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Synergistic evaluation of energy security and environmental sustainability in BRICS geopolitical entities: An integrated index framework

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Abstract

Research background: The increasing demand for energy, driven by economic growth and population expansion, is a critical driver of societal progress. However, the predominant reliance on fossil fuels to meet this demand presents significant challenges, particularly in the rapidly developing BRICS nations (Brazil, Russia, India, China, and South Africa). These countries are faced with a complex interplay of energy security and environmental sustainability issues, stemming from their substantial fossil fuel reserves and the associated environmental consequences. The challenges manifest as inequalities in access to clean energy, environmental degradation, and heightened vulnerability to the impacts of climate change. Addressing these multifaceted issues requires a comprehensive approach. Metrics-based strategies, which employ aggregated indices derived from a diverse set of energy and environmental indicators, have the potential to provide valuable insights into these complexities. However, the development of a universally applicable energy sustainability index is complicated by the heterogeneity of metrics, disparities between countries, and methodological challenges, emphasizing the need for an innovative and holistic analytical framework.

Purpose of the article: This study aims to develop a tailored Energy Security and Environmental Sustainability Index for BRICS economies to evaluate the robustness of their energy systems and the viability of their ecological practices. The index serves as an instrument to assess the progress of these nations in the Energy and Environment domain and identify areas that require targeted interventions and improvements.

Methods: The construction of the composite ESESI involves the selection of relevant parameters and the application of a Multi-Criteria Decision Analysis (MCDA) framework in conjunction with the Weighted Product Method (WPM). To ensure objectivity in the determination of optimal and least favorable weights for each indicator, the study employs the Multiplicative Data Envelopment Analysis (MDEA) model.

Findings & value added: The ESESI analysis reveals disparities in the progress made by BRICS nations in enhancing energy security, promoting renewable energy deployment, and mitigating environmental impacts. While some countries demonstrate substantial advancements, others face challenges in improving energy efficiency and reducing carbon emissions. The study underscores the necessity for tailored policies and targeted infrastructural enhancements that align with the unique challenges and strengths of each nation. Harnessing the abundant renewable energy potential through advanced energy trade mechanisms and fostering cross-border investments are identified as crucial strategies for ensuring environmental sustainability and long-term energy in the BRICS region. The ESESI provides a valuable tool for policymakers and researchers to evaluate the progress of BRICS nations in achieving sustainable energy goals and to inform evidence-based decision-making processes. By offering a comprehensive and scientifically rigorous assessment framework, this study contributes to the ongoing discourse on sustainable energy transitions and environmental stewardship in the context of rapidly developing economies.

Introduction

Energy serves as a fundamental driver of modern society, acting as a vital enabler for poverty alleviation, social development, and economic growth. The pursuit of a sustainable and reliable energy supply has become a paramount objective of scientific research, engaging scholars worldwide (Aceleanu *et al*., 2017; Balcerzak, 2018; Chyhryn *et al*., 2022). Researchers in this domain grapple with intricate challenges that impede the sustainable and sufficient provision of energy, such as increasing energy demands and climate changes (Aceleanu *et al*., 2017; Balcerzak, 2018). The global demand for energy resources is escalating rapidly, fueled by intensifying economic activities and demographic expansion. Recent global energy developments indicate a 5.8% increase in primary energy demand in 2021, surpassing 2019 levels by 1.3%, with fossil fuels accounting for 82% of primary energy consumption. Simultaneously, CO2 emissions from energy use, industrial processes, flaring, and methane increased by 5.7% to 39.0 GtCO2e, while oil consumption rose by 5.3 million barrels per day. Natural gas prices experienced a significant recovery, and the demand increased by 5.3% in 2021. Coal consumption grew by 6%, with China and India contributing to over 70% of this growth. Renewable primary energy sources displayed an annual growth rate of 15%, predominantly propelled by expansions in solar and wind capacity in China. Hydroelectricity generation decreased by 1.4% in 2021, whereas nuclear generation rose by 4.2%. Finally, electricity generation increased by 6.2%, with wind and solar contributing 10.2% to power generation, surpassing nuclear energy's share (Shah *et al*., 2019).

The BRICS region, comprising Brazil, Russia, India, China, and South Africa, stands as one of the most rapidly developing regions worldwide. However, the availability of energy resources might constrain sustained economic advancement in these nations (Rasul, 2016). Energy security emerges as a paramount concern within the BRICS, primarily due to the challenges associated with securing energy resources while maintaining ecological equilibrium. Despite possessing substantial reserves of fossil fuels, these countries face mounting energy demands driven by rapid economic growth and population increases. For example, China is the world's largest energy consumer and is projected to become the top oil importer by 2030. Similarly, Brazil and Russia heavily rely on their vast oil and gas reserves to satisfy their energy requirements (BP, 2023a, 2023b; Brodny & Tutak, 2023). Moreover, a major challenge for the BRICS countries is ensuring access to clean energy, particularly in rural areas. According to the International Energy Agency (IEA, 2022), over 800 million people worldwide lack access to electricity, with a significant number residing in the BRICS nations. The use of traditional fuels, such as coal and wood, for cooking and heating not only contributes to air pollution, but also poses serious health risks, particularly affecting women and children (BP, 2023a, 2023b).

In the context of environmental sustainability, the BRICS nations grapple with a myriad of challenges, encompassing deforestation, soil degradation, water scarcity, and air pollution. Brazil, for instance, is home to the Amazon rainforest, the most significant global carbon sink. Despite this, the country experiences rising deforestation rates driven by economic development and agricultural expansion. Similarly, Russia faces considerable obstacles in curbing its carbon emissions due to its heavy reliance on coal-fired power plants. China, recognized as the world's largest emitter of greenhouse gases, primarily attributes this status to its reliance on coal and heavy industries. However, the nation has taken proactive steps to mitigate its carbon footprint, including substantial investments in renewable energy sources and the implementation of energy efficiency measures (Ahmed *et al.*, 2022a; Awosusi *et al.*, 2022; Shah *et al.*, 2023).

Furthermore, the BRICS nations are highly susceptible to the detrimental impacts of climate change. The increasing frequency and intensity of natural disasters such as floods and droughts carry grave implications for the socio-economic development of the region. For example, India confronts a severe water crisis, with numerous urban centers grappling with acute water shortages. The accelerating retreat of Himalayan glaciers presents critical challenges to the region's water security. In Brazil, intensifying droughts adversely affect the country's hydropower generation capacity (Abbass *et al.*, 2022; Ahmed *et al.*, 2022a; Brodny & Tutak, 2023).

The challenges posed by energetic instability and ecological vulnerability may lead to diminished economic growth and exacerbated poverty levels. Furthermore, the absence of effective policy formulation to address these challenges could hinder international cooperation (Ahmed *et al.*, 2023; Shah *et al.*, 2019). Therefore, it is imperative to develop methodologies that tackle the escalating concerns related to energy and the environment (E&E). This necessitates conducting comprehensive assessments of energy security and ecological stability in the region. Consequently, the study embarks on a multifaceted analysis centered on a diverse range of E&E indicators (Javadpoor *et al.,* 2021).

Employing a metric-based approach proves to be an effective means to understand the intricate functioning of E&E systems, as it unveils complex interactions with societal, economic, energetic, and environmental progression that might otherwise remain obscure (Ahmed *et al.*, 2022b; Brambila & Flombaum, 2017). Recognizing the utility and instrumental nature of indices in effectively disseminating critical data, international agencies regularly update their repositories of energy metrics. The development of these metrics has facilitated the emergence of numerous simple and aggregated indices. However, the plethora of metrics can sometimes obscure understanding, as aggregated metrics are complex, have uncertain relative importance, assess similar attributes, and can produce conflicting results. For instance, the International Atomic Energy Agency (IAEA) collaborates with the Energy Indicators for Sustainable Development (EISD), the European Environment Agency (EEA), the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), and Eurostat to employ thirty metrics (Eurostat, 2008). Conversely, Sovacool and Mukherjee (2011) have compiled an extensive array of 320 basic and 52 complex energy metrics, rendering the task of achieving consistent and coherent results challenging, given the vast multidimensional array of energy indicators. Numerous efforts have been made to amalgamate these measures and develop an index that enhances data comprehensibility. Such an index aids in assessing a country's progress over time, identifying critical trends that might otherwise remain obscure, and evaluating trade-offs across various dimensions while highlighting areas in need of improvement (Martchamadol & Kumar, 2013; Ahmed *et al.*, 2023; Sovacool, 2012; Sovacool & Mukherjee, 2011). Attempts to establish an index that encompasses both energy security and sustainability have been widely recognized among stakeholders (Shah *et al.*, 2019), although achieving a universally accepted index remains elusive, primarily due to disagreements over the fundamental concepts and substantial variations in the energy structures of different nations. Additionally, interdependencies between metrics, methodological challenges, data limitations, and spatial considerations (local, regional, global) complicate the development of such indices.

This investigation has developed an ESESI specifically tailored for the BRICS region, providing a holistic, contemporary, and methodological examination. The metrics were carefully selected to cover the broad aspects of ESES. This study includes metrics such as electrification ratio, the rate of change in forestry, the proportion of renewable energy sources (RES) in electricity generation, CO2 emission from electricity generation, Carbon Dioxide intensity, CO2 emission per capita, Gross Domestic Product per capita, per capita energy consumption, diversity in total primary energy supply (TPES), energy intensity, and energy dependency. Employing an innovative approach inspired by Data Envelopment Analysis (DEA), the model was utilized to facilitate the allocation and integration of weights, thereby minimizing the influence of personal biases often associated with Multi-Criteria Decision Analysis techniques due to the arbitrary nature of weight distribution (Hatefi & Torabi, 2010; Velasquez & Hester, 2013; Zhou *et al*., 2006). The weighted product (WP) method was used to merge sub-metrics, proving to be superior to other strategies such as simple additive weighting and the ideal distance weighting method (WDI), which tend to result in significant data degradation (Zhou *et al*, 2006).

The primary objective of this study is to conduct a comprehensive analysis of Energy Security and Environmental Sustainability (ESES) for the BRICS nations, utilizing a comprehensive index methodology. The research focuses on establishing and applying the Energy Security and Environmental Sustainability Index (ESESI) — a tool designed to amalgamate eleven relevant indicators, thus facilitating a detailed evaluation of sustainable development trajectories in the context of BRICS countries. The objective further extends to pinpoint achievements, challenges, and sectors necessitating improvement concerning energy security, adoption of renewable energy, and environmental consequences across these nations. The first hypothesis posits that a comprehensive assessment of energy security requires the integration of environmental factors for a thorough understanding of a nation's energy security status. The second hypothesis anticipates significant disparities in ESES among BRICS countries, attributable to various factors including climatic conditions, geographic and economic disparities, infrastructural investments, endowment of natural resources, policy strategies, and degree of industrialization. The final hypothesis asserts that the ESESI could serve as an effective instrument for gauging ESES achievements and identifying areas requiring interventions, thereby aiding in the development of tailored policies, infrastructural advancements, and initiatives to foster renewable energy adoption and mitigate dependence on fossil fuels. This investigation initially examines the trajectory of individual sub-metrics for each nation, followed by the computation of ESESI scores and ranking of countries accordingly. This process enables underperforming nations to adopt best practices exhibited by their higher-ranked counterparts. In addition, a comprehensive assessment functions as a tool for decision-makers to develop forward-thinking, enduring approaches that emphasize energy assurance and ecological preservation, reinforcing fiscal steadiness and local serenity.

The rest of this paper is structured as follows: Section 2 provides a comprehensive overview of the energy landscape and environmental vulnerabilities in the BRICS region. Section 3 delineates the theoretical framework for constructing the ESESI, encompassing the meticulous selection of submetrics, the rigorous assignment of weights, and the systematic aggregation process. Section 4 presents the research findings, while Section 5 engages in a critical discussion of the results. Finally, Section 6 concludes the study and offers evidence-based policy recommendations.

Literature review

The extensive body of scientific research explores the complexities of ESES from diverse perspectives (Sovacool, 2012; Sovacool & Mukherjee, 2011; Le Coq & Paltseva, 2009). These inquiries span from local contexts (hamlets/islands) to broader scales (regions/nations). A systematic review of the literature reveals three distinct categories of studies; the first group primarily focuses on the financial dimensions, with limited attention to environmental considerations (Kara, 2018). The second group emphasizes the safeguarding of primary energy resources, particularly oil (Vivoda, 2009; Zhang & Hsu, 2024), and to a lesser extent, natural gas (Ahmed *et al.*, 2022d; Findlater & Noël, 2010), while often neglecting other crucial energy sources including coal, nuclear, and renewables. The third group addresses the reliability of supply, but fails to adequately consider essential factors like energy intensity (Matsumoto & Shiraki, 2018; Narula *et al.*, 2017). These categories underscore the diverse approaches to conceptualizing energy security and sustainability, each with its own focus and limitations.

Further investigating the intricate interplay between economic complexity, renewable energy adoption, and sustainable development across various global contexts, elucidating the nuanced impacts of these factors on energy security (Chu, 2023; Ha, 2023). For example, Chu (2023) examines the impediments posed by economic complexity to renewable energy development in G7 countries, while Bilgili and Bağlıtaş (2022) and Doğan *et al.* (2023) highlight the positive impacts of renewable energy on sustainable development and the complex interrelations involving energy security, economic stability, and environmental sustainability. Jonek-Kowalska (2022) contributes to this discourse by proposing a methodological approach to assess the energy security of 32 European countries based on their energy mixes and the availability of internal energy sources. The study reveals that most countries have low energy security due to their reliance on non-renewable resources, underscoring the importance of considering resource and economic conditions in energy security assessments. Moreover, researchers have explored the implications of energy poverty for sustainable energy transitions (Nasir *et al.*, 2022; Streimikiene & Kyriakopoulos, 2023), the intricate relationship between natural resources, environmental degradation, and energy security (Shittu *et al.*, 2021), and the development of indicators and frameworks for assessing low-carbon, just energy transitions (Streimikiene *et al.*, 2021). The sustainable development of the fuel and energy industry has also garnered research attention (Chernyaev & Rodionova, 2017).

While the aforementioned studies provide valuable insights into energy security and sustainability in various contexts, there is a growing body of literature specifically addressing the unique challenges faced by BRICS economies. For instance, Zhang and Hsu (2024) investigate the role of emission trading schemes, energy innovation, and technology transfer in BRICS economies' shift towards sustainability, finding positive effects of carbon taxes, energy innovation, and technology transfer on economic performance. Kuang (2023) analyzes the impact of natural resources and technology on CO2 emissions and economic development in BRICS using the extended STIRPAT model, confirming the environmental Kuznets curve, energy push emissions, and causal relationships. However, these studies focus on specific aspects of energy security and sustainability, rather than provide a comprehensive assessment using a multidimensional index approach, as proposed in the current study.

Previous research has also examined the complex interrelationships among energy security, energy equity, and environmental sustainability, which may influence decision-makers' choices due to their challenging connections (Herrero *et al.*, 2011; Biresselioglu *et al.*, 2018; López-González *et al.*, 2019; Alola, 2019; Dočekalová & Kocmanová, 2016; Gupta & Keen, 2014; Cao & Alanne, 2018). Numerous studies have investigated the intricate relationship between energy, economic, and environmental issues (Le *et al.*, 2019; Malik *et al.*, 2020; Iram *et al.*, 2020), and the challenge of sustainable food production has been linked to energy demand (Bartocci *et al.*, 2017; He *et al.*, 2010).

Within these studies, a diverse range of indices has been developed, each underpinned by distinct sets of metrics selected according to the researchers' perspectives. While some metrics are common across multiple studies, others are chosen for evaluating specific attributes related to particular studies. However, an energy index may provide limited information if the selection of metrics is not conducted with meticulous care. Conversely, an index gains significance only when it incorporates a comprehensive and relevant collection of metrics. The academic consensus acknowledges the absence of a definitive set of energy metrics and recognizes the dynamic nature of these metrics, which evolve in response to country-specific contexts, capabilities, and priorities, thus necessitating ongoing research in most countries for thorough and systematic analyses (Ahmed *et al.*, 2022c; Singh & Dikshit, 2009). This underscores the need for a comprehensive and tailored index, such as the ESESI proposed in the current study, to effectively assess ESES in the BRICS region.

Energy status and environmental vulnerability of BRICS

Energy status

The BRICS region has emerged as a dominant force in the global energy consumption. According to data from the International Energy Agency (IEA, 2022), these countries accounted for approximately 44% of total global energy consumption in 2020, with China alone consuming about 24%. Table 1 presents the proportion of domestic production meeting the demand for crude oil, natural gas, and coal within the BRICS nations. Brazil demonstrates a high level of energy self-sufficiency, with a significant percentage of its energy needs being met through domestic production across all three types of fuels. In contrast, India and China show relatively lower levels of energy independence, particularly in natural gas and crude oil. Russia maintains a higher level of self-sufficiency in coal and crude oil compared to natural gas, while South Africa fulfills its coal requirements entirely through domestic production (BP, 2023a, 2023b; IEA, 2022).

In summation, Table 1 highlights the varying levels of reliance on domestic production among the BRICS nations, reflecting their diverse energy policies, resource availability, and market dynamics. This data provides a foundation for further analysis of their energy strategies and sustainability goals, offering insights into the unique energy mix of each country. Figure 1 provides a comparative analysis of electricity generation sources within the BRICS nations, emphasizing the differences and similarities in their energy portfolios. Brazil and South Africa exhibit a heavy reliance on coal for electricity generation, accounting for 60% and 84% of their respective electricity outputs. Similarly, Russia and India primarily generate their electricity from fossil fuels, including coal and natural gas, which constitute 83% and 75% of their electricity generation, respectively. China, as the leading energy consumer within the BRICS group, predominantly produces its electricity from coal and hydro, contributing 63% and 16% to its electricity generation, respectively. Renewable energy sources such as bioenergy, wind, and solar are relatively underdeveloped in most of the BRICS countries. However, India has made considerable strides in expanding its renewable energy capacity, with bioenergy, wind, and solar contributing 10%, 4%, and 0.2% to its electricity generation, respectively (BP, 2023a, 2023b; IEA, 2022).

Figure 2 reveals that fossil fuels, primarily coal, continue to dominate the electricity generation mix in the majority of these nations. Although renewable energy sources such as bioenergy, wind, and solar have been gaining momentum in recent years, they still represent a small fraction of the electricity generation mix in most of the BRICS countries. This underscores the urgent need for these nations to diversify their energy portfolios and invest in more sustainable and cleaner energy sources to meet their growing energy demands while mitigating their carbon footprint.

Environmental vulnerability

The BRICS consortium, representing over 40% of the global population, exhibits rapid economic growth (BP, 2023a, 2023b). However, these nations face a myriad of interconnected environmental challenges, including anthropogenic climate change, atmospheric and aquatic pollution, and land degradation, which pose significant risks to their ecosystems, economies, and populations. For example, Brazil experiences extensive deforestation and wildfires within the Amazon rainforest, leading to biodiversity loss, habitat destruction, and increased greenhouse gas emissions (Laurance *et al.*, 2018). Russia contends with permafrost thaw, resulting in infrastructure damage and the release of methane, a potent greenhouse gas (Schuur *et al.*, 2015). In India, a significant water shortage affects many regions, exacerbated by climate variability and suboptimal water management practices, threatening both agricultural productivity and public health. China deals with severe urban air pollution, causing respiratory and other health issues, which place a substantial burden on its healthcare system and economy. South Africa encounters land degradation and water scarcity, particularly in rural areas, exacerbating socioeconomic inequalities and hindering sustainable development. These environmental issues have profound social and economic impacts, especially on vulnerable populations, necessitating urgent attention and action from policymakers and the public (Ahmed *et al.*, 2022e; Joof & Ali, 2022; Kıprızlı & Köstem, 2023; Martins, 2019; Nawaz *et al.*, 2021).

Table 2 highlights the primary climate hazards faced by the BRICS nations. All five countries are vulnerable to extreme weather events and sea-level rise, which could cause significant damage to infrastructure, agriculture, and public health. Biodiversity loss is a critical concern for Brazil, India, and South Africa, threatening the resilience and functioning of their ecosystems, while permafrost thaw and glacial retreat pose significant challenges for Russia, with far-reaching implications for its infrastructure and carbon cycle. Air pollution affects both China and India, contributing to a substantial disease burden and premature mortality, with South Africa also impacted by water scarcity, which constrains its socioeconomic development. These hazards may have cascading effects on each other and exacerbate existing vulnerabilities, making it crucial for BRICS nations to develop effective adaptation and mitigation strategies that address the complex interactions between these environmental challenges (Joof *et al.*, 2022; Kıprızlı & Köstem, 2023; Kubota, 2020; Martins, 2019; Nawaz *et al.*, 2021).

Climate hazards affecting BRICS countries have been the focus of numerous scientific studies, highlighting the severity and complexity of these challenges. China's coastal cities are at considerable risk from sea-level rise, potentially leading to widespread flooding and critical infrastructure damage (Ahmed, *et al.*, 2023; Li & Shapiro, 2020). Meanwhile, research by Vasiliev *et al.* (2020) underscores the importance of addressing permafrost thaw in Russia, which can trigger landslides and destabilize buildings and infrastructure, with significant implications for public safety and the economy. Biodiversity attrition poses another significant hazard faced by BRICS nations. Cooke *et al.* (2021) found that Brazil, India, and South Africa have some of the highest global biodiversity levels, with extreme vulnerability to biodiversity loss due to climate changes, underscoring the urgent need for conservation efforts and sustainable land management practices. The study emphasizes the importance of preserving biodiversity and ecosystem services for human well-being and highlights the need for coordinated international efforts to address this issue. Air pollution is another significant climatic hazard affecting BRICS nations, particularly China and India. Gupta (2014) determined that air pollution is a major contributor to morbidity and mortality in India, underscoring the need for comprehensive air quality management strategies and public health interventions. Similarly, Wang *et al*. (2019) found that air pollution is a significant public health concern in China, advocating for policies to reduce emissions and improve air quality, which could yield substantial health and economic benefits.

These investigations underscore the importance of addressing climate hazards within BRICS nations to protect human well-being, safeguard critical infrastructure, and conserve natural ecosystems. Developing effective adaptation and mitigation strategies that account for the complex interactions between these hazards is crucial to building resilience and promoting sustainable development in the face of climate change. Moreover, international cooperation is essential to ensure a coordinated and comprehensive response to climate change in BRICS countries and beyond, leveraging shared knowledge, resources, and best practices to address these common challenges.

Methods

Indicators selection

The development of composite indicators, serving as robust measures for complex concepts that defy quantification through a single metric, is critical for providing insightful data for decision-making on national or international scales (Ahmed *et al*., 2022a; Nardo *et al*., 2005). To ensure the credibility and reproducibility of the index, the process of developing these indicators must maintain transparency, enabling future studies to replicate, revise, and scrutinize the methodology (Ahmed *et al*., 2022c; Saisana *et al*., 2005). The judicious selection of constituent indicators is a crucial initial step in developing a coherent composite indicator. When examined thoroughly, these indicators provide a comprehensive set of information related to ESES concerns, equipping researchers and decision-makers with a versatile tool to analyze and understand trends, conditions across different nations, and the effects of policy changes specific to each country (Dialga & Giang, 2017).

Recognizing the critical role of indicator selection, meticulous consideration was given to this aspect while developing the ESESI for BRICS countries. The origins, justification, and contextualization for the inclusion of each sub-indicator are given below, which are divided into two categories: (i) Energy Security and (ii) Environmental Sustainability indicators.

Energy security

The paramount objective of energy security lies in ensuring the uninterrupted provision of energy resources at a cost level that mitigates the potential for adverse impacts on economic productivity. The precursor definition of energy security focused on energy and economic aspects (Ahmed *et al*., 2022c; Sanahuja & Bonilla, 2022). Kemmler and Spreng (2007) incorporated social indicators into the assessment of energy security. The modern interpretation of energy security encompasses a broader range of dimensions, including access to energy, diversification in energy generation, international relations, environmental conservation, equitable pricing, energy supply adequacy, and energy dependency (Ahmed *et al*., 2022d; Malik *et al*., 2020, Jonek-Kowalska, 2022). Due to the evolving dimensions and definitions, a plethora of methodologies have been employed to assess energy security, utilizing a wide array of indicators. In pursuit of achieving a balance between a comprehensive set of indicators and pragmatic considerations regarding data availability, the ensemble of energy security indicators comprises electrification ratio, DTPES, proportion of RES in electricity generation, GDP per capita, energy consumption per capita, and energy dependency.

Energy Consumption per Capita: The majority of energy security definitions frequently emphasize the imperative to provide adequate energy for human welfare. Consequently, ECPC is recognized as an appropriate measure for assessing energy security (Okafor *et al*., 2021). The importance of ECPC stems from the observation that nations at various developmental stages tend to show differences in ECPC and quality of life (Ahmed *et al*., 2022a; Shah *et al*., 2019). Gunnarsdóttir *et al* (2020) characterized ECPC as an acronym denoting the Economic Cumulative Intensity. They astutely postulated that this metric not only serves as a reliable indicator of the collective vigor of a society, but also has the potential to function as an apt gauge for the evaluation of economic prosperity. In addition, evidence suggests that ECPC is crucial for predicting energy security, as small nations with low per capita are susceptible to heightened risks (Ahmed *et al.*, 2022e; Sweidan, 2023). In the context of this investigation, the concept of ECPC is considered a proxy measure, employed to assess the standard of living. Serving as an economically driven indicator, ECPC's computation follows the subsequent methodology:

$$ECPC = \frac{TPE_{con}}{T_{pop}} \tag{1}$$

wherein TPE_{con} represents the aggregate primary energy consumption and population is signified by T_{pop}.

Energy dependency

Numerous studies have highlighted the potential risks associated with high energy dependency, suggesting that it can undermine a nation's energy stability and overall security (Shah *et al.*, 2019). Countries that heavily depend on energy-intensive practices for economic growth, despite having limited domestic energy resources, are particularly susceptible to vulnerabilities. Economic progress in these nations may be hindered by fluctuations in the energy market. Consequently, energy dependency is considered a crucial indicator of energy stability (Greene, 2010). This metric functions as a cost-type indicator, with lower values being more favorable. Energy dependency can be calculated using the following formula:

$$Energy\ dependence = \frac{TPE_{con} - TPE_{prd}}{TPE_{con}} \tag{2}$$

wherein the cumulative primary energy production is delineated by TPE_{prd}.

Diversity in total primary energy supply

As energy consumption continues to rise at an unprecedented rate, the significance of energy security has become increasingly apparent. This is further coupled by the uncertainties associated with price fluctuations, resource availability, and transportation challenges. To address these concerns and ensure a stable energy supply, diversifying energy sources is essential. This approach not only enhances energy security in the short term but also serves as a long-term strategic measure. In this study, we employed the Shannon-Wiener index to evaluate the diversity of 10 energy sources, including geothermal, biomass, solar, wind, nuclear, hydro, coal, gas, oil, and other renewable energy sources (RES). Originally proposed by Stirling (1998), the Shannon-Wiener index, also referred to as the Shannon index, is a powerful tool for quantifying diversity across various domains. This index measures the amount of information contained within a variable and expresses it through the concept of entropy (Vajapeyam, 2014). While initially developed for analyzing the entropy of textual sequences in information science (Shannon, 1948), the Shannon-Wiener index has found widespread application in ecology for assessing species diversity (Tuomisto, 2010a, 2010b). Additionally, this index is valuable for evaluating extended strategies related to energy security.

$$D_{TPES} = -\sum(p_i ln p_{i)} \tag{3}$$

where p_i designates energy production for source i, encompassing petroleum, natural gas, coal, renewable energy modalities, and alternative energy generation methods. DTPES functions as a utility-based index, whereby an elevated value insinuates a non-reliance on a singular energy generation source, but rather exhibits a more equitable distribution across multiple energy resources within an economic system.

Gross Domestic Product per capita

Per capita GDP, a crucial economic performance indicator, serves to assess the level of economic output per individual within a nation. This metric, a benefit-type indicator, facilitates the evaluation of living standards, economic prosperity, and a nation's overall economic well-being (Lambiri *et al.*, 2006). A higher per capita GDP value signifies greater prosperity and well-being of the population. The computation of per capita GDP requires dividing a nation's GDP by its total population. The formula describing this calculation is presented as:

$$GDP\ per\ capita = \frac{GDP}{T_{pop}} \tag{4}$$

Ratio of renewable energy sources in electricity generation

This indicator reflects the proportion of a country's electricity generation generated from renewable energy technologies. While the environmental advantages of renewable energy sources (RES) are well-documented, their potential impact on energy security is often overlooked. However, several studies have investigated the relationship between RES and energy security. For nations grappling with energy security issues stemming from a growing reliance on imported energy, RES can offer alternative, often domestic, electricity generation options. Furthermore, RES contributes to the diversification of electricity sources, enhances system resilience, and reduces vulnerability to energy security risks through decentralized generation. The incorporation of RES has been shown to have positive impacts on a country's energy security, especially in the long run, by reducing dependency on imported fossil fuels to a certain extent (Verbruggen, 2008). The advantageous effects of RES deployment on energy security have been observed in developing nations that heavily rely on imported fossil fuels (Zafar *et al.*, 2018), as well as in developed countries, particularly over extended periods (Scarlat *et al.*, 2015; Wolde-Rufael & Menyah, 2010). This benefit-type indicator can be calculated using the following formula:

$$\text{Renewable energy share} = \frac{\text{Renewable electricity generation}}{\text{Total electricity generation}} \tag{5}$$

Electrification ratio

This parameter represents the proportion of the population with reliable access to electricity. Disparities in electrification rates exist among countries, and the degree of electricity accessibility can potentially reflect the level of development in a particular country. This implies that the metric for electricity access could be utilized as an appropriate representation for other indicators related to development. Consequently, the electrification ratio is a benefit-type indicator, which is calculated as:

$$\text{Electrification ratio} = \frac{\text{Population with access to electricity}}{\text{T}_{\text{pop}}} \tag{6}$$

Environmental sustainability

The energy system's cyclical nature creates an inextricable link between environmental sustainability and energy utilization, spanning from energy generation to end-use applications. This intertwining is reinforced by the emission of greenhouse gases (GHGs), which contribute to the exacerbation of global temperature escalation (Brodny & Tutak, 2023). Large-scale energy projects may engender deleterious environmental ramifications during the construction, decommissioning or disposal, and operation of energy infrastructure. The allocation of natural resources and land for energy infrastructure development may impact natural ecosystems, including aquatic resources, vegetation, wildlife, and the human environment (Brodny & Tutak, 2023). In this context, increased energy consumption may lead to further environmental degradation. Consequently, the global community struggles to strike a balance between ensuring energy security and mitigating environmental harm. Indicators measuring the effect of energy on ecological equilibrium preservation serve as invaluable tools for policymakers and researchers in devising appropriate environmental conservation strategies. Within the realm of energy security, the preservation of ecological equilibrium emerges as an imperative, as emphasized by the European Commission (Ahmed *et al*., 2022e; Laponche & Tillerson, 2001). Azzuni and Breyer (2018) underscore the significance of environmentally sustainable, socially acceptable, reliable, efficient, and affordable energy services for energy security. The selected ecological equilibrium conservation indicators in this research include CO2 emission from electricity production, CO2 intensity, CO2 emission per capita, energy intensity, and the forest area modification ratio.

Energy intensity

Utilized as a ubiquitous metric, energy intensity offers an evaluation of a nation's energy efficiency trajectory. It provides a fundamental method to determine the amount of energy expenditure required for generating a single unit of GDP. A lower energy intensity value indicates increased energy security, thereby reducing the environmental burden. Iddrisu and Bhattacharyya (2015) suggest the improvement of energy efficiency and reduction of energy intensity as principal strategies for addressing energy security concerns. Hughes (2009) also endorses minimizing energy use as one of the key approaches to energy security, alongside substituting, decreasing, and reassessing energy sources. Nonetheless, the metric's limitations have incited criticism. Essentially, this indicator is composed of data on energy consumption and GDP, both precise ratios that influence the nature and magnitude of impact (Ahmed *et al.*, 2022b; Filipović *et al*, 2015; Yuan *et al.*, 2008). Secondly, energy intensity fluctuations do not inherently signify efficient energy utilization. Moreover, a decreased GDP can lead to improved energy intensity, potentially occurring due to an economic crisis (Andreoni, 2020). Despite these limitations, energy intensity remains the optimal energy efficiency proxy metric (Kabir *et al.*, 2021) and is employed herein. This cost-type metric can be determined using the following equation:

$$\text{Energy Intensity} = \frac{\text{TPE}_{\text{con}}}{\text{GDP}} \tag{7}$$

CO2 intensity

The predominant proportion of CO2 emissions originates from the energy sector due to the combustion of fossil fuels, which serves as the primary source of energy. In 2018, global carbon emissions related to energy experienced a rise of 1.7%, reaching a total of 33.1 Gt CO2 — the highest spike since 2013. This increase was recorded as the most significant since 2013, according to the International Energy Agency (IEA, 2022). The rate of CO2 emissions from energy generation, referred to as CO2 intensity, can serve as a proxy metric to assess the impact of energy production on ecological balance, especially over extended periods (Ahmadi *et al.*, 2022; Kang *et al.*, 2020). Moreover, CO2 intensity reveals the progress made in technology pertaining to energy consumption, transportation, and production (Trotta *et al.*, 2018). Quantifying CO2 intensity, a cost-based metric, can be achieved using the following formula:

$$\text{CO}_2\ \text{Intensity} = \frac{\text{Carbon emission}}{\text{GDP}} \tag{8}$$

Per capita CO2 emission

A country's total CO2 emissions do not accurately reflect its role in environmental deterioration.

Using the given formula, this study determines CO2 emission per capita, which is a cost-oriented indicator and a more relevant measure for this objective.

$$\text{Carbon emission per capita} = \frac{\text{Carbon emission}}{\mathrm{T_{pop}}} \tag{9}$$

CO2 emission from electricity generation

This metric quantifies the quantity of CO2 discharged via electricity generation. It can be ascertained using the following methodology:

$$\text{Carbon emission from electricity} = \frac{\text{Carbon emission}}{\text{Electricity generation}} \tag{10}$$

Forest area ratio

The proportion of forested regions serves as a crucial indicator of the relative importance of tree-covered landscapes within a specific geographical area or country.

Forested areas play a crucial role in mitigating climate change impacts, such as rising temperatures and irregular precipitation patterns, as highlighted by Nielsen (2013). As a result, monitoring changes in the extent of these forested zones provides insights into the demand for timber resources and the environmental effects of disturbances like natural disasters on ecological systems. Nations with smaller forest cover are generally more susceptible to the consequences of climatic shifts. Calculating the forest area ratio is a relatively straightforward process, and this indicator serves as a valuable means of assessing environmental health. Recognizing its global relevance, the United Nations has incorporated the forest coverage ratio as one of the 48 indicators used to track progress towards achieving the Millennium Development Goals. The formula to determine the ratio of forest area is:

$$\text{Ratio of forest area} = \frac{\text{forest area}}{\text{total area of country}} \tag{11}$$

Weighting and aggregation

After identifying the sub-indicators, the next crucial step involves assigning respective weights to each indicator and integrating them to form a comprehensive index. The disciplines of operations research and management science provide numerous techniques and methodologies to develop such a composite index (Charnes *et al*., 1982; Cherchye *et al*., 2007). Among these, the Multi-Criteria Decision Analysis (MCDA) (Brodny & Tutak, 2023; Reiff *et al*., 2016) and Data Envelopment Analysis (DEA) stand out as the primary approaches for allocating weights and consolidating indicators in the development of an Energy Security and Environmental Sustainability Index (ESESI) (Brodny & Tutak, 2023; Zhou & Ang, 2009). MCDA techniques are widely employed to tackle complex decision-making problems that often involve multiple, conflicting objectives and goals (Weistroffer & Li, 2016).

Within the MCDA framework, three prominent aggregation methods include the Weighted Product (WP) (Brodny & Tutak, 2023; Zhou & Zhang, 2018), Simple Additive Weighting (SAW) (Devi & Sihotang, 2019; Ibrahim & Surya, 2019; Puspa, 2019), and ideal distance weighting method (WDI) methodology (Shah *et al*., 2019). These MCDA methodologies have been applied in various contexts (Diaz-Balteiro & Romero, 2004; Yoon & Hwang, 1995; Zhou *et al*., 2006). However, Zhou and Ang (2009); Zhou *et al*. (2010) argue that the WP method has a comparative advantage over other MCDA techniques due to its ability to minimize information loss during the aggregation of indicators.

Drawing from the insights of Zhou *et al*. (2009) and Zhou *et al*. (2010), this study employs the WP methodology to construct the ESESI for BRICS countries. The framework for optimally assigning weights to individual sub-indicators, as proposed by (Hatefi & Torabi, 2010), involves the application of the Multiplicative Data Envelopment Analysis (MDEA) model. This model effectively integrates the geometric aggregation property of the WP strategy with a technique to circumvent subjective weight allocation. The MDEA model consists of two components: the first component identifies the optimal weight set, while the second component assigns the least favorable weights to each sub-indicator.

$$gSj = max \prod_{k=1}^{n} x_{jk}^{\mathrm{gw_k}}$$

$$s.t. \ \prod_{k=1}^{n} x_{jk}^{\mathrm{gw_k}} \leq e, j = 1, 2, \dots \dots ., m \tag{12}$$

$$\mathrm{gw_k} \geq 0, \qquad k = 1, 2, \dots \dots ., n$$

In this equation, x_{jk} represents the value of country j concerning sub-indicator k, gSj signifies the highest aggregated performance metrics for a given country j, and $\mathrm{gw_k}$ represents the optimal weight set assigned to sub-indicators. However, achieving superior performance in a particular sub-indicator can lead to a country consistently attaining maximum scores, even when other sub-indicators register extremely low values. To address this issue, an additional DEA-like model is introduced to ensure a more balanced and comprehensive assessment of a country's performance across all sub-indicators.:

$$\mathrm{bS_j} = min \prod_{k=1}^{n} x_{jk}^{\mathrm{bw_k}}$$

$$s.t. \ \prod_{k=1}^{n} x_{jk}^{\mathrm{bw_k}} \geq e, \ j = 1, 2, \dots \dots ., m \tag{13}$$

$$\mathrm{bw_k} \geq 0, \qquad k = 1, 2, \dots \dots ., n$$

In contrast to Equation 12, Equation 13 allocates the least favorable weight set to sub-indicators. $\mathrm{bS_j}$ represents the lowest performance metric for a given country j, and $\mathrm{bw_k}$indicates the least favorable weight set assigned to sub-indicators. These equations are nonlinear and may pose difficulties when solving them. Hence, logarithms are employed to derive their linear equivalents, which can be calculated as:

$$gS_j' = max \sum_{k=1}^{n} \mathrm{gw_k} \, x_{jk}'$$

$$s.t. \ \sum_{k=1}^{n} \mathrm{gw_k} \, x_{jk}' \leq 1, j = 1, 2, \dots \dots ., m \tag{14}$$

$$\mathrm{gw_k} \geq 0, \qquad k = 1, 2, \dots \dots ., n$$

$$bS'_j = min\sum_{k=1}^{n} \mathrm{bw_k}\, x'_{jk}$$

$$s.t.\ \sum_{k=1}^{n} \mathrm{bw_k}\, x'_{jk} \geq 1, j = 1, 2, \dots \dots ., m \qquad (15)$$

$$\mathrm{bw_k} \geq 0, \qquad k = 1, 2, \dots \dots ., n$$

As these two indices allocate the optimal and least favorable weight sets, it is reasonable to merge them to generate an aggregate index for evaluating overall performance. Equation 5 combines gSj' and bSj' to construct the ESESI,

$$\mathrm{ESESI_j}(\lambda) = \lambda . \frac{gS'_j - gS'_{min}}{gS'_{max} - gS'_{min}} + (1 - \lambda) . \frac{bS'_j - bS'_{min}}{bS'_{max} - bS'_{min}} \qquad (16)$$

where

$$\begin{aligned} gS'_j - \ln(gS'_j), bS'_j - \ln(bS'_j), gS'_{max} = \max\{gS'_j, j = 1, 2, \dots \dots ., m\}, gS'_{min} \\ = \min\{gS'_j, j = 1, 2, \dots \dots ., m\}, bS'_{max} \\ = \max\{bS'_j, j = 1, 2, \dots \dots ., m\}, bS'_{min} \\ = \min\{bS'_j, j = 1, 2, \dots \dots ., m\}, \end{aligned}$$

and $0 \leq \lambda \leq 1$ is a control parameter.

The implementation of weight restriction serves as a suitable methodology when devising a compound index. By confining the magnitude of individual sub-parameters, the subsequent approach is established:

$$\mathrm{L_k} \leq \frac{\mathrm{w_k} x'_{jk}}{\sum_{k=1}^{n} \mathrm{w_k} x'_{jk}} \leq \mathrm{U_k},\ k = 1,2, \dots \dots , n \qquad (17)$$

Here, $\mathrm{L_k}$ and $\mathrm{U_k}$ respectively signify the lower and upper thresholds for the k-th sub-indicator's input in ESESI and satisfy $0 \leq \lambda \leq 1$. Expert consensus can ascertain the values of $\mathrm{L_k}$ and $\mathrm{U_k}$. Cherchye *et al.* (2007) and Cherchye *et al.* (2006) contend that deriving weights through expert consensus is more feasible and pragmatic. In accordance with the agreement among our co-authors, we allocate $\mathrm{L_k} = 0.05$ and $\mathrm{U_k} = 0.20$, implying that the k-th sub-indicator's contribution to ESESI can vary from 5 to 20 percent.

Data sources

In this study, data from 2000 to 2020 was meticulously gathered through an assortment of reputable sources, such as the BP Statistical Review, National Bureau of Statistics of China, US Energy Information Administration, International Energy Agency, World Bank, and Global Carbon Project. In addition, several national data repositories were tapped into, including Brazilian Institute of Geography and Statistics, Russian Federal State Statistics Service, Ministry of Statistics and Programme Implementation, Statistics South Africa.

Results

Sub-indicators analysis

Per capita Energy consumption: The per capita energy consumption in the BRICS nations exhibited significant heterogeneity in 2020. Russia recorded the highest per capita energy consumption at 6.37 metric tons of oil equivalent (MTOE), followed by China (3.17 MTOE), Brazil (1.92 MTOE), South Africa (0.67 MTOE), and India (0.60 MTOE). Russia's elevated energy consumption can be attributed to its cold climate, necessitating substantial energy expenditure for heating, and its vast geographical area, requiring energy for transportation. The moderate per capita energy consumption in China and Brazil is linked to their rapidly growing economies and industrialization. Conversely, the lower energy consumption in India and South Africa reflects their developing economies and less energy-intensive industries. The disparities in per capita energy consumption among the BRICS countries can be ascribed to a combination of factors, including climatic conditions, geographical characteristics, industrialization levels, and economic development stages (BP, 2023a, 2023b).

Energy dependency: From 2000 to 2020, Russia consistently demonstrated the lowest energy dependency on imports among the BRICS countries, with its self-sufficiency increasing from 95.4% to 100.4%. Brazil also exhibited high energy self-sufficiency, rising from 85.1% to 93.6% during the same period. China maintained relative stability, with its energy self-sufficiency fluctuating between 84.9% and 88.9%. India gradually increased its self-sufficiency from 67.1% to 72.5%. South Africa had the highest dependency on imported energy, with a limited increase in self-sufficiency from 53.2% to 56.8%. These trends highlight the varying degrees of energy self-sufficiency among the BRICS nations, with Russia and Brazil leading the way and South Africa remaining the most dependent on energy imports (BP, 2023a, 2023b).

Diversity in total primary energy supply: The total primary energy supply in the BRICS countries exhibited diverse trends between 2000 and 2021. Brazil's oil consumption increased from 3.73 EJ to 4.46 EJ, while natural gas consumption rose from 0.35 EJ to 1.46 EJ. South Africa's oil consumption experienced a slight uptick from 0.95 EJ to 1.04 EJ, with natural gas consumption also increasing from 0.04 EJ to 0.14 EJ. China's oil consumption surged from 9.46 EJ to 30.6 EJ, and its natural gas consumption followed suit, jumping from 0.89 EJ to 13.63 EJ. India's oil consumption grew from 4.61 EJ to 9.41 EJ, and its natural gas consumption rose from 0.91 EJ to 2.24 EJ. The Russian Federation experienced an increase in oil consumption from 5.28 EJ to 6.71 EJ and natural gas consumption from 13.18 EJ to 17.09 EJ. Coal consumption increased in China and India, while it decreased in Brazil, South Africa, and Russia. Nuclear energy consumption increased across all countries. Hydroelectricity consumption increased in China and Russia, while it decreased in Brazil, South Africa, and India. Renewables consumption saw growth in all five countries, with China witnessing the most significant increase from 0.04 EJ to 11.32 EJ (BP, 2023a, 2023b).

Gross Domestic Product per capita: The per capita Gross Domestic Product (GDP) among the BRICS nations demonstrates substantial heterogeneity. According to World Bank data for 2020, the Russian Federation exhibited the highest per capita GDP at $10,769, followed by China at $10,261, Brazil at $8,703, South Africa at $5,278, and India at $1,947. Russia's elevated per capita GDP can be attributed to its abundant natural resources, including hydrocarbons and mineral deposits. In contrast, China's high per capita GDP is driven by its rapidly growing economy, robust manufacturing sector, and increasing foreign capital inflows. Brazil's relatively high per capita GDP reflects its diversified economic structure and abundant natural resources. South Africa's lower per capita GDP mirrors its significant income inequality and slow economic growth. India's per capita GDP remains the lowest among the BRICS nations, indicative of its large population, insufficient industrialization, and stark income inequality. In summary, the disparities in per capita GDP within the BRICS nations are driven by a range of factors, including natural resource endowments, economic diversity, foreign capital investments, and income stratification.

The ratio of renewable energy sources (RES) in electricity generation: The sustainability and energy security of BRICS nations are significantly influenced by the proportion of renewable energy sources (RES) utilized in their electricity production. Over the years, these nations have exhibited varying degrees of reliance on renewable energy sources. Brazil has consistently maintained a high percentage of renewable energy in its electricity generation, ranging from 80.5% to 84% between 2000 and 2020. In contrast, South Africa's renewable energy ratio has been considerably lower, with a gradual increase from 1.6% to 5% over the same period. Russia, India, and China have also experienced fluctuations in their renewable energy ratios, with India exhibiting the most significant growth, from 12.6% in 2000 to 34.7% in 2020. These varying ratios across the BRICS countries underscore the need for continued efforts to promote the adoption of renewable energy sources and reduce dependency on fossil fuels, in order to address global environmental challenges and achieve long-term energy sustainability (BP, 2023a, 2023b).

Electrification ratio: The availability of electricity in the BRICS countries has exhibited notable differences over the 2000–2020 period, reflecting the varying degrees of investment in power infrastructure, population growth, and economic development across these nations. China, being the world's largest energy consumer, has substantially expanded its electricity availability over the two decades, driven by rapid industrialization and urbanization. Similarly, India has demonstrated remarkable progress in enhancing electricity access, although significant disparities still exist between urban and rural areas. In contrast, Russia has maintained relatively stable electricity availability, benefiting from its extensive natural resources and well-developed power grid. Brazil, with its vast hydropower resources, has provided a consistent level of electricity availability, although the country has faced challenges related to power supply reliability due to climatic factors. South Africa, on the other hand, has grappled with persistent electricity supply constraints, primarily resulting from an aging power infrastructure and inadequate investment in new generation capacity. Overall, the diverse electricity availability trajectories in the BRICS countries underscore the importance of tailored policy interventions and infrastructure investments to ensure universal access to reliable and sustainable power supplies.

Energy intensity: Comparing the energy intensity of the BRICS countries from 2000 to 2020 reveals notable variations. China has consistently exhibited the highest levels, mainly driven by its energy-intensive industrial sector and rapid economic expansion. Russia has also maintained relatively high energy intensity levels, attributable to its resource-based economy and the high energy demands associated with its cold climatic conditions, necessitating substantial energy utilization for heating purposes. India and South Africa have experienced moderate energy intensity levels, reflecting the increasing energy requirements of their growing economies. Brazil, on the other hand, has recorded the lowest energy intensity among the BRICS nations, benefiting from its abundant hydropower resources and heightened emphasis on energy efficiency initiatives in recent years.

CO2 intensity: Throughout the 2000–2020 period, the CO2 intensity of the BRICS countries has displayed considerable variation. China and India have generally exhibited higher CO2 intensity levels due to their substantial reliance on coal for electricity generation and industrial processes. Russia's CO2 intensity has been relatively lower, owing to its substantial natural gas reserves and the nation's commitment to reducing greenhouse gas emissions. South Africa has faced challenges in reducing CO2 intensity, with coal-fired power plants constituting a dominant component of its energy landscape. Brazil has consistently maintained the lowest CO2 intensity among the BRICS nations, facilitated by its extensive utilization of renewable energy sources, particularly hydropower and bioenergy.

CO2 emission per capita: Over the two decades from 2000 to 2020, CO2 emissions per capita have varied significantly among the BRICS countries. Russia has consistently registered the highest levels, stemming from its vast fossil fuel reserves and energy-intensive industries. China has experienced a substantial increase in CO2 emissions per capita, propelled by its rapid economic growth and urbanization. South Africa and India have reported moderate levels, with both nations confronting the challenge of balancing economic development and environmental concerns. Brazil has maintained the lowest CO2 emissions per capita among the BRICS nations, attributable to its extensive utilization of renewable energy sources and substantial forest cover.

CO2 emission from electricity generation: Between 2000 and 2020, CO2 emissions from electricity generation in the BRICS countries have followed diverse trajectories. China has recorded a significant upsurge, primarily due to the proliferation of coal-fired power plants. India has similarly witnessed growth in CO2 emissions from electricity generation, albeit at a more moderate pace. Russia has maintained a relatively stable level of CO2 emissions, as its power sector increasingly transitions towards cleaner energy sources such as natural gas. Brazil has consistently maintained low CO2 emissions from electricity generation, benefiting from its abundant hydropower resources. South Africa, despite its smaller economy, has struggled with high CO2 emissions from electricity generation, resulting from its reliance on coal-fired power plants.

The ratio of forest area: The ratio of forest area in the BRICS countries has displayed notable differences from 2000 to 2020. Brazil, home to the vast Amazon rainforest, has consistently reported the highest forest area ratio, although deforestation remains a pressing concern. Russia, encompassing the world's largest boreal forest, has maintained a high forest area ratio, but has also faced challenges in forest management and conservation. China and India have registered moderate forest area ratios, with both countries undertaking afforestation initiatives to augment forest cover. South Africa has consistently recorded the lowest forest area ratio among the BRICS nations, attributable to its predominantly arid and semi-arid landscapes, and historical land-use patterns.

Overall ESESI scores

Figure 3 then displays the ESESI values for the year 2020, highlighting disparities in energy security and environmental sustainability among the BRICS. Brazil leads with the highest score, reflecting its robust integration of renewable energy sources, primarily hydropower and biofuels. In contrast, South Africa's low score points to its heavy reliance on coal, suggesting a critical policy area requiring focus to facilitate the transition towards more sustainable energy sources. The scores of Russia, China, and India indicate varying stages of their energy transitions, emphasizing their ongoing endeavors towards adopting cleaner energy sources and enhancing efficiency.

The ESESI scores from 2000 to 2020, as shown in Table 3, provide valuable insights into the potential and progress of each country in terms of energy security and environmental sustainability. While comparing the 2020 ESESI scores alone may not suffice to project a country's future potential, analyzing the trajectory of these scores over the past two decades offers a more comprehensive understanding of their dedication and accomplishments in this domain. An examination of the ESESI scores illustrates a consistent elevation for Brazil, indicative of its unwavering commitment to renewable energy integration and environmental sustainability objectives. Brazil's achievements in elevated index values can be attributed to investments in renewable energy, specifically hydropower, biofuels, and wind energy (Goldemberg, 2018; Silva *et al*., 2016). Brazil's energy security has improved through transforming its energy matrix and focusing on regional power, economic growth, and internationalization of its energy policy in South America, thereby enhancing its long-term sustainability prospects (Granados Erazo, 2012). Despite these achievements, Brazil has faced challenges in maintaining a low-carbon transition, as documented from 2001 to 2015 (Rutherford, 2020). Extreme weather events impacting hydropower generation, transmission infrastructure, bioenergy production, and cooling demand pose additional challenges, necessitating the implementation of adaptation measures to address these vulnerabilities (Bezerra *et al*., 2021). Furthermore, Brazil's diversified supplies, market access, sustainable production, and strategic partnerships align with domestic and international preferences for energy integration and security enhancement (de Jesus, 2013).

Moderate improvements in ESESI scores are observed in Russia and South Africa, indicating steady enhancement of their energy security and environmental sustainability performance. Russia's progress is attributed to energy efficiency improvements, greenhouse gas emission reductions, and efforts to diversify its energy mix by investing in renewable energy sources such as solar, wind, biomass, and geothermal power generation. Efforts to bolster energy security in Russia have been driven by the imperative to reduce dependence on traditional energy sources and ensure stability in the face of geopolitical challenges (Baboshkin, 2020). Russia has also explored energy-efficient technologies and sustainable development strategies to mitigate threats to energy security and ensure economic stability. However, Russia still faces challenges such as rising energy costs, and affordability and economic efficiency remain areas necessitating further improvement (Merkulova *et al*., 2022). South Africa's strides in increasing renewable energy's share in its energy mix are substantial, yet coal dependency for electricity generation persists, and index value improvement remains relatively sluggish, suggesting the potential for optimization in energy efficiency and carbon emission reduction. The depletion of fossil fuels used for electricity generation by 1% annually, increasing domestic and industrial consumption, rising coal prices, and decreased production volumes pose threats to the reliability of South Africa's electricity grid (Nkomo, 2009). South Africa's transition towards cleaner energy sources, such as underground coal gasification, is pivotal for addressing energy security challenges sustainably (Ateba *et al*., 2018).

India and China exhibit a gradual rate of enhancement in their ESESI scores. Both countries heavily rely on imports for oil and gas, and face challenges in effectively diversifying their energy sources (Nainan, 2022; Li *et al*., 2022). India's ambitious targets for increasing the share of renewable energy contrast with the gradual pace of index value improvement, underscoring the need for further promotion of renewable energy adoption and enhancement of energy efficiency measures. Moreover, the lack of strategic intent and clear articulation of energy capture goals hinders India's efforts in this domain (Rajeev, 2010). Additionally, the competition for energy sources, especially fossil fuels, between China and India has further compounded their respective energy security challenges. Moreover, India has faced difficulties in securing supplier relationships globally, lagging behind China in this aspect (Kulkarni & Nathan, 2016).

Sensitivity analysis

During our calculations for the ESESI, we maintained the control parameter λ at a constant value of 0.5. To evaluate the robustness and sensitivity of our model, we varied λ across a range from 0.1 to 0.9 and generated ESESI scores for the BRICS countries across this spectrum. The analysis revealed that the ESESI scores and rankings exhibited stability across these variations, thereby supporting our decision to fix λ at 0.5 for standard evaluations.

Figure 4 presents a comparative box plot depicting the ESESI values for the BRICS nations and highlighting their minimal sensitivity to variations in λ. This observation underscores the robustness of the ESESI, as it provides consistent evaluations regardless of minor parameter adjustments. Such consistency ensures the index's reliability in guiding policy decisions without necessitating frequent methodological modifications.

Conclusions

The ESESI encompasses crucial concepts that necessitate precise definition and quantification. It is imperative to develop an index that can accurately evaluate the interplay between energy and environmental (E&E) challenges and economic performance within communities. Such an index facilitates the assessment of E&E performance, identification of areas requiring improvement, and elucidation of how these factors influence economic development. Consequently, this study constructs the ESESI to quantify the energy security and environmental achievements of BRICS nations from 2000 to 2020. This research rigorously examines ESES in BRICS nations through a systematic investigation employing the Data Envelopment Analysis (DEA) model and the Weighted Product (WP) method. The employed research methodology enables a comprehensive analysis of ESES within the BRICS context. Our hypothesis, postulating that a nuanced understanding of a nation's energy security status, through the integration of environmental factors, correlates with economic outcomes, was substantiated by the ESESI. This index elucidated the varied progress and challenges faced by BRICS nations regarding renewable energy sustainability, efficiency, and their impact on economic performance.

The observed variations in ESESI scores, influenced by climatic, geographic, economic factors, infrastructural investments, natural resource endowments, policy initiatives, and industrialization levels, have confirmed the expected disparities among the BRICS nations. The ESESI also identified areas necessitating focused policy interventions, infrastructural enhancements, and efforts to promote renewable energy adoption, thereby demonstrating its utility as a comprehensive tool for assessing ESES achievements, areas requiring improvement, and their implications for economic performance.

Prior to calculating aggregate ESESI values, this research analyzed constituent indicators for each nation, providing in-depth insights into a country's E&E achievements and their economic implications. Findings from sub-indicators revealed that heterogeneity in per capita energy consumption, energy dependency, diversity of primary energy supply, per capita GDP, renewable energy share in electricity generation, electrification ratio, energy intensity, CO2 intensity and emissions, forest area ratio, and renewable energy share among BRICS nations between 2000 and 2020 can be attributed to various factors, including climatic conditions, geographic and economic disparities, infrastructural investments, natural resource endowments, policy interventions, and industrialization levels. The results demonstrate that economic outcomes, such as GDP, are inextricably linked to energy security and environmental sustainability.

While Russia and Brazil exhibited higher energy self-sufficiency and per capita GDP, South Africa displayed increased energy import dependency, and India reported the lowest per capita GDP. Variations in renewable energy adoption were evident, with Brazil maintaining a consistently high share, India demonstrating significant growth, and South Africa's share remaining persistently low. These differences underscore the need for tailored policy measures, infrastructural advancements, and continuous efforts to promote renewable energy deployment and reduce fossil fuel reliance, thereby fostering economic growth and sustainability.

The findings delineate the performance trends of each country, contrasting their respective accomplishments and elucidating the intrinsic link between energy security and environmental sustainability. Furthermore, the results unveil that no country within the region can solely rely on domestic energy resources to meet its energy demands. The inability to satisfy their energy requirements through local resources raises concerns regarding future energy security and economic stability. The region is currently experiencing an energy deficit amidst unprecedented surges in energy demands and economic activities. However, most countries in the region are endowed with abundant renewable energy resources, which could benefit all nations within the region if an advanced energy trade mechanism is implemented. Cross-border investments in renewable energy could potentially mitigate the impacts of climate change, enhance energy security, and bolster economic stability within the region.

Limitation and further development

While this study provides valuable insights into the ESES performance of BRICS nations, it is imperative to identify areas for further research and exploration. The selection of indicators utilized to construct the ESESI could be expanded to encompass additional relevant indicators, such as energy affordability, energy storage capacity, energy import diversity, energy efficiency in the building sector, and transport sector energy efficiency. Furthermore, it is crucial to acknowledge that the relationship between energy security and environmental sustainability is intricate and multifaceted. While the ESESI captures the cumulative changes in these areas, examining them separately and investigating their interactions could yield a more nuanced understanding of their specific dynamics. ESES are inextricably intertwined, and their relationship necessitates further exploration.

Improvements in energy security through the adoption of renewable energy sources can contribute significantly to environmental sustainability by reducing greenhouse gas emissions and mitigating the adverse impacts of climate change. Conversely, environmental degradation, such as air and water pollution caused by fossil fuel combustion, can pose serious threats to energy security by compromising the availability and reliability of energy resources. By examining these relationships in depth and extending the analysis to investigate the causal links between energy security, environmental sustainability, and economic performance, future research can contribute to a more holistic understanding of the challenges and opportunities facing the BRICS nations in their pursuit of sustainable development.

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Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement

All data generated or analyzed are included in the published article. The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. The raw anonymized data can be provided by emailing the primary author.

Author contributions

All listed authors have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the source analysis.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Annex

Table 1. Percentage of resource demand met by domestic production

Country	Coal	Natural Gas	Crude Oil
Brazil	87%	95%	90%
Russia	99%	66%	89%
India	77%	58%	52%
China	94%	55%	77%
South Africa	100%	99%	95%

Source: IEA (2022).

Table 2. Key perils of climate change in the BRICS countries

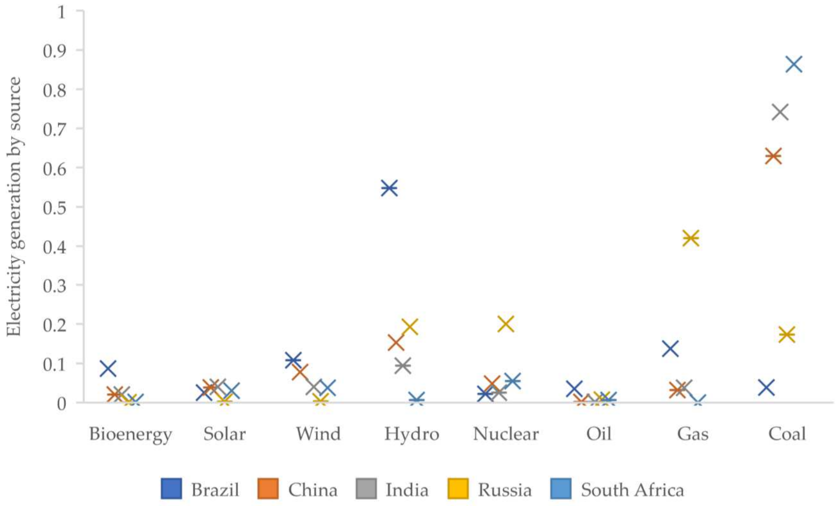
Country	Key Climate Change Hazards
Brazil	Extreme weather events, sea level rise, biodiversity loss
Russia	Glacier retreat, permafrost thaw, extreme weather events
India	Extreme weather events, sea level rise, air pollution, biodiversity loss
China	Extreme weather events, sea level rise, air pollution, biodiversity loss
South Africa	Extreme weather events, sea level rise, biodiversity loss, water scarcity, air pollution

Source: (G20 Climate Risk Atlas; IEA, 2023).

Table 3. Overall results of ESESI (2000–2020)

Year	Brazil	Russia	India	China	South Africa
2000	0.85	0.57	0.40	0.51	0.27
2001	0.83	0.57	0.40	0.51	0.27
2002	0.82	0.57	0.41	0.51	0.28
2003	0.82	0.57	0.41	0.51	0.28
2004	0.83	0.57	0.41	0.51	0.29
2005	0.84	0.57	0.42	0.51	0.28
2006	0.84	0.57	0.42	0.51	0.28
2007	0.85	0.58	0.43	0.51	0.28
2008	0.85	0.58	0.43	0.52	0.28
2009	0.86	0.58	0.44	0.52	0.29
2010	0.86	0.58	0.45	0.53	0.29
2011	0.86	0.59	0.45	0.54	0.30
2012	0.86	0.59	0.46	0.55	0.29
2013	0.86	0.59	0.48	0.56	0.29
2014	0.86	0.59	0.49	0.56	0.30
2015	0.86	0.59	0.50	0.57	0.30
2016	0.86	0.59	0.51	0.58	0.30
2017	0.87	0.59	0.53	0.58	0.31
2018	0.87	0.59	0.53	0.59	0.31
2019	0.87	0.59	0.54	0.59	0.31
2020	0.87	0.60	0.54	0.59	0.31

Figure 1. Electricity generation in BRICS countries by source



Source: BRICS Energy Report (2021)

Figure 2. Change in cummulative energy consumption in BRICS countries

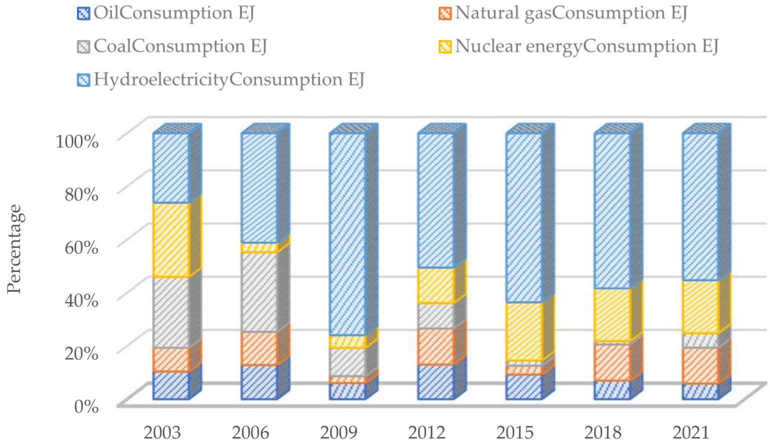


Figure 3. ESESI values for BRICS (2020)

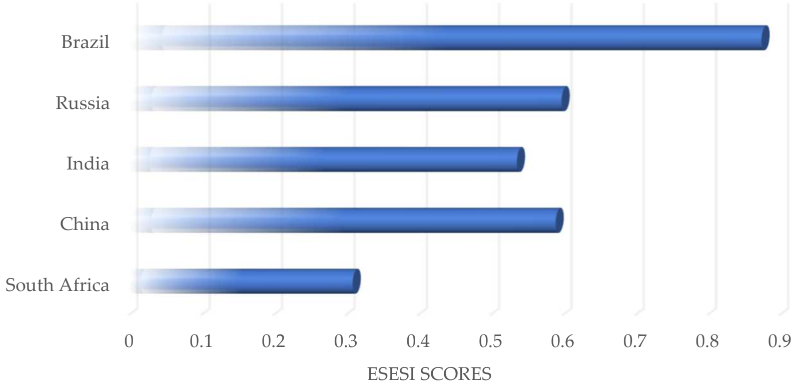
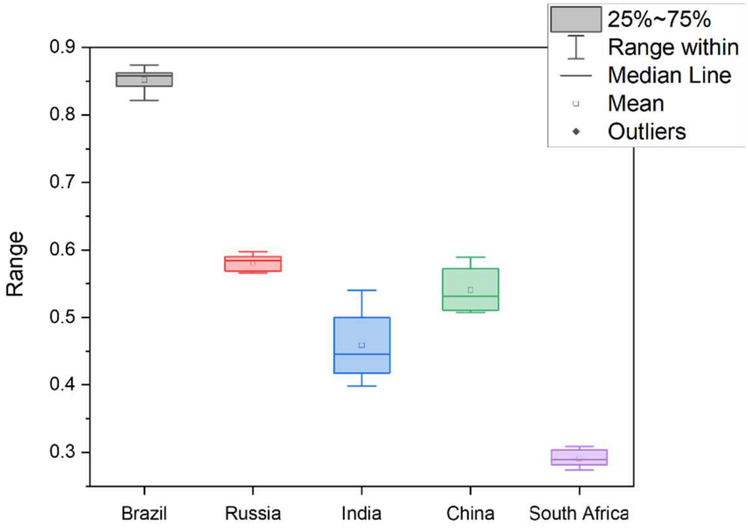


Figure 4. Comparative box plot of ESESI values for BRICS



Appendix

List of acronyms used in this study

Acronym	Full Form
BRICS	Brazil, Russia, India, China, and South Africa
ESES	Energy Security and Environmental Sustainability
ESESI	Energy Security and Environmental Sustainability Index
DTPES	Diversity in Total Primary Energy Supply
GDP	Gross Domestic Product
ECPC	Energy Consumption Per Capita
TPE	Total Primary Energy
RES	Renewable Energy Sources
CO2	Carbon Dioxide
GHGs	Greenhouse Gases
IEA	International Energy Agency
MCDA	Multi-Criteria Decision Analysis
DEA	Data Envelopment Analysis
WP	Weighted Product
SAW	Simple Additive Weighting
WDI	Weighted Ideal Distance
MDEA	Multiplicative Data Envelopment Analysis