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# Geopolitics of renewable energy under scrutiny

# Géopolitique des énergies renouvelables sous la loupe

**Ismail BENSLIMANE**
Doctor of Philosophy in Business Administration and Economics
Full-Time Professor at the Moroccan School of Engineering Sciences (EMSI), Rabat, Morocco.

**Yassire ELOTMANI**
Doctor of Philosophy in Business Administration and Economics
Full-Time Professor at the Moroccan School of Engineering Sciences (EMSI), Rabat, Morocco.

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**Abstract**

Nowadays, the world is witnessing a shift from a traditional paradigm that encourages the use of non-renewable energy sources to a new one that supports the development and adoption of renewable energy technologies. Given this, several issues arise that require in-depth study regarding the future ramifications of this transition and the challenges faced by stakeholders. To this end, the current work aims to examine the ultimate goals of the energy transition, the potential reordering of countries and the establishment of a new global order, the repercussions of this transition on international relations, and the accessibility of renewable energy for all countries without discrimination or restriction. Furthermore, it investigates the challenges of the energy transition in terms of the availability of critical materials and cybersecurity risks.

**Keywords:** Geopolitics; renewable energy; paradigm shift; future ramifications; critical materials; cybersecurity issues.

**Résumé**

À l'heure actuelle, le système énergétique mondial connaît une transformation structurelle profonde, caractérisée par le recul progressif du paradigme fondé sur l'exploitation des ressources fossiles au profit d'un modèle reposant sur le déploiement et la généralisation des technologies issues des énergies renouvelables. Cette mutation d'envergure soulève un ensemble de problématiques complexes qui nécessitent une analyse approfondie de ses implications à long terme, ainsi que des défis auxquels sont confrontés les différents acteurs impliqués. Dans ce contexte, le présent article vise à analyser les objectifs de la transition énergétique, les recompositions potentielles de la hiérarchie étatique et l'émergence d'un nouvel ordre international, ainsi que les effets de cette dynamique sur les relations internationales. Il s'intéresse également à la question centrale de l'accès équitable et non discriminatoire aux énergies renouvelables, tout en examinant les enjeux liés à la disponibilité des matériaux critiques et les risques croissants en matière de cybersécurité associés à cette transition.

**Mots-clés:** Géopolitique; énergie renouvelable; changement de paradigme; répercussions futures; matériaux critiques; enjeux de cybersécurité.

## Introduction

> *"To truly transform our economy, protect our security, and save our planet from the ravages of climate change, we need to ultimately make clean, renewable energy the profitable kind of energy." US President Barack Obama Address to Joint Session of Congress, Feb. 24, 2009*

Energy is the cornerstone of all economic activity. The absence of energy leads to the deterioration of every sector, whether primary, secondary, tertiary, quaternary, or even quinary. Consider for a moment a world devoid of energy: a universe where the extraction and exploitation of natural resources come to a halt, where both technological and non-technological production ceases, and where logistical and information technology services almost entirely disappear. Consequently, the availability or scarcity of energy inevitably results in the creation or destruction of value at the microeconomic level, which in turn translates into the creation or destruction of wealth at the macroeconomic level. Moreover, it is worth pausing for a moment to reflect on the profound connection between the emergence of new energy sources and the various industrial revolutions. The first unfolded under the impetus of coal, while the second was shaped by the advent of oil and electricity. Later on, the third gained momentum through information technologies, whereas the fourth industrial revolution is firmly rooted in the rise of renewable energies (Wrigley, 2013; Onu & Mbohwa, 2018).

Aware of the crucial importance of energy, the international community engages in a complex interplay of actors, positioning itself on major strategic issues. Some alliances have been forged to benefit from the energy resources of certain countries, while other relationships have deteriorated, or even become paralyzed, sometimes necessitating military interventions and resulting in significant material, human, and financial damages (Singh, 2007).

Since the 2010s, both academic and professional circles have increasingly debated the transition from traditional energy sources to renewable energy (Scholten & Bosman, 2016). In response to this growing interest and the anticipated future implications, the present study places particular emphasis on renewable energy, rather than non-renewable alternatives. Recent studies have highlighted a positive relationship between renewable energy deployment and economic growth across diverse contexts, including Brazil, European countries, China, and

Turkey (Wang et al., 2022; Pao & Fu, 2013; Ntanos, 2018; Lin & Moubarak, 2014; Ocal & Aslan, 2013).

As a matter of fact, this transition must not escape rigorous analysis: what is the ultimate goal of the energy transition? Does this strategic decision appear to reorder the countries of the world and establish a new global order? What are the repercussions of this transition on relations between states? Will all countries be able to access renewable energies without discrimination or restriction? Whatever the answer, the assessment of its impact is required with both fairness and rigor. Finally, what are the challenges of this energy transition in terms of the availability of critical materials and cybersecurity risks?

To address these inquiries, the present work is structured as follows. The first section defines and delimits the concepts under study, namely geopolitics and renewable energies. The second section emphasizes the main reasons behind the paradigm shift from the classical model, which favored the adoption of non-renewable energies, to the contemporary model, which supports the use of renewable sources. The third section provides a brief historical overview of the geopolitics of renewable energies. The fourth section presents a critical reflection on future geopolitical implications, with particular attention given to the reordering of countries worldwide. The final section meticulously examines critical material issues and cybersecurity risk challenges.

## 1. Research methodology

This study adopts an analytical literature review approach to examine the evolving relationship between renewable energies and geopolitics. The objective of the review is to identify dominant analytical frameworks, assess how renewable energy deployment reshapes geopolitical dynamics, and highlight areas of convergence and divergence within the existing literature. Particular attention is paid to issues of energy security, power redistribution, resource dependency, and international cooperation and competition. To this end, a search was conducted across major academic databases to ensure broad disciplinary coverage. The databases consulted included **Web of Science**, **Scopus**, **Google Scholar**, and **JSTOR**, selected for their relevance to geopolitical, energy, and international relations research. The search strategy combined keywords related to geopolitics and renewable energy systems using Boolean operators. The following search strings were used, with variations applied across databases:

(geopolitic* OR "geopolitical dynamics" OR "energy security")

AND
("renewable energy" OR "energy transition" OR "solar power" OR "wind energy" OR hydropower OR "green hydrogen")
The search was restricted to publications written in English and published between (2018 - 2025) reflecting the period during which renewable energy has become a significant geopolitical factor. To ensure analytical rigor and relevance, the selection of sources for this study was guided by a set of clearly articulated inclusion and exclusion criteria. The review encompassed peer-reviewed journal articles, scholarly books, and conference proceedings that explicitly examine the geopolitical implications of renewable energy. Both theoretical and empirical contributions were considered, including comparative analyses addressing dynamics at national, regional, and global levels. In contrast, publications were excluded if they focused solely on the technical or engineering aspects of renewable energy without incorporating a geopolitical perspective. Non-peer-reviewed sources were likewise excluded in order to uphold academic standards and ensure the reliability of the findings.

**2. Delimitation of constructs**

Now, the most important inquiry is: what is meant by renewable energy? In contrast to conventional non-renewable energy sources, namely oil, natural gas, coal, etc., which undergo combustion to release energy—a process that is, by nature, non-renewable—renewable energies such as solar radiation, hydropower, wind, geothermal, wave and tidal energy, and biomass are considered ***inexhaustible from an anthropogenic perspective***. However, they present a major limitation in terms of the ***amount of energy they can provide***, ***as they are inherently limited***. These points have been strongly emphasized by the *United States Energy Information Agency* and *European Policy Circles*. Still, the concept of sustainable energy can easily be confused with that of renewable energy. So, let's think together! Not every source of renewable energy is necessarily sustainable. Consider the vast areas of land exploited by so-called renewable energy projects—doesn't this come at the expense of agriculture and the overall well-being of local communities? According to the widely accepted definition of sustainable development, which is *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs,"* do the examples presented truly represent sustainable energy? Honestly, we don't think so (Criekemans, 2011).
After defining the first construct, it is essential to turn to the second one, namely *'geopolitics.'* A brief overview of the literature reveals that this concept has been defined from multiple

perspectives, giving rise to a variety of definitions. However, as noted in the work ***Definitions of Geopolitics*** by the scholar Igor Kovac, published by Oxford University Press, some scholars and members of the policy community use the term without providing any conceptualization, which can lead to misunderstandings. As a matter of fact, what is really meant by 'geopolitics'? Etymologically, geopolitics is derived from two words: *"on one hand, geo, from the Greek word gê, which means 'earth' or 'land'; on the other hand, politics, from the Greek word politikós, meaning 'of the state' or 'politics.' Together, the term can be understood as the 'politics of the earth.'"* According to the definition proposed by the Oxford Dictionary, geopolitics is *"the study of how a country's geography (size, location, resources) influences its international relations and power, or more broadly, the political dynamics between nations shaped by such geographic factors."* In a similar vein to the Oxford Dictionary, Indra Overland has proposed a useful definition that serves our research: *"over time, "geopolitics" came to denote the influence of geography on the power of states and international affairs more broadly, with less emphasis on determinism and greater focus on the strategic importance of natural resources, their location, transportation routes, and chokepoints"* (Overland, 2019).

## 3. A brief history of renewable energy geopolitics

As noted by Vakulchuk et al., between 1950 and 2018, scholars and journalists alike devoted considerable attention to the analysis of energy geopolitics, focusing predominantly on petroleum resources. An examination of the curricula offered in universities and higher education institutions corroborates this observation, particularly in courses related to international relations and energy studies. It was only from approximately 2006 and 2010 onward that some academics began to draw attention to the rising significance of renewable energy. Nevertheless, the substantial expansion of research in this field emerged only after 2018 (see Table 1) (Vakulchuk et al., 2020).

**Table 1: Searches for geopolitics, oil and renewable energy (11 September 2018).**

| | Search string A: "geopolitic* and oil", in title, keywords, or abstract 2016–2018 | Search string B: "geopolitic* and renewable energy", in title, keywords, or abstract 2016–2018 |
|---|---|---|
| **ISI Web of Science** | 131 | 23 |
| **Scopus** | 100 | 38 |

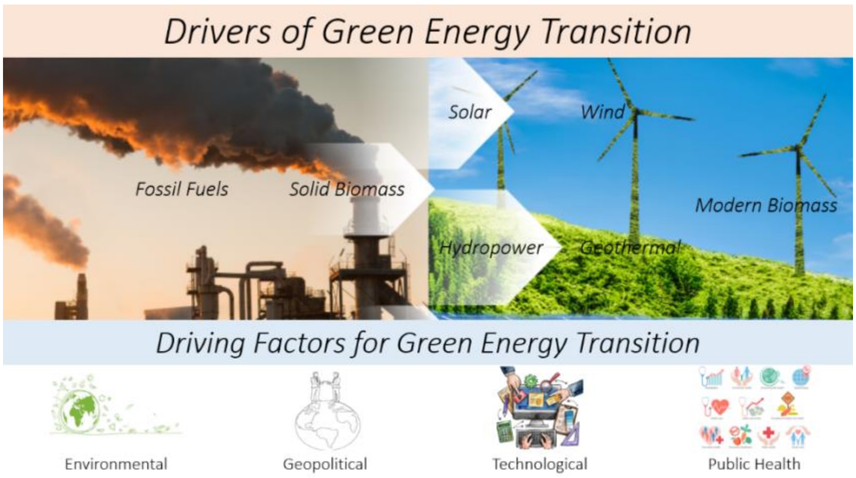
*Source:* Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews, 122,* 109547.

Contrary to claims that this disciplinary field emerged only in the last decade, Vakulchuk et al. note that internationally renowned institutions such as the National Science Foundation (NSF) and the National Aeronautics and Space Administration (NASA) had already stressed the crucial need to study the environmental, social, and political repercussions of solar energy as early as 1972. Later, in the early 1980s, the California Academy of Sciences prepared a report for the U.S. Federal Emergency Management Agency aimed at demonstrating the benefits of renewable energy in reducing the United States' energy vulnerability and potentially lowering the risk of war (Vakulchuk et al., 2020).

### 4. Reasons for a paradigm shift

While reviewing scientific studies, it becomes clear that the paradigm shift is undoubtedly the result of six main causes: the limitations of fossil resources, the climate emergency, health impacts, energy security, technological advances, and, lastly, the reduction of environmental damage (see Figure 1).

**Figure 1: Drivers of energy transition.**




*Source: Authors*

- First, traditional sources of energy are limited by nature, which does not guarantee their availability in the long term.
- Second, the combustion of non-renewable energies emits considerable amounts of $CO_2$, $CH_4$, and $N_2O$, thereby contributing to global warming.
- Third, classical sources produce fine particles and atmospheric pollutants such as nitrogen oxides and sulfur dioxide, degrading air quality and causing serious health impacts, including an increase in cancer rates, a surge in cardio-respiratory diseases, and an exponential rise in premature deaths each year.

- Fourth, oil is concentrated in a few regions of the world, such as the Middle East and Russia, creating geopolitical dependence, risks of conflict, and market instability.
- Fifth, the use of non-renewables destroys ecosystems — such as through mining, drilling, and oil spills — disrupts natural cycles, and ultimately leads to ocean acidification.
- Sixth, scientific research has greatly contributed to the development of renewable energy technologies, making it possible to significantly improve the efficiency of solar panels, drastically reduce the cost of wind energy, and develop highly efficient batteries (Lebrouhi et al., 2022; Et-taleby et al., 2022; Ait Tchakoucht et al., 2024; Charadi et al., 2021).

In the same vein, **table 2** presents a comparative synthesis of renewable and non-renewable energy systems based on the existing literature. It systematically examines their respective characteristics across technological, geopolitical, public health, environmental, and resource sustainability dimensions. This comparison aims to support a comprehensive assessment of the broader implications associated with different energy pathways.

**Table 2: Overview of differences between fossil fuels and renewables based on published studies.**

| Perspective | Renewable Energies | Non-Renewable Energies |
|---|---|---|
| Technological | Rapid technological innovation<br>Modular and scalable systems<br>Declining costs<br>Intermittency issues requiring storage and grid integration | Mature technologies<br>High energy density reliable baseload supply<br>Aging infrastructure in many regions<br>High capital costs for nuclear |
| Geopolitical | Enhances energy security through local resource availability<br>Reduces dependence on energy imports<br>Decentralized production | Concentrated resource distribution<br>Dependence on imports<br>Exposure to supply disruptions<br>Price volatility and geopolitical conflicts |
| Public Health | Low direct air pollution<br>Significant reductions in respiratory and cardiovascular diseases<br>Minimal occupational health risks | Major source of air pollution<br>Associated with respiratory illnesses<br>Cardiovascular disease<br>Premature mortality<br>Occupational hazards in extraction and processing |
| Environmental | Low greenhouse gas emissions over life cycle<br>Limited ecosystem disruption when properly managed<br>Land-use and biodiversity impacts may occur | High greenhouse gas emissions (fossil fuels)<br>Contribution to climate change<br>Land degradation<br>Water contamination |
| Resource Sustainability | Inexhaustible on human timescales<br>Dependent on natural variability | Finite resources<br>Depletion over time<br>Long-term waste management challenges |

*Source: Authors, based on the literature.*

A comparison of the advantages and disadvantages of different energy sources makes it increasingly evident that it is necessary to position oneself within a new energy paradigm that promotes the adoption and deployment of renewable technologies. These technologies reduce dependence on energy-producing countries and contribute to the democratization of economic and social life within nations, as will be demonstrated later in this article.

## 5. Challenging the canon: managing dynamic tension

Peace and conflict, the rise and fall of nations, and the emergence and dissolution of relationships between states—all of these constitute a real dynamic tension, necessitating, in a certain sense, a balance to harness the benefits of renewable energies while mitigating potential negative future repercussions.

### 5.1 Speculations about future ramifications

An in-depth review of the literature reveals that renewable energies can exert a significant influence both on the emergence of conflicts and on the consolidation of peace at the global level.

Proponents of the first approach argue that renewable energies may generate tensions comparable to those caused by fossil fuels. This position is supported in particular by the scarcity of critical materials required for their development, as well as by the growing risks associated with cybersecurity. Moreover, a very high level of renewable energy consumption could create new forms of vulnerability, potentially undermining the geopolitical stability of producing countries (Capellán et al., 2017).

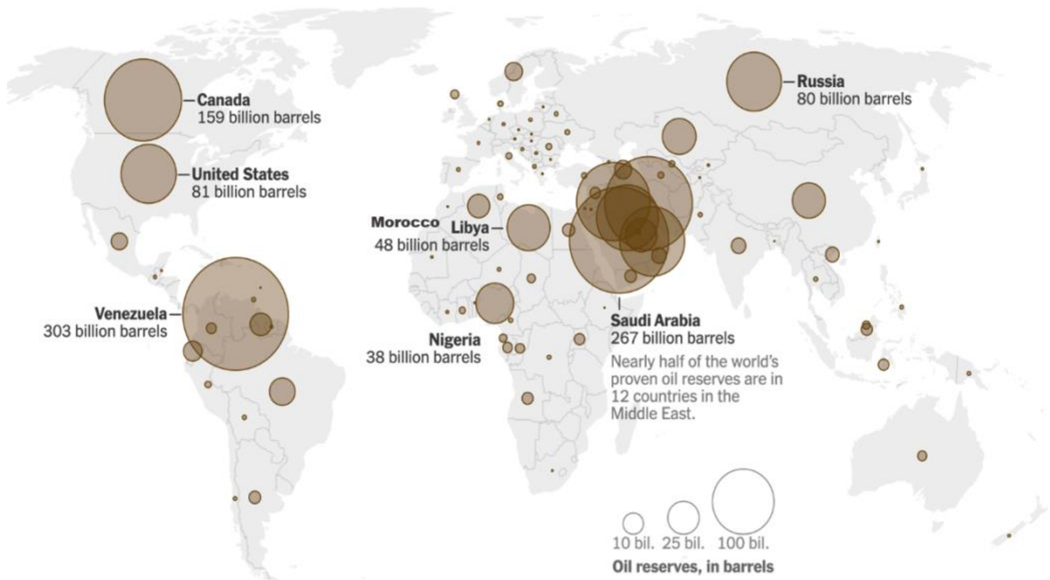
Conversely, advocates of the second perspective contend that renewable energies, owing to their broad geographic availability and the difficulty of manipulating their prices, foster greater energy autonomy. This autonomy tends to reduce interstate rivalries and, consequently, mitigate the risk of conflict (Habib et al., 2016).

Finally, when compared to the energy insecurity caused by traditional energy sources—often responsible for aggressive behaviors and conflict—renewable energies appear to be a less conflict-prone alternative, as they are theoretically inexhaustible. The only exception lies in the dependence on critical materials required for their production, which remains a potential source of tension (Jaffec & Soligo, 2008).

### 5.2 Rise and fall of countries worldwide

The strategic significance of renewable energies cannot go unnoticed, particularly for countries with vast fossil fuel reserves, such as Saudi Arabia, Canada, Russia, Venezuela, United States, Nigeria and Libya (See Figure 2).

**Figure 2: Mapping global oil reserves.**




*Source:* Visualization adapted from Elliott, R. F., & Gamio, L. (2025, December 5). *Lots of Oil, Little Production: What to Know About Venezuelan Energy.* **The New York Times**, underlying data from the Oil & Gas Journal.

These states risk facing the gradual obsolescence of their energy resources, a phenomenon often referred to as *"stranded geopolitical assets."* Consequently, global demand for traditional energy resources is expected to decline significantly, which could have profound economic repercussions for these countries, whose prosperity largely depends on the export of fossil fuels. This transition could also lead to a reconfiguration of their geopolitical influence, weakening their strategic position in international relations (Rothkopf, 2009).

Conversely, countries that have invested heavily in renewable energies and developed substantial knowledge capital, notably through patenting and technological innovation, are likely to benefit from particularly favorable economic momentum. The exponential increase in demand for technologies and infrastructure related to renewable energies offers them a significant competitive advantage. These nations will thus be better positioned to dominate emerging markets, attract international investment, and strengthen their energy autonomy, while consolidating their role in global energy governance (Eisen, 2011; Freeman, 2018).

In the long term, this transition may help reshape international power dynamics by establishing innovative economies as new centers of power, to the detriment of traditional actors heavily dependent on fossil fuels.

In analyzing the seminal article by Vakulchuk et al. (2020), entitled *"Renewable energy and geopolitics: A review",* we observed that several researchers have proposed a comprehensive list of *"losers"* and *"winners,"* including Sweijs et al. (2014) [1], Smith Stegen (2018) [2], and Overland et al. (2019) [3] (see Table 3).

**Table 3: Classification of winners and losers.**

| Least and most exposed to EU energy transition [1] | Geopolitical winners vs. laggards [2] | | GeGaLo Index of 156 countries [3] |
|---|---|---|---|
| Saudi Arabia (least exposed) | **Main winners:** | **Main losers:** | **Main winners:** |
| Qatar | Uruguay | Brunei | Iceland (no. 1 in the index) |
| Kazakhstan | Namibia | Qatar | Mauritania (2) |
| Egypt | Kenya | Bahrain | Guyana (3) |
| Libya | Mali | Kuwait | Bhutan (4) |
| Russia | Sweden | Timor-Leste | New Zealand (5) |
| Algeria (most exposed) | Finland | Trinidad & | Uruguay (6) |
| | France | Tobago | C. African Rep. (7) |
| | Nicaragua | Bhutan | Mauritius (8) |
| | Honduras | Slovakia | **Main losers:** |
| | India | Belize | Nigeria (149) |
| | Jordan | Georgia | Sudan (150) |
| | Mongolia | Bangladesh | Venezuela (151) |
| | Sri-Lanka | Gabon | Qatar (152) |
| | China | Samoa | North Korea (153) |
| | USA | Puerto Rico | DRC (154) |
| | Algeria | | Iraq (155) |
| | | | Yemen (156) |

*Source:* Vakulchuk, R., Overland, I., & Scholten, D. (2020). Renewable energy and geopolitics: A review. *Renewable and Sustainable Energy Reviews, 122,* 109547.

[1] The report ***Time to Wake Up: The Geopolitics of EU 2030 Climate and Energy Policies***, produced within the framework of ***The Hague Centre for Strategic Studies*** and under the direction of ***Tim Sweijs***, devotes its sixth section, entitled ***Which States are Most Vulnerable to a European Renewable Energy Transition?,*** to the analysis of states that could potentially be losers or winners of the European energy transition, drawing the following conclusions. The EU relies heavily on external energy suppliers, importing 53% of its energy, with the highest dependency for crude oil (≈90%) and natural gas (66%). Key suppliers include Russia, Algeria, Egypt, Qatar, Saudi Arabia, Kazakhstan, and Libya. Russia and Algeria are most vulnerable to

a European energy transition due to their heavy reliance on EU exports and oil/gas revenues. Although Egypt and Libya exhibit characteristics similar to those of the aforementioned states (Russia and Algeria), it is important to note that the hydrocarbon sectors in both countries have been experiencing significant challenges since the unrest associated with the Arab uprisings of 2011. In Libya, LNG exports have been suspended since early 2011, following damage to the LNG plant during the civil war and a sharp decline in oil production. While natural gas exports resumed in 2012, the only gas currently supplied to Europe is transported via the Greenstream pipeline to Italy. In Egypt, oil transit through the Suez Canal was comparatively less affected by the civil unrest; however, gas exports ceased entirely, rendering the country a net importer of natural gas for the first time. Although LNG exports have gradually increased since then, the sector continues to face constraints due to high domestic consumption and persistent underinvestment. Kazakhstan is less exposed to a European energy transition due to its expanding trade with China and the recent opening of a pipeline providing an alternative export route. Qatar and Saudi Arabia are the least exposed, as a smaller share of their hydrocarbon exports goes to Europe. While Qatar exports nearly a third of its gas to Europe, these are LNG supplies that can be relatively easily redirected to the Asian market if European demand declines (see the first row of Table 3).

[2] Chapter 3, entitled *"Redrawing the Geopolitical Map: International Relations and Renewable Energies,"* authored by Karen Smith Stegen and published in *The Geopolitics of Renewables*, proposes a formula for classifying countries as winners and losers.

The formula is as follows: **(R + P + H) / 3**, where:

- R Raw Potential Variable;
- P Political Receptiveness Indicator;
- H Hydrocarbon Lobby Variable.

Each variable is measured on a scale ranging from 1 (lowest level) to 10 (highest level). This methodology resulted in Table 3.1, presented on page 86 of the volume, which ranks countries according to these criteria (An excerpt from this table appears in the second row of Table 3). However, it is essential to note that the author specified that this analysis is preliminary and that the results are merely indicative. Under no circumstances should they be interpreted as definitive. Nevertheless, it is interesting to observe that some of these findings overlap with those of other studies seeking to identify which countries may be at the forefront of the transition to renewable energy. *The Climate Reality Project (2016)*, for example, presents a list of eleven countries, including Sweden, Costa Rica, Nicaragua, Scotland, Germany, Uruguay, Denmark, China, Morocco, the United States, and Kenya. These states are considered likely to achieve a degree of energy self-sufficiency. Karen Smith Stegen also raises a central question: *could these potential beneficiaries of the transition to renewable energy also become the major geopolitical powers of tomorrow?* It is difficult to envisage how some of the smaller and ostensibly weaker states identified as potential beneficiaries could assume a significantly enhanced role in international affairs. Nevertheless, historical precedent cautions against such skepticism. Denmark, for instance, was once a major geopolitical power, and little more than a century ago the British Empire exercised global dominance. History demonstrates that the relative fortunes of states are subject to often unexpected ascents and declines. Moreover, past large-scale transitions in energy systems—such as the shift from coal to oil and natural gas—have produced profound social, political, and economic transformations, frequently giving rise to unforeseen power configurations and geopolitical realignments. There is strong reason to expect that the ongoing transition from hydrocarbons to renewable energy will generate similar effects. As in previous energy transitions, those states that position themselves at the forefront of this transformation are likely to accrue substantial advantages associated with their early-mover status.

[3] In his paper *'The GeGaLo Index: Geopolitical Gains and Losses after Energy Transition,'* Overland developed the GeGaLo (Geopolitical Gains and Losses) index for 156 countries, assessing the potential impacts of a complete transition to renewable energy. The index incorporates several indicators, including fossil fuel production and reserves (representing potential geopolitical losses), renewable energy resources (representing potential geopolitical gains), and governance and conflict measures (reflecting the capacity to manage shifts in geopolitical influence). Based on the calculation formulas of the study index presented in Annex 1 of the article, he developed a summary table included in the second annex, covering the 156 countries studied, ranked in order, and highlighting the winners and losers (see the third row of Table 3). At first glance, many authors argue that the United States, China, the European Union, and Japan appear to be winners in the energy transition, as it would reduce their dependence on imported energy. However, if this is the case, *how can the alleged kidnapping of the President of Venezuela by the United States be explained?* Overland anticipated this paradox by advancing the critical argument that the United States may, in fact, suffer geopolitical losses due to its economy's heavy reliance on fossil fuels and coal.

### 5.3 Renewable energy, democracy, and the industrial revolution

Laird (2003), Omo-Fadaka (1980), and Rifkin (2011) argue that the decline of fossil fuels will have a greater impact on global politics than the rise of renewable energy. They explain that countries heavily dependent on oil and gas revenues—so-called rentier states—may face economic crises as fossil fuels lose importance, potentially leading to the fall of entrenched leaders and the emergence of more democratic governments if populations are ready for change. In contrast, renewable energy is often produced in a decentralized way, such as solar panels on homes, which reduces the control of political and economic elites and promotes a more balanced distribution of power. This decentralization fosters *"energy democracy,"* encouraging wider participation in energy management and creating a more stable political environment. The same authors suggest that this shift could spark a *"Third Industrial Revolution,"* as the global energy system becomes more equal and accessible, given that renewable resources like sun and wind are more evenly distributed than fossil fuels.

## 6. Basic needs: some issues

The transition to renewable energy is redefining the power lines of energy geopolitics. Two major issues dominate current debates: dependence on critical materials and cybersecurity risks associated with the digitization of electrical systems. According to Vakulchuk, Overland, and Scholten, there are divergences in the literature, with some emphasizing new vulnerabilities and others downplaying these risks (Vakulchuk et al., 2020). Thus, a paradox emerges: the transition can create new dependencies while mitigating certain traditional geopolitical risks, as noted by Overland (Overland, 2019).

### 6.1 Critical materials challenges related to renewable energy

This dynamic highlights the growing dependence on metals in place of hydrocarbons. The value chains of low-carbon technologies rely on strategic minerals and metals. For example, rare earth elements are essential for certain wind turbines, lithium and cobalt are critical for batteries, and copper is vital for electrical grids (Bazilian, 2018; Eggert, 2017).

Three key elements should be considered. First, the geographical concentration of supply, such as rare earth elements in China and cobalt in Central Africa, creates asymmetries between exporting and importing countries (Eggert, 2017). Second, scenarios involving the large-scale deployment of renewable energy raise concerns about bottlenecks in essential materials, which could slow down or complicate the transition (Eggert, 2017). Finally, the notion of the *"resource curse"* remains relevant; in countries with fragile governance, revenues from "green" minerals can trigger corruption and local conflicts (Vakulchuk et al., 2020; Church & Crawford, 2018).

Bazilian also emphasizes that achieving climate objectives requires substantial volumes of materials, with economic, environmental, and geopolitical implications that are often poorly managed. The risks of 'green conflict minerals' must also be considered, as they come from violent contexts without robust transparency standards (Bazilian, 2018).

In contrast to this alarmist view, other studies offer a more nuanced perspective. Many so-called 'rare' materials are, in fact, relatively abundant geologically, with tensions explained more by high costs and environmental constraints than by an actual scarcity. Crises, such as the Chinese embargo on rare earths in 2010, have led to innovations and new production capacities, thereby reducing the potential pressure on these resources (Overland, 2019; Wilson, 2018).

The transition to renewable energies is a dynamic process, involving efforts to reduce the intensity of critical materials, develop substitutes, and promote recycling. Unlike fossil fuels, the materials in wind turbines and batteries are recyclable, and appropriate policies could reduce dependence on primary extraction (Overland, 2019).

Thus, two visions oppose each other: some view critical materials as new vectors of power, while others see them as issues of industrial governance (Overland, 2019; Vakulchuk et al., 2020).

### 6.2 Cybersecurity risks associated with renewable energy

The second axis of discussion explores the cybersecurity of electrical systems. With the integration of renewable energies, grids are becoming more digitized, making the security of control systems and connected devices crucial (Vakulchuk et al., 2020). This development expands the attack surface for cybercriminals, who could cause major disruptions (Tuyen, 2022). Moreover, attributing attacks remains difficult, making their use as a tool of pressure uncertain (Vakulchuk et al., 2020; Fischhendler et al., 2017).

Furthermore, studies show the diversity of attack vectors, such as false data injection and the takeover of network support functions. These analyses recommend multi-layered defense strategies, incorporating detection, isolation, and redundancy (Tuyen, 2022; Qi et al., 2016). It is worth noting that with the rise of renewable energies, system complexity increases, which also heightens cyber risks (Vakulchuk et al., 2020).

However, other analyses provide a different perspective on these issues. They emphasize that cybersecurity concerns the entire modern energy system, including oil and gas infrastructure as well as nuclear power plants, all of which are vulnerable to cyberattacks. Thus, cybersecurity should be seen as a cross-cutting issue rather than a specificity of renewable energies (Overland, 2019).

Moreover, the increase in decentralized production, such as rooftop photovoltaics and self-consumption, can enhance system resilience. A grid using multiple small producers is harder to paralyze than a centralized system with major points of failure (Overland, 2019).

Finally, several studies emphasize that pessimistic scenarios can serve as a warning. By prompting regulators and operators to improve standards and protection tools, these analyses reduce the likelihood of the worst-case scenarios occurring. In this perspective, cybersecurity is constantly evolving, guided by regulation, technical standards, and cooperation between states and operators (Overland, 2019).

## Conclusion

A review of the scientific literature at the nexus of geopolitics and renewable energy indicates that this domain is characterized by considerable instability and uncertainty. On the one hand, the increasing prominence of renewable energy sources has the potential to disrupt global stability, reconfigure the international hierarchy of states, and fundamentally transform the structure of international relations. On the other hand, renewable energy technologies exhibit a substantial dependence on critical materials, the availability of which remains severely limited, while simultaneously introducing potentially irreversible cybersecurity vulnerabilities.

It is important to emphasize that this study focuses specifically on certain negative aspects of renewable energy, aiming to raise awareness within academic and professional communities about the associated risks. It also highlights pathways for strategic consideration to prevent the recurrence of challenges observed in conventional energy systems. By delineating areas of uncertainty and ambiguity, states and institutions can collaboratively establish a regulatory framework that protects all stakeholders. Beyond the legislative dimension, promoting innovation emerges as a critical strategy for mitigating potential resource shortages, which, at present, remain largely hypothetical.

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