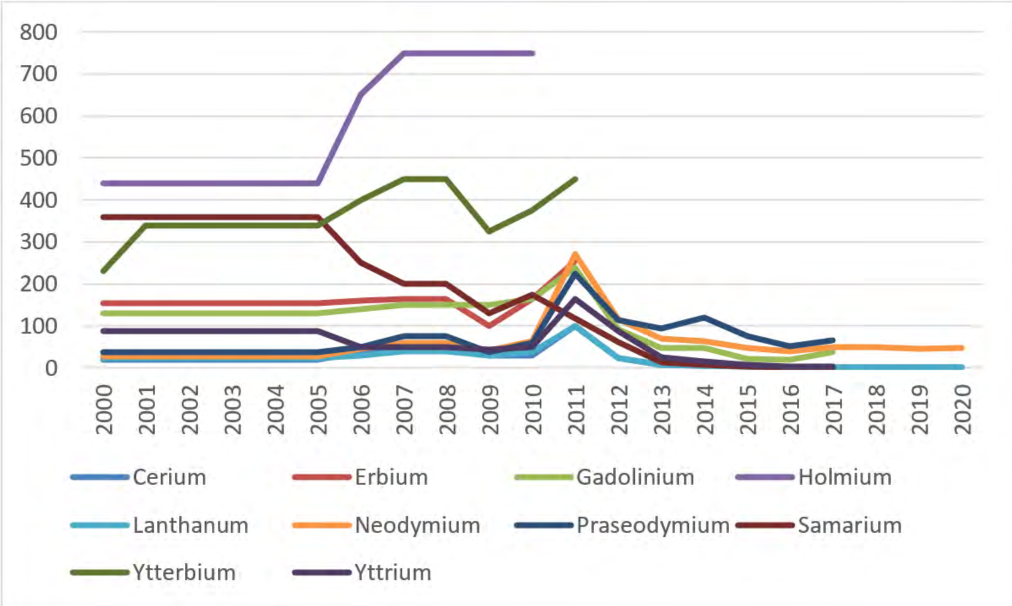
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Thailand | | | | 2.200 | 2.200 | - | - | | | | |
| Brazil | 200 | 200 | 200 | | | 750 | 730 | 650 | 650 | 550 | 550 |
| Vietnam | | | - | | | | | | | | |
| Burundi | | | | | | | | | | | |
| Malaysia | 450 | 450 | 450 | 250 | 250 | 750 | 200 | 380 | 380 | 350 | 30 |
| Commonwealth | | | 2.000 | 2.000 | 2.000 | | | | | | |
| Ex-USSR | 2.000 | 2.000 | 2.000 | | | | | | | | |
| Malawi | | | | | | | | | | | |
| Others | - | - | - | - | - | 400 | | | | | |
| World total (rounded) | 83.500 | 83.500 | 98.300 | 99.100 | 102.000 | 123.000 | 123.000 | 124.000 | 124.000 | 133.000 | 133.000 |
| | No data | | | | | | | | | | |
| | Not on the list | | | | | | | | | | |

| Year/ country | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|---|---|---|---|---|
| China | 105.000 | 100.000 | 95.000 | 105.000 | 105.000 | 105.000 | 105.000 | 120.000 | 132.000 | 140.000 |
| United States | - | 800 | 5.500 | 5.400 | 5.900 | - | - | 18.000 | 28.000 | 39.000 |
| Myanmar | | | | | | | - | 19.000 | 25.000 | 31.000 |
| Sri Lanka | | | | | | | | | | |
| Australia | 2.200 | 3.200 | 2.000 | 8.000 | 12.000 | 15.000 | 19.000 | 21.000 | 20.000 | 21.000 |
| Madagascar | | | | | | | | 2.000 | 4.000 | 2.800 |
| India | 2.800 | 2.900 | 2.900 | | 1.700 | 1.500 | 1.800 | 2.900 | 2.900 | 2.900 |
| Russia | | 2.400 | 2.500 | 2.500 | 2.800 | 2.800 | 2.600 | 2.700 | 2.700 | 2.700 |
| Thailand | | | 800 | 2.100 | 760 | 1.600 | 1.300 | 1.000 | 1.900 | 3.600 |
| Brazil | 250 | 140 | 330 | - | 880 | 2.200 | 1.700 | 1.100 | 710 | 600 |
| Vietnam | | 220 | 220 | 200 | 250 | 220 | 200 | 920 | 1.300 | 700 |
| Burundi | | | | | | | - | 630 | 200 | 300 |
| Malaysia | 280 | 100 | 180 | 240 | 500 | 300 | 180 | 200 | - | |
| Commonwealth | | | | - | - | - | - | - | - | |
| Ex-USSR | | | | | | | | - | - | |
| Malawi | | | | | - | - | - | | | |
| Others | | | | | | | - | 60 | 66 | 100 |
| World total (rounded) | 111.000 | 110.000 | 110.000 | 123.000 | 130.000 | 129.000 | 132.000 | 190.000 | 220.000 | 240.000 |
| | No data | | | | | | | | | |
| | Not on the list | | | | | | | | | |

Source: Own elaboration based on USGS data (2001-2021).

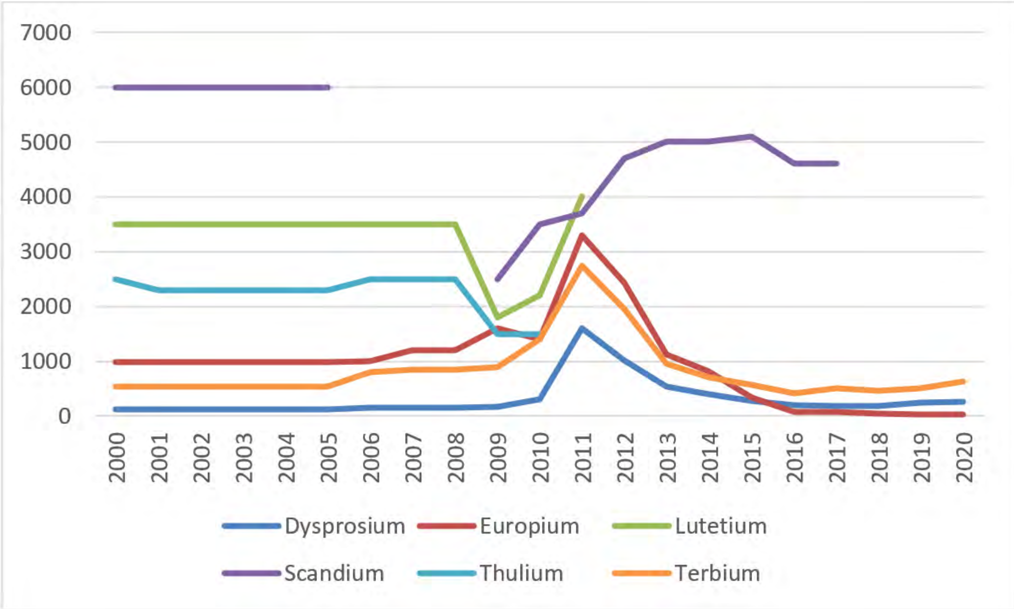
The price level graphs generated for this work were separated into two categories: 1) rare-earths that remained below the value of US$ 800/kg throughout the time series (Figure 4); and 2) rare-earths that reached this value in at least one moment of the period covered (Figure 5). The division was designed so that the data visualization was made clearer. The data collected were not entirely made available by the USGS, so not all time series could cover the 20 years of our time frame.

**Figure 4: rare-earth prices with values below US$ 800 (US$/kg)**




Source: Own elaboration based on USGS data (2001-2021).

**Figure 5: rare-earth prices with values above US$ 800 (US$/kg)**




Source: Own elaboration based on USGS data (2001-2021).

## Discussion

What is the feasibility of an energy transition dependent on renewable energy matrices, when in its production chain there is extensive use of finite mineral resources? Non-fuel critical minerals fulfil essential functions in most high-tech equipment in modern economies (FIZAINE, 2014). Through the data provided in the previous section, we identify some obstacles to rare-earths production that could hinder the energy transition.

According to USGS data, the international production of rare-earths was led by the Chinese market throughout the time frame of our research. In 2020, the top five producers of rare-earths were China, with 140,000 t (representing 58% of the total), the United States, with 30,000t (13%), Malaysia, with 30,000t (13%), Australia, with 17,000t (7%), and Madagascar, with 8,000t (3%). China's leadership in the rare-earths market is expressive, due to its production being more than 4 times higher than that of the United States, in the second position. Based on the time series, Chinese production is the only one to sustain high production throughout the period covered. In turn, the United States, despite being ranked in second place, does not have a regular production in the observed period.

In the same way that risks associated with the production chain of oil products are observed, these are also present in the clean energy value chains (HENSEL, 2011). Changes in clean energy technologies or systemic changes in electrification and digitalization of the energy environment have different profiles in terms of critical mineral requirements when compared to the existing portfolio (BAZILIAN, 2018), noting the need to ensure, for example, the production of chips for actors to achieve the technological goals of the Fourth Industrial Revolution. Furthermore, while oil is a unique commodity with a large global market, there are several minerals essential to the energy sector, with their own complexities and supply dynamics (IEA, 2021).

Macroeconomic factors may limit the growth in demand for critical minerals. High unemployment over an extended period could reduce the demand for electric cars. Fiscal austerity in different areas of the budget could impact the number of subsidies to the wind and solar sector or other emerging technologies dependent on rare-earths (HENSEL, 2011).

In the past, tensions in the balance between supply and demand for different minerals have generated additional investment and measures to alleviate or replace demand. These responses caused shortfalls and were accompanied by considerable price volatility. Similar episodes in the future could delay the transition and increase its cost. Given the urgency of reducing greenhouse gas (GHG) emissions, this poses a heightened risk. As transitions gain momentum, clean energy technologies are becoming the fastest-growing demand segment for critical minerals (IEA, 2021).

IRENA (2019b) points out the fast decline in renewable energy costs as the main factor of transformation in the sector. The global weighted average cost of electricity from all commercially available renewable sources followed a downward trend in 2018. For onshore wind projects commissioned in 2018, the global weighted average cost of electricity reached a low of US$0.056 per kilowatt-hour (kWh), which was 13% lower than in 2017 and 35% lower than in 2010 (US$0.085/kWh).

The discussion of reports from the electricity sector aimed at projecting scenarios allows us to approach the energy security-critical non-fuel minerals nexus, considering the existing trends involving all the elements present in the elaboration of this nexus. The reports presented provide us with appropriate informational inputs when addressing the issue of energy security, energy transition, critical minerals, and changing trends. IRENA's mention to minerals used in the production chains suggests the agency's recognition of the nexus proposed, even though it considers the advent of renewable energies a factor that tends to increase the states' energy security.

The costs of onshore wind electricity would already be competitive and could reduce new costs of polluting energy generation in many cases. With the fast decline in solar PV costs in recent years (the flattened cost of electricity decreased by 77% in 2018 compared to 2010), the complementary nature of the two technologies and the availability of resources in different seasons could result in a system of low costs (IRENA, 2019b).

In a scenario that meets the Paris Agreement targets, the share of clean energy technologies in total demand increases significantly over the next two decades to over 40% for copper and rare-earth elements, 60-70% for nickel and cobalt, and almost 90% for lithium. Electric vehicles and battery storage have already replaced goods becoming the biggest demand for lithium and are expected to replace stainless steel as the biggest end-user of nickel by 2040 (IEA, 2021).

Despite reports from the energy sector pointing out that the US enjoys an advantageous position in the development of new technologies, and its mineral reserves being significant, the country's control over the production chain is not constant. The search for stability in value chains is observed in measures taken by different administrations. Based on a historical series of 20 years, two gaps in which US production was extinct: between 2003 and 2011 and from 2016 to 2017.

Despite the reduction in economic activity as a result of the coronavirus pandemic, there was no reduction in the production of rare-earths in 2020. On the contrary, in eight of the ten main producers of rare-earths in 2020, there was an increase in relation to 2019. This may suggest prioritizing a strategic sector of economies. Likewise, transitions to clean energy gained momentum in 2020 despite major economic and social disruptions caused by the pandemic (IEA, 2021).

IRENA claims that in the reported episode about the restriction of Chinese exports in 2010, rare-earths were understood as scarce in part because of the cyclical nature of their market. When demand increases, supply is slow to respond because new mining projects have long lead times. The time-lapse caused prices to skyrocket, which can lead companies to overinvest. Thus, investment flowed into new projects, causing prices to collapse in 2012. As a result, in 2014 the US, Japan, and the European Union requested the initiation of a WTO dispute, contesting the Chinese restriction (IRENA, 2019a)

The Chinese strength in the rare-earths market was also demonstrated in the context of the Trade War promoted between the United States and China when the Asian country raised the possibility of restricting its exports of rare-earths to the US as a means of coercion (GASPAR FILHO, 2019; GASPAR FILHO; SANTOS, 2019). Thus, dependence on critical minerals for the economy, energy, and defense presents itself as a potential cause of insecurity for importing states (GASPAR FILHO; SANTOS, 2019; DELGADO; MARQUES; GASPAR FILHO, 2020).

Despite reports from the energy sector presenting the possibility of costs tending to fall in all proposed scenarios for renewable energies, it is possible to see the impact on the price level of the rare-earths market in 2010 as a serious precedent for the sector. This event, with an increase of more than 200% in less than a year, in the same year that Chinese production of rare-earths made up 98% of the international total (USGS, 2011), cannot be disregarded. It is in line with Ang et al. (2015), who, when dealing with the price levels in the energy market as a defining criterion of an actor's energy security, name volatility and the degree of market competitiveness as components. The response of policymakers and companies will determine whether critical minerals will enable the energy transition or become a bottleneck in the process (IEA, 2021).

IRENA considers the emergence of cartels in the renewable energy market as unlikely as minerals can be obtained in different ways, even through the recycling of used materials. These factors, added to the rules of international trade, would impede the cartelization of the sector (IRENA, 2019a). However, there is no tendency towards the formation of cartels, but towards the concentration of international production of rare-earths tending towards the Chinese monopoly. This would cause a concentration of power in an actor at an early stage of the production chain of clean-energy technologies, which could make them become a price-maker in the sector.

The approach to the obstacles imposed by critical minerals to the energy transition is consistent with the need to analyse the products' life cycle as brought by Wang et al. (2019) and Watari et al. (2019). It happens because research in the area often does not consider the consumption of finite resources in the construction of equipment or even the socio-environmental impacts caused by stages of their production chains. It should also be considered that the mining process itself is energy intensive and difficult to decarbonize (SOVACOOL et al., 2020).

By holistically analysing the production chain, we facilitate the development of mechanisms to reduce existing risks. This would involve changing existing positions between states with different technological development capabilities, patent owners, producers, and consumers (HENSEL, 2011).

Ensuring that essential minerals enable clean energy transitions requires a broad view of supply chains, from mining to processing. Even if raw mineral materials are physically available, a bottleneck in processing and refining capacity can drive up the prices of refined products and affect investment in clean energy. In addition, higher concentration of production imply that disruptions can have broader impacts across the entire value chain (IEA, 2021).

Unlike the availability of renewable energy resources, the distribution of minerals across the earth's crust is not homogeneous, as is the extraction and refining capacity between states (SCHOLTEN et al., 2019). The mapping of mineral demands linked to national energy policies could lead to new partnerships and increased awareness of the issue, generating gains, particularly for climate policies and energy studies. Mitigating the effects of climate change should be followed by the issue of mineral security and industrial strategies in order to generate broader benefits, such as in the environmental, political, and economic fields (SOVACOOL et al., 2020).

IRENA (2019a) states that three categories of countries have the potential to emerge as new leaders in renewable energy: those with high technical potential for renewable energy generation; mineral-rich countries, which can become part of the global production and value chains needed for renewable technologies; and leaders in technological innovation positioned to get the most out of the global energy transformation.

Notwithstanding, the agency argues that the largest reserves of metals and minerals needed for renewable technologies are found in weak states with poor governance. Efforts are undertaken to address the issue of so-called "conflict minerals" to increase transparency and accountability along the global supply chain. The OECD has published guidelines for companies exploring or trading minerals, and the UN Security Council seeks accountability for actors in conflict-affected states (IRENA, 2019a). Besides, interstate relations and conflict dynamics tend to change as a result of the change in the energy matrix of countries (SCHOLTEN et al., 2019).

The network of interdependencies between nations in terms of reserves and production of critical minerals for clean energy technologies distributes the risk between producing and consuming countries. The key to developing a risk mitigation strategy in the production chain must involve understanding the interrelationships between the roles of actors (producers, consumers, and holders of intellectual property rights of applied technologies) and the need for continuous flexibility in the reformulation of national strategies focused on natural resources (HENSEL, 2011).

There is an international articulation in the sector: despite not having any occurrence in the historical series of rare-earth production, Canada is the country with the ninth largest rare-earth reserve in the world. Today, Canada, Australia, the US, Peru, and Botswana are member countries of the Energy Resources Governance Initiative (ERGI), an initiative on governance in the mining sector, focused on inputs for the clean energy sector. Cooperation seems to be a possibility to increase the energy security of states, given the variation in the endowment of mineral resources in their soils, the geographically distributed productive infrastructure, and the recognition of the member countries as strategic partners. The IEA (2021) states that given the complex nature of mineral supply chains that span the globe and involve multiple minerals, no country alone will be able to individually drive the necessary changes.

## Conclusion

Ensuring a stable supply of critical non-fuel minerals at an affordable price is essential for the current energy transition to take place, regardless of the form of energy generation used. We currently witness the impossibility of decoupling energy availability from non-energetic primary materials. The proper governance of these resources will depend on the articulation of global actors so that critical minerals are a facilitator of the process, and that the energy transition is undertaken in a way that is not harmful to the environment at different stages of the process.

Considering the concentrated production chain of these resources and the gradual reduction in the consumption of fossil energy sources driven by the commitment to international regimes, the energy transition results in a phenomenon called energy security transition. This is because the axis of external dependence is shifted to countries capable of providing the necessary inputs for the generation of clean energy, progressively taking the place of fossil fuel exporters.

The presence of the discussion on critical minerals in reports by international agencies such as the IEA and IRENA is indicative of the recognition of the nexus proposed by this article, even though the agencies consider the advent of renewable energies a factor that tends to increase the energy security of states. There is a pressing demand to decarbonize international economies that will only be met with the proper provision of critical minerals. Poor resource governance can lead to a more expensive, slower, and more polluting energy transition.

In fact, the relevance of the study of minerals critical to energy security is very recent, despite their historical role also in fossil energy generation infrastructures. However, the context of an energy transition to clean matrices requires reconsidering some basic concepts of energy security. The decarbonization and energy independence desired by an actor can only be reached in a context in which there is sufficient availability of resources capable of enabling its energy transition.

Considering the political factor as one of the variables that determine the criticality of minerals and energy security, it is important to note that vulnerability to external dependence is not always the same, since there are traditionally partner states that do not offer a high level of risk. In the case of the United States, for example, we observe in its list of critical minerals resources imported from Canada in its entirety, which does not offer as high a risk as imports from China, a strategic competitor.

Mineral deposits modelling will continue to evolve in order to increase understanding of where mineral exploration should take place and how it can be most efficient. In the short term, investment in research and development should be a priority for states that wish to carry out an efficient energy transition, as well as alliances with actors capable of meeting their needs in natural resources or refining infrastructure. Actors that today write strategies to reduce vulnerability in the critical minerals market, such as the US, Japan, Australia, Canada, and the European Union, look to traditional partners for the possibility of cooperation.

Finally, it is essential to note that the transition to renewable energies, depending on the composition of their infrastructure, is also essentially dependent on finite resources. Even if the consumption of fossil fuels is reduced, the use of non-fuel critical minerals in production chains tends to increase, creating new dependencies and providing new scenarios of scarcity.

This research met some difficulties due to the lack of complete data referring to the mineral sector. Gaps in the elaboration of the historical series resulted from the scarcity of data referring to some years. The use of rare-earths as a research parameter allowed us to conclude the article, but a complete view of the mineral sector would allow more comprehensive analyses. Future articles that focus especially on energy storage in batteries of different materials may contribute to more robust analyses. The elaboration of studies on different dependencies of advanced states in the energy transition such as China, the United States, members of the European Union, or Japan will offer a significant contribution to the field. Likewise, studies must be prepared to project the role of developing countries in the global energy transition, avoiding scenarios analogous to the so-called “resource curse”.

## Bibliography

ARENT, D.; ARNDT, C.; MILLER, M.; ZINAMAN, O. Introduction and Synthesis. In: ARENT, D *et al.* (ed.). **The Political Economy of Clean Energy Transitions**. 1. ed. Oxford: Oxford University Press, 2017. p. 292-312.

ANG, B.W.; CHOONG, W.L.; NG, T.S. Energy security: Definitions, dimensions and indexes, **Renewable Sustainable Energy Review**, v. 42, pp. 1077–1093.

BAZILIAN, M; SOVACOOL, B.; MOSS, T. Rethinking Energy Statecraft: United States Foreign Policy and the Changing Geopolitics of Energy. **Global Policy**, v. 8, n. 3, p. 422-425, 2017.

BAZILIAN, M. The mineral foundation of the energy transition. **The Extractive Industries and Society**. v. 5, n. 1, p. 93 - 97, 2018.

DELGADO, F.; MARQUES, J. V.; GASPAR, V. The Geopolitics of Renewable Energy: the Rare--Earth Elements Case. **Geopolitics of Energy**. v. 42, n. 2, p. 8-12, fev 2020.

DUFFIELD, J S. Energy and Security. In: DENEMARK, R. (ed.). **The International Studies Encyclopedia**, 2010.

FIZAINE, F. **Analyses de la disponibilité économique des métaux rares dans le cadre de la transition énergétique**. 2014. Tese (Doutorado em Ciências Econômicas) - Faculté de Sciences Economiques et de Gestion. Université de Bourgogne, Bourgogne, 2014.

FOUQUET, R., PEARSON, G. Past and Prospective Energy Transitions: Insights from History. **Energy Policy**, v. 50, n. 1, p. 1-7, 2012.

GASPAR FILHO, V. Chineses miram em vulnerabilidade estadunidense no mercado de terras--raras. **Boletim Geocorrente**, Rio de Janeiro, v. 95, p 5-5, jun. 2019.

GASPAR FILHO, V.; SANTOS, T.; Mineral-Resource Security: niobium's criticality to the US Defense. In: **International Conference of Economics and Security**, 26-28 junho, 2019, Madrid.

GRUBLER, A. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. **Nature Energy**. v. 3, p. 515 - 527, 2016.

HENSEL, N. Economic Challenges in the Clean Energy Supply Chain: The Market for Rare Earth Minerals and Other Critical Inputs. **Business Economics**. v. 46, p. 171-184, 2011.

HESHMATI, A.; ABOLHOSSEINI, S. European Energy Security: Challenges and Green Opportunities. In: ARENT, D et al. (ed.). **The Political Economy of Clean Energy Transitions**. 1. ed. Oxford: Oxford University Press, 2017. p. 292- 312.

INTERNATIONAL RENEWABLE ENERGY AGENCY. **A New World**: the geopolitics of the energy transformation. 1. ed. Abu Dhabi: IRENA, 2019.

INTERNATIONAL RENEWABLE ENERGY AGENCY. **Future of Wind**: deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper). 1. ed. Abu Dhabi: IRENA, 2019.

INTERNATIONAL ENERGY AGENCY. **The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions**. 2021.

JENKIN, G. R. T.; LUSTY, P. A. J.; MCDONALD, I.; SMITH, M. P.; BOYCE, A. J.; WILKINSON, J. J. Ore deposits in an evolving Earth: an introduction. In: JENKIN, G. R. T.; JIN, Y.; KIM, J.; GUILLAUME, B. Review of critical material studies. **Resources, Conservation and Recycling**, v. 113, p. 77-87, out 2016.

JIN, Y.; KIM, J.; GUILLAUME, B. Review of critical material studies. **Resources, Conservation and Recycling**, v. 113, p. 77-87, out 2016.

LADISLAW, S.; CAREY, L.; BRIGHT, H. Critical Minerals and the Role of U.S. Mining in a Low-Carbon Future. **Center for Strategic & International Studies**, 2019.

LØVIK, A.; HAGELÜKEN, C.; WÄGERA, P. Improving supply security of critical metals: Current developments and research in the EU. **Sustainable Materials and Technologies**, v. 15, p. 9-18, abril 2018.

LUSTY, P.A.J.; GUNN, A.G. Challenges to global mineral resource security and options for future supply. *In:* JENKIN, G. R. T.; LUSTY, P. A. J.; MCDONALD, I.; SMITH, M. P.; BOYCE, A. J.; WILKINSON, J. J. (eds.). **Ore Deposits in an Evolving Earth.** Geological Society. London: Geological Society, Special Publications, p. 265-276, 2015.

MCLELLAN, B.; CORDEN, G.; SALEEM, A.; GOLEV, A. Rare metals, unconventional resources, and sustainability. **Special Paper of the Geological Society of America**. v. 520, p. 57 - 65, 2016.

ÖZDAMAR, Ö. Energy, Security, and Foreign Policy. In: DENEMARK, R. (ed.). **The International Studies Encyclopedia**, 2010.

ÖZDEMIROĞLU, E. **Measuring Natural Resource scarcity: A study of the Price Indicator CSERGE**, University of East Anglia, Norwich, England, GEC 93-14, ISSN 0967-8875, 1993.

PARKER, C. Energy Transition in South America: Elite's Views In The Mining Sector, Four Cases Under Study. **Ambiente & Sociedade**. São Paulo. Vol. 21, 2018.

RAPHAEL, S.; STOKES, D. Energy Security. In: COLLINS, A. (org.). **Contemporary Security Studies**. Oxford: Oxford University Press, p. 378-393, 2010.

SABBATELLA, I.; SANTOS, T. The IPE of regional energy integration in South America. In: VIVARES, Ernesto (Ed.). **The Routledge Handbook to Global Political Economy:** Conversations and Inquiries. Cap. 42. Routledge, 2020.

SANTOS, T. **Regional Energy Security**: Re-evaluating concepts and policies to promote energy integration in Mercosur. Tese de Doutorado, PPE/COPPE/UFRJ, 2018.

SCHOLTEN, D. *et al.* The geopolitics of renewables: New board, new game. **Energy Policy**. v, 138, p. 1 - 6, 2019.

SINGHA, H.; BOCCA, R.; GOMEZ, P.; DAHLKE, S.; BAZILIAN, M. The energy transitions index: An analytic framework for understanding the evolving global energy. **Energy Strategy Reviews**, v. 26, n. 1, p. 1-10, 2019.

SOVACOOL, B. K. An international assessment of energy security performance. **Ecological Economics**, v. 88, p. 148–158, 2013.

SOVACOOL, B. K. The history and politics of energy transitions: comparing contested views and finding common ground. Working paper, **World Institute for Development Economics Research**, 2016/81, 2016.

SOVACOOL, B. K., MUKHERJEE, I. Conceptualizing and measuring energy security, a synthesized approach. **Energy**, v. 36, n. 8, p. 5343–5355, 2011.

SOVACOOL, B.; SALEEM H., A; BAZILIAN, M.; RADLEY, B.; NEMERY, B.; OKATZ, J.; MULVANEY, D. Sustainable minerals and metals for a low-carbon future. **Science Magazine**, v. 367, n. 6473, p. 30-33, 2020.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2003**. 1. ed. Reston: U.S. Geological Survey, 2003.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2004**. 1. ed. Reston: U.S. Geological Survey, 2004.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2005**. 1. ed. Reston: U.S. Geological Survey, 2005.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2006**. 1. ed. Reston: U.S. Geological Survey, 2006.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2007**. 1. ed. Reston: U.S. Geological Survey, 2007.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2008**. 1. ed. Reston: U.S. Geological Survey, 2008.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2009**. 1. ed. Reston: U.S. Geological Survey, 2009.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2010**. 1. ed. Reston: U.S. Geological Survey, 2010.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Com-**

**modity Summaries 2011**. 1. ed. Reston: U.S. Geological Survey, 2011.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2012**. 1. ed. Reston: U.S. Geological Survey, 2012.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2013**. 1. ed. Reston: U.S. Geological Survey, 2013.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2014**. 1. ed. Reston: U.S. Geological Survey, 2014.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2015**. 1. ed. Reston: U.S. Geological Survey, 2015.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2016**. 1. ed. Reston: U.S. Geological Survey, 2016.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2017**. 1. ed. Reston: U.S. Geological Survey, 2017.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2018**. 1. ed. Reston: U.S. Geological Survey, 2018.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2019**. 1. ed. Reston: U.S. Geological Survey, 2019.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2020**. 1. ed. Reston: U.S. Geological Survey, 2020.

UNITED STATES GEOLOGICAL SURVEY (EUA). Departamento do Interior. **Mineral Commodity Summaries 2021**. 1. ed. Reston: U.S. Geological Survey, 2021.

WANG, P.; CHEN, L.; GE, J.P.; CAI, W.; CHENA, W.Q. Incorporating critical material cycles into metal-energy nexus of China's 2050 renewable transition. **Applied Energy**, v. 253, 2019.

**Victor Gaspar Filho**

✉ victorgasparfilho@gmail.com

ORCiD: https://orcid.org/0000-0002-2491-3811

Submitted on: 16/10/2021

Accepted on: 28/06/2022

2022;25e:01791

**Thauan Santos**

✉ thauan@marinha.mil.br

ORCiD: https://orcid.org/0000-0002-4001-4322

AMBIENTE & SOCIEDADE 25 anos años years

SciELO

# Transição da Segurança Energética: energias limpas, minerais críticos e novas dependências

Victor Gaspar Filho
Thauan Santos

**São Paulo. Vol. 25, 2022**

*Artigo Original*

***Resumo:*** Dinâmicas distintas podem ser observadas entre os mercados de energias renováveis e fósseis, sugerindo a necessidade de abordagens diversas no campo teórico e prático da segurança energética. Entretanto, no contexto da atual transição energética, observa-se uma concentração geográfica das cadeias produtivas dos novos equipamentos geradores de energias limpas, o que cria novas dependências por insumos e parceiros comerciais. Consequentemente, a segurança energética é afetada pela sua relação com insumos não-energéticos, como minerais críticos. Neste artigo, empreende-se uma pesquisa documental para posterior análise quantitativa dos dados da United States Geological Survey (USGS). Após a apresentação da discussão teórica acerca da segurança energética, da transição energética e de minerais críticos, analisamos documentos dos setores energético e mineral redigidos no recorte temporal de 2000 a 2020. Conclui-se que a transição em direção a matrizes energéticas menos poluentes pode resultar na criação de novas dependências e que o acesso a recursos não energéticos é condicionante para o êxito do processo de transição energética.

***Palavras-chave*:** Segurança energética; transição energética; energia; minerais críticos; mineral; recursos naturais.

AMBIENTE & SOCIEDADE
25 anos años years



# Transición de la Seguridad Energética: energías limpias, minerales críticos y nuevas dependencias

Victor Gaspar Filho
Thauan Santos

***Resumen:*** Se observan dinámicas diferentes entre los mercados de energías renovables y fósiles, lo que sugiere la necesidad de adoptar enfoques diferentes en el ámbito teórico y práctico de la seguridad energética. Sin embargo, en el contexto de la actual transición energética, existe una concentración geográfica de las cadenas de producción de nuevos equipamientos de generación de energía limpia, lo que crea nuevas dependencias de insumos y socios comerciales. En consecuencia, la seguridad energética se ve afectada por la relación con los insumos no energéticos, como los minerales críticos. En este trabajo se realiza una investigación documental para un posterior análisis cuantitativo de los datos obtenidos. Tras la presentación de la discusión teórica sobre la seguridad energética, la transición energética y los minerales críticos, se analizan documentos de los sectores de la energía y los minerales redactados en el período comprendido entre 2000 y 2020. Se plantea que la transición hacia matrices energéticas menos contaminantes puede dar lugar a la creación de nuevas dependencias y que el acceso a recursos no energéticos es una condición para el éxito de la transición energética.

***Palabras-clave:*** Seguridad energética; transición energética; energia; minerales críticos; recursos naturales.

**São Paulo. Vol. 25, 2022**

*Artículo Original*