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Papers

Data Centers, Critical Minerals, Energy, and Geopolitics: The Foundations of Artificial Intelligence

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Abstract
Artificial Intelligence (AI) has expanded significantly in recent years, permeating various sectors of the economy and daily lives. However, this rapid adoption requires an analysis of the underlying trade-offs associated with its operation, which are often unknown to the public. Based on an analysis of data extracted from academic articles, technical reports, data repositories, and government documents, this article explores the physical, energy, and geopolitical dimensions underpinning AI. Despite often being perceived as immaterial, AI relies on a vast and complex physical infrastructure, supported by data centers that house thousands of pieces of equipment manufactured from a wide range of minerals and metals, many of which are classified as critical. Currently, approximately 12,000 data centers are in operation worldwide, including 992 hyperscale facilities that cover areas of thousands of square meters. The short life cycle of data center equipment, combined with inadequate disposal, removes valuable metals from the supply chain, intensifying mineral extraction and exacerbating socio-environmental impacts. Meanwhile, the competition between the United States and China for control over critical minerals and leadership in AI technologies has heightened geopolitical tensions, with mutual restrictions on the export of advanced technologies and essential minerals. Another key aspect is the high energy consumption of AI applications: in the United States, data centers already account for about 4% of national electricity consumption, with projections reaching 9.1% by 2030. Although major technology companies invest in renewable energy sources, such as solar and wind, to meet this growing demand, these sources also require significant volumes of critical minerals. This set of factors highlights the complex interconnection between Artificial Intelligence, Data Centers, Critical Minerals, Energy, and Geopolitics.

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INTRODUCTION

In recent years, the term "artificial intelligence (AI)" has become one of the most discussed topics in news and research around the world. Although its definition is broad and complex, the diversity of fields it encompasses and the different approaches used to understand and employ AI, most interpretations converge on the idea that machines developed by humans can not only perform exhaustive tasks, but also acquire intellectual capabilities similar to their creators (Jiang *et al.*, 2022).

A example of this growth is ChatGPT, a chatbot developed by the American company OpenAI. Designed to facilitate communication and solve problems via interactive and dynamic conversations, ChatGPT has become the fastest growing internet application among consumers, reaching 100 million users just two months after its launch in late 2022 (Milmo, 2023).

Since then, artificial intelligence has integrated deeply into daily life, with almost all sectors of the economy adopting the technology in search of greater efficiency and better results (Rashid; Kausik, 2024). Examples include robots used by companies in telephone customer service, navigation applications that use AI to provide optimized routes and real-time traffic information, social networks that customize feeds based on preferences detected by algorithms, ultra-realistic videos and images that challenge the distinction between real and artificial, autonomous cars, translation tools and academic text correction, among countless other applications.

Following this growth trend, market projections for artificial intelligence indicate significant advancement, with estimates of a leap from approximately US$ 90 billion in 2020 to US$ 250 billion in 2025, and reaching about US$ 830 billion by 2030 (Statista, 2024a).

This recent advancement of artificial intelligence and its widespread dissemination across various sectors of society were driven, among other factors, by the significant increase in computational power (Hwang, 2018) and the vast availability of data, which serve as the basis for model training (Zha *et al.*, 2023).

However, as AIs are broadly adopted, it becomes essential to analyze the complex interrelationship between "Data Centers, Critical Minerals, Energy, and Geopolitics" as foundations of Artificial Intelligence, in addition to the multiple trade-offs associated with its operation, many of which are still little known by the general public. As a society, we will need to face, contest, or seek solutions to these challenges, especially if we opt for a widespread expansion of AI.

Motivated by this issue, this article first presents and analyzes the physical infrastructure that supports artificial intelligence, with emphasis on the significant increase in the number and capacity of data centers. These facilities house millions of essential components to meet the growing demands for computing power and data storage, highlighting their close relationship with a wide range of minerals and critical metals indispensable to their manufacture. Then, we explore the recent geopolitical developments related to the dispute for dominance in AI development and control of the critical minerals necessary for building this technological infrastructure, focusing on the rivalry between the United States and China. The third point addresses the high energy intensity of AI, significantly higher than that of traditional digital applications, presenting global and national estimates of the energy consumption demanded by this technology. Finally, we analyze the interconnection between AI's growing energy consumption and the energy transition, highlighting the dependence of renewable sources, such as wind and solar energy, on critical minerals, which further expands the direct and indirect relationship of AI with these resources.

METHODOLOGY

To examine and discuss the relationship between "Data Centers, Critical Minerals, Energy, and Geopolitics" as pillars of Artificial Intelligence, this research was based on a broad collection and analysis of data from various scientific sources, including academic articles, technical reports, data repositories, official documents, and investigative reports.

To quantify the number of data centers in the world, identify those classified as hyperscale, and evaluate the growth of these structures over time, data from the German consultancy Statista (2024b; 2024c; 2024d; 2024e) were retrieved. Examples of hyperscale data center infrastructure and their illustrative images were extracted from communication portals of companies Switch (2024) and Google (2024a).

Strategic and geopolitical issues involving the dispute between the United States and China over critical minerals and AI dominance were explored via articles and books by Chinese and American researchers, as well as official documents from the United States government

(Nakano, 2021; United States, 2022; The White House, 2024) and the World Economic Forum (Zhou, 2024; Edmond, 2025). Additionally, reports and articles from major media outlets following the developments of this dispute were analyzed (Areddy; Follow, 2023; Hoskins, 2023; Bradsher, 2024; Freifeld; Potkin, 2024; Friesen, 2025; Holland, 2025; Milmo *et al.,* 2025).

To discuss the high energy consumption of artificial intelligence and data centers both global and national estimates were used. Reports from the Electric Power Research Institute (EPRI, 2024), the International Energy Agency (IEA, 2024), and the United Nations (2024), as well as specialized studies (Vries, 2023; Bourzac, 2024; Luccioni *et al.*, 2024) were used.

Data on the energy consumption of data centers from major technology companies and their relationships with renewable energy sources were obtained from corporate websites and reports from Microsoft (Welsch, 2022), Amazon (2024a; 2024b), and Google (2024b), as well as news reports and specialized studies (Calma, 2024a; 2024b; SP Energy, 2024).

Information regarding the connection between renewable sources - such as solar and wind - and the demand for critical minerals was discussed based on a previous article published by the authors (Stacciarini; Gonçalves, 2025a), based on data and reports from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and the World Bank (WB).

THE "PHYSICAL" STRUCTURE OF ARTIFICIAL INTELLIGENCE: DATA CENTERS AND MINERALS

The frequent mention of "Artificial Intelligence" in the news, accompanied by abstract terms such as "Cloud," "Big Data," "Algorithms," "Machine Learning," and "Virtualization," may convey the mistaken idea that these technologies operate in an immaterial form, without any connection to physical infrastructure.

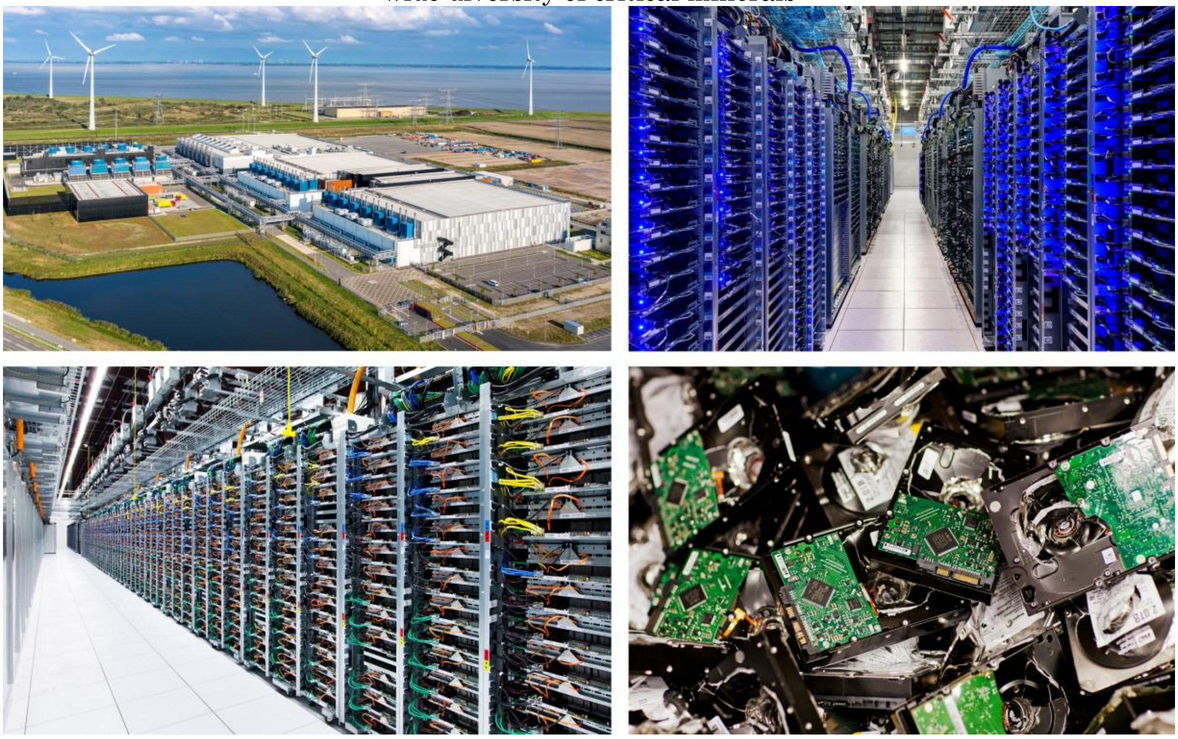
Behind these nomenclatures, however, lies a vast and complex infrastructure, generally located in data centers. These facilities are designed to house and operate thousands of servers organized in racks, accompanied by storage systems, network devices, processing units, power supplies, backup power systems, cooling systems, sensors for environmental monitoring, connection cables, and various other essential devices (Chatterjee; Venugopal, 2023).

Data centers represent the backbone of a world driven by artificial intelligence, providing the essential infrastructure to meet the growing demands for computing power and data storage. The construction of these facilities depends on a wide variety of minerals and metals - such as gallium, germanium, metallurgical silicon, tantalum, platinum-group metals, copper, rare earth elements, silver, and gold - ranging from common materials to critical raw materials (Pehlken *et al.*, 2019; Robbins; Van-Wynsberghe, 2022).

These resources are extracted and refined to achieve high levels of purity, meeting the electronic, magnetic, mechanical, and optical requirements essential to the functioning of these systems (United Nations, 2024). It is estimated that the production of complex electronic devices consumes from 50 to 350 times the final weight of the product in raw materials (Ademe, 2021). For example, manufacturing a laptop requires mobilizing approximately 600 kg of materials, while an internet router demands about 500 kg (Ademe, 2021).

Currently, there are approximately 12,000 data centers worldwide (Statista, 2024b). Of these, 992 are hyperscale (Statista, 2024c). Although there is no precise definition, IBM - a multinational American technology company - indicates that to be considered hyperscale, a data center needs to contain at least 5,000 servers and occupy more than 10,000 square feet (about 929 m²) (Powell; Smalley, 2024). The largest data centers, however, can reach much larger dimensions. An example is "The Citadel Campus," located in Reno, Nevada, USA. Operated by the American company Switch, which specializes in the design, construction, and operation of large-scale data centers, the project was developed for a data center complex of 7.2 million square feet (approximately 669,000 m² or 66.9 hectares) (Switch, 2024). These figures illustrate the vast quantity of minerals needed to sustain this process.

Figure 1 - Data centers, the physical infrastructure that sustains artificial intelligence, require a wide diversity of critical minerals



Source: Google (2024a). Elaborated by the authors (2025).

This demand for mineral raw materials necessary to meet the requirements of Artificial Intelligence tends to grow continuously, accompanying the significant increase in the number of data centers. Hyperscale data centers, for example, have quadrupled in the last eight years, going from 259 in 2015 to 992 in 2023 (Statista, 2024c). Projections suggest that this growth will be maintained in the coming years (Statista, 2024b; 2024d), driving a market valued at hundreds of billions of dollars (Statista, 2024a; 2024d; 2024e).

Another factor that intensifies the issue is the high rate of disposal of hardware-housing facilities that support artificial intelligence, resulting from rapid technological advancement (United Nations, 2024; Wang *et al.*, 2024). Many data center components have a limited service life, being frequently replaced at short intervals, generally from two to five years (Statista, 2024f). This disposal, besides representing a potential risk to human health and the environment due to the presence of hazardous or toxic materials, removes these metals from the supply chain (Wang *et al.*, 2024), requiring their replacement via the extraction of new raw materials.

MINERALS, ARTIFICIAL INTELLIGENCE, AND GEOPOLITICS

In recent years, it has been found that the supply of critical minerals necessary to meet the demands of artificial intelligence infrastructure is not determined solely by market logics, but is also deeply influenced by geopolitical dynamics. The availability of these minerals, as well as the technologies associated with them, has become a central element in the dispute for global supremacy between the United States and China (Nakano, 2021; Xinyue, 2024; Zhou, 2024), triggering intense confrontations.

Currently, China leads the market for critical minerals indispensable to the production of essential raw materials for artificial intelligence infrastructure, such as antimony, gallium, germanium, and rare earth elements (Areddy; Follow, 2023; Xinyue, 2024). In contrast, the United States excels in the manufacturing stage of these products, a process highly dependent on advanced knowledge, encompassing intellectual property, design, automation, and manufacturing technology, among other fundamental aspects (Xinyue, 2024).

Amid a fierce technological, economic, and political dispute, which began in 2018 during the Trump administration and intensified under Joe Biden's administration, the USA government announced, in October 2022, measures aimed at restricting the export of advanced technologies to China (Reuters, 2023). Among these actions, the prohibition of the sale of advanced chips and the imposition of restrictions on the export of equipment used in the manufacture of semiconductors stood out (United States, 2022).

In July 2023, in response to restrictions imposed by the United States and other countries on chip exports, China implemented limits on the export of two essential minerals for the production of technologies related to artificial intelligence: gallium and germanium, for which it is responsible for about 90% and 60% of global production, respectively (Areddy; Follow, 2023).

In October 2023, the United States intensified restrictions on the export of artificial intelligence chips, determining that the American company Nvidia suspend the supply to China of specific chips that already met previous regulations and had been developed with specific performance limitations for the Chinese market (Hoskins, 2023). Later, in November 2024, the American government expanded these measures, requiring that the multinational Taiwan Semiconductor Manufacturing Company (TSMC) also stop shipping advanced chips intended for artificial intelligence applications in China (Freifeld; Potkin, 2024). Nvidia and TSMC lead the global market for high-efficiency chips aimed at artificial intelligence (Statista, 2024g).

In response to these measures, the Chinese government intensified, in October 2024, restrictions on the export of rare earth metals and other strategic minerals crucial for advanced technologies, with a special focus on semiconductor manufacturers (Bradsher, 2024).

Amid the disputes, the European Union and the United States are seeking new strategies to enable access to critical minerals essential for the development of these technologies (Zhou, 2024). The U.S. government has been promoting a set of efforts - estimated at more than US$ 120 billion - aimed at strengthening national supply chains for critical minerals, with the goal of reducing dependence on China (The White House, 2024).

As we were finalizing this article, Donald Trump took office on January 20, 2025, for his second (non-consecutive) term as President of the United States. On his second day in office, the American president met at the White House with executives from major companies in the Artificial Intelligence sector to announce a set of legislative restructurings and private investments in the order of US$ 500 billion, intended to finance infrastructure for AI (Friesen, 2025; Holland, 2025). On the occasion, Larry Ellison, executive of Oracle Corporation - an American technology and computing company - announced the construction of 20 new data centers, each with half a million square feet (approximately 46,500 m²) (Holland, 2025).

A week after the announcement, the previously little-known Chinese company DeepSeek launched DeepSeek-R1, an artificial intelligence chatbot developed to compete with OpenAI's ChatGPT. Built at a significantly lower cost than its competitors and with competitive performance, the model was made available for free and in open source, allowing any AI developer to use it (Edmond, 2025). The launch occurred despite the restrictions and prohibitions imposed by Joe Biden's government on access to advanced AI chips (United States, 2022; Hoskins, 2023; Freifeld; Potkin, 2024). As a consequence, American technology companies lost approximately US$ 1 trillion in market value in a single day. Nvidia, the leader in manufacturing high-efficiency chips for AI and, until then, the most valuable company in the world, recorded a historic drop of about US$ 600 billion in its market value - the largest daily devaluation ever recorded in the United States stock market (Milmo *et al.*, 2025).

This set of episodes reinforces the strategic role of artificial intelligence and critical minerals in contemporary global geopolitics, showing that numerous developments will still occur in the coming years.

ENERGY CONSUMPTION OF ARTIFICIAL INTELLIGENCE AND DATA CENTERS

Due to intrinsic characteristics - such as the use of complex neural networks and the movement of vast data sets among thousands of physical components of its infrastructure (Bourzac, 2024) - artificial intelligence models generally consume significantly more energy than traditional applications, such as accessing emails, data retrieval, communication, or content streaming (EPRI, 2024; Luccioni *et al.*, 2024).

A request in ChatGPT, for example, consumes approximately ten times more electricity than a query in traditional search engines, such as Google (EPRI, 2024). Emerging technologies, such as the generation of audio, images, and videos, present an even higher consumption (Luccioni *et al.*, 2024).

Furthermore, since the successful launch of ChatGPT at the end of 2022, Big Tech companies have expanded the integration of artificial intelligence into an increasing number of online interactions and technological tools (Vries, 2023). With 5.52 billion active internet users in the world (Statista, 2024h) intensifying their contact with AI-based technologies, the energy consumption associated with these interactions continues to increase.

Although some authors point out that the evolution of hardware has historically been accompanied by advances in energy efficiency, playing an important role in containing the accelerated growth of energy consumption (Bourzac, 2024), advances in processors aimed at artificial intelligence seem to challenge this logic. Thus, although new processors present higher performance per watt than their predecessors, their capacity and production volume have increased so significantly that the final result is a constant growth in total energy demand (United Nations, 2024).

The report from the International Energy Agency (IEA, 2024), a reference on the subject, estimates that data centers, cryptocurrencies, and artificial intelligence consumed approximately 460 TWh of electricity in 2022, which represents about 2% of global electricity demand. The same report projects that this consumption could double by 2026, reaching from 620 to 1,050 TWh. This increase is equivalent to adding, in the lowest estimate, the annual energy consumption of Sweden, or, in the highest, that of Germany (IEA, 2024).

In countries with a higher concentration of these infrastructures, the energy consumption by them is already significant. In the United States, which holds the largest number of data centers in the world (Statista, 2024b), electricity consumption by these facilities corresponds to approximately 4% of national demand (IEA, 2024; EPRI, 2024). Driven, among other factors, by the advancement of artificial intelligence, it is estimated that this proportion will increase to 6% in 2026 (IEA, 2024) and up to 9.1% in 2030 (EPRI, 2024). In China, it is estimated that electricity demand by data centers will reach about 300 TWh in 2026 and 400 TWh in 2030 (IEA, 2024).

An investigative report published by Bloomberg, conducted by Saul *et al.* (2024), revealed that the growing demand for electricity by data centers has exceeded the available supply in various regions of the world. This imbalance has caused overloads in local electrical systems, generating concerns among residents about interruptions in supply and increases in electricity prices.

ENERGY TRANSITION AND MINERALS IN THE CONTEXT OF ARTIFICIAL INTELLIGENCE

Big tech companies have intensified investments in renewable energy sources, both as part of their sustainability strategies and to strengthen their corporate image before the public and investors. Examples include Google (2024b) and Amazon (2024a), which claim to offset 100% of their energy consumption - including that from data centers - via corporate renewable energy purchase mechanisms. Microsoft, in turn, has committed to achieving this goal by 2030 (Welsch, 2022).

To achieve this goal, Amazon claims to maintain, under its ownership or in partnerships, about 500 solar and wind energy projects distributed globally (Amazon, 2024a). Google, meanwhile, reported that, from 2010 to 2023, it signed more than 115 clean energy purchase contracts, corresponding to a generation capacity equivalent to approximately 36 million solar panels (Google, 2024b). In 2024, the company also announced that its future data centers will be strategically located close to solar and wind parks, ensuring their direct supply from these renewable sources (Calma, 2024a). In the same year, Microsoft revealed the signing of one of the largest corporate contracts for future purchase of renewable energy, valued at approximately US$ 17 billion (Calma, 2024b).

However, such as chips and other components of the physical infrastructure of data centers, solar and wind energy sources also depend significantly on critical minerals. This dependence stems from intrinsic characteristics of these technologies, such as lower energy density, shorter lifespan compared to traditional energy sources, and recycling difficulties - aspects that we addressed in detail in the article entitled "Global Geography of the Energy Transition and Mineral Extraction" (Stacciarini; Gonçalves, 2025a).

A land-based wind farm, for example, can consume up to nine times more mineral resources than a natural gas plant with similar capacity (IEA, 2021). In offshore wind projects - in which Amazon declares itself the largest corporate buyer of energy (Amazon, 2024b) - the consumption of critical minerals can be up to fifteen times greater (IEA, 2021) due to the need for large stakes for turbine fixation, underwater foundations, and an extensive network of submarine cables and ducts (Stacciarini; Gonçalves, 2025a).

The issue also applies to solar panels. Modern solar parks often include millions of units. As this technology depends on a significant set of critical minerals in its composition (Stacciarini; Gonçalves, 2025a), the pressure on mineral resource extraction continues to increase (Alonso, 2024; Milanez; Dorn, 2024; Stacciarini; Gonçalves, 2025b). An example is the Orion Solar Belt complex in Texas, designed to supply energy to Google's data centers. With more than 1.3 million solar panels, the complex has the capacity to generate 900 MW (SP Energy, 2024).

A proportional analysis suggests that to meet the projected consumption of 35 GW by data centers in the United States by 2030 (Newmark, 2024), approximately 50 million solar panels would be needed if all energy came from this source, exemplifying the growing dependence on critical minerals.

CONCLUSIONS

This study analyzed the complex and often neglected interconnection between "Data Centers, Critical Minerals, Energy, and Geopolitics" as foundations of Artificial Intelligence. Initially, we highlighted how artificial intelligence, a technology that currently moves approximately US$ 250 billion per year - with projections to reach US$ 830 billion by 2030 - has become a central element in global debates, integrating comprehensively into various aspects of daily life.

Although often perceived as immaterial, this study demonstrated that artificial intelligence depends on a vast and complex physical infrastructure, concentrated in data centers. This infrastructure includes essential elements, such as servers, storage systems, processing units, and cooling systems, designed to meet the growing demands for computing power and data storage. The production of these equipment requires a wide variety of minerals and metals, many of them classified as critical. An example is the manufacture of a single internet router, which can require the mobilization of up to 500 kg of raw materials.

Another critical point identified is the short life cycle of equipment used in data centers, which, on average, varies from two to five years. The inadequate disposal of these devices, without proper recycling, results in the removal of valuable metals from the supply chain, which demands new extractions from primary sources via mining activity.

The data gathered indicates the existence of approximately 12,000 data centers in global operation, with large ones (hyperscale) quadrupling in the last eight years, totaling 992 units. It is projected that this growth will continue in the coming years.

Although precise studies on the volume of minerals used in the construction and maintenance of this infrastructure are still lacking, difficulties in the supply of certain resources are already observed, aggravated by geopolitical and strategic factors. The dispute between the United States and China for control of critical minerals and leadership in AI-related technologies exemplifies these tensions. Since 2022, the American government has implemented a set of restrictions on the export of advanced technologies, such as chips and semiconductors, to China, which, in response, imposed limitations on the export of essential minerals for the manufacture of AI-related technologies.

We also highlighted the high energy consumption of artificial intelligence applications. With the increase in the number of users interacting with these technologies, the energy demand continues to grow. Currently, it is estimated that approximately 2% of global electricity is allocated to data centers, cryptocurrencies, and AI, a proportion that could double in the coming years. In the United States, data centers already consume about 4% of national electricity, with projections to reach 9.1% by 2030. In some regions, overloads in local electrical systems are already observed.

Although large technology companies are investing in renewable energy sources, such as solar and wind, to meet the demands of their data centers and artificial intelligence applications, these sources also require significant volumes of critical minerals due to intrinsic characteristics, such as lower energy density, reduced lifespan, and recycling difficulties. Large-scale projects, such as the Orion Solar Belt, which is installing more than 1.3 million solar panels in Texas (USA) to supply Google's data centers, exemplify this growing dependence on critical minerals. Moreover, proportional analyses indicate that, to meet the projection of future energy consumption of data centers, tens of millions of new solar panels will be needed.

This set of data and reflections shows that the expansion of AI and its associated infrastructure imposes challenges that go beyond the technological field, encompassing environmental, social, economic, and geopolitical dimensions. Understanding these interconnections is essential for the scientific community, society, policymakers, companies, and nations to evaluate more clearly the trade-offs involved and seek alternatives and solutions to these challenges, if the bet on a widespread expansion of AI is maintained.

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