BRICS YEA

BRICS 2025 YOUTH ENERGY OUTLOOK

Inside the Outlook

Acknowledgments

This year's BRICS Youth Energy Outlook 2025 is a result of an ambitious effort delivered through the BRICS Youth Energy Agency's Young Expert Groups. This initiative unites young researchers from across the globe with the invaluable support of governments, institutions, and organizations. The document is structured around four central thematic pillars, aligned with the energy priorities of Brazil's BRICS 2025 presidency.

The overall coordination of the Outlook 2025 was managed by Outlook Coordinator Ms. Ulyana Rybachik (BRICS YEA), who served as task team leader of the project and coordinated activities at different stages of the Outlook's development. The overall guidance was provided by Chairperson Mr. Alexander Kormishin (BRICS YEA). We also acknowledge the support of the Mission Impact, Rosatom's International Development Programme, and the partnership with the BRICS Nuclear Platform on the special report.

The core team was composed of chief experts Pâmela Silveira Costa (Brazil), Bruno Santana de Albuquerque (Brazil), Olga Kelebogile Mmelesi (South Africa) and Nan Hao (China), who served as editors of their respective chapters under the Outlook 2025, executed communication, run the meetings and submitted research papers. The chief experts were assisted by secretaries, including Nadya Nurul Utami (Indonesia), Olyad Hunduma Legesse (Ethiopia), Akanksha Warade (India) and Disha Dinesha Lagadamane (India), who ensured that deadlines were met, and members were well informed about the development.

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The Outlook 2025 as a leading energy study for and in the interests of the BRICS nations has been acknowledged by energy and youth policy state authorities. We acknowledge the endorsement of the initiative by the 10th BRICS Energy Ministers Meeting and the Leaders of BRICS countries following the XVII BRICS Summit in Rio de Janeiro, Brazil.

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We would like to acknowledge a growing support for the project from various stakeholders representing BRICS companies and public organizations who have pronounced their interest in the project and considered cooperation in the years to come, and we are looking forward to it.

Finally, the team apologizes to any individuals or organizations that contributed to this Report but were inadvertently omitted from these acknowledgments.

Executive Summary

As we present the BRICS Youth Energy Outlook 2025, it is clear that the strategic role of youth extends far beyond being mere beneficiaries or future leaders of the energy transition. The young researchers and professionals of the BRICS countries are emerging as its most objective and essential voice for justice. Their unique position, free from entrenched sectoral biases and endowed with a long-term perspective on the climate crisis, allows them to articulate a vision for a transition that is both ambitious and pragmatic.

This objectivity enables youth to champion a balanced approach that navigates the complex interplay between environmental imperatives, social equity, and economic development. They intuitively understand that a just energy transition must be nationally contextualized, respecting the specific resource endowments and developmental stages of each country. It must be technologically inclusive, leveraging all available tools, without ideological prejudice, while maintaining a clear trajectory towards deep decarbonization. Crucially, their vision is socially anchored, insisting that the pathway forward must guarantee energy security, universal access, and the protection of communities and workers.

The collective work of 47 young researchers from across the BRICS nations, reflected in the pages of this Outlook, powerfully confirms this conclusion. Their analysis, grounded in diverse national realities yet united by a common purpose, offers a uniquely credible and forward-looking perspective. It is a testament to their dedication and intellectual rigor. I extend my deepest gratitude to the entire team, whose collaborative effort has made this comprehensive assessment possible.

Ulyana Rybachik
Outlook Coordinator
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The BRICS Youth Energy Outlook 2025 presents a comprehensive analysis of the pivotal challenges and opportunities shaping the global energy transition, with a specific focus on the strategic role of the BRICS bloc.

The document is structured around four central thematic pillars, aligned with the energy priorities of Brazil's BRICS 2025 presidency: financing energy transitions and ensuring clean energy transition minerals; energy access in addressing energy poverty with affordable solutions; sustainable fuels for energy transitions; and technological advancements for low-carbon power systems.

As a collective representing over 40% of the world's population and a dominant force in the global energy and mineral landscape, BRICS countries are central to achieving global climate goals while ensuring energy security, equity, and sustainable development. This sixth edition of the Outlook, prepared by young experts from across the bloc, underscores that the just energy transition is not merely a shift in energy sources but a complex, systemic transformation of economies, finance, and supply chains.

A core finding of the report is the inextricable link between financing the energy transition and securing a sustainable supply of critical minerals. The shift to low-carbon energy systems is significantly more mineral-intensive than the fossil fuel-based economy, driving unprecedented demand for lithium, cobalt, nickel, graphite, and rare earth elements. BRICS nations hold a dominant position in the reserves and production of these minerals, granting the bloc substantial influence over the pace and security of the global transition. However, this brings forth significant socio-environmental challenges, including the need for responsible mining practices, community engagement, and building resilient, diversified value chains that capture more local economic value. To address the massive financing gap, estimated in the trillions of dollars annually, the report emphasizes the critical role of the New Development Bank (NDB). It recommends that the NDB act as an anchor investor by de-risking projects, developing innovative financial products like transition bonds, expanding local currency financing to mitigate exchange rate risks, and leading the creation of a common BRICS transition finance framework.

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The Outlook further highlights that universal energy access remains a fundamental, unfulfilled prerequisite for sustainable development. While significant progress has been made in electrification, energy poverty persists as a multidimensional trap, deeply linked to a lack of clean cooking, reliable power, and productive-use energy, particularly in rural and remote communities. The analysis, utilizing the World Bank's Multi-Tier Framework, reveals a stark stratification within BRICS, from nations achieving high-tier, reliable access to those still grappling with foundational service levels. The report advocates for a technologically neutral portfolio of decentralized solutions – including solar PV with battery storage, geothermal, natural gas microgrids, small modular reactors (SMRs), and bioenergy – tailored to local contexts. Success hinges on overcoming barriers through harmonized regulatory frameworks, innovative business models like pay-as-you-go, and targeted policies that prioritize gender inclusion and community ownership.

The modern energy sources overview is strategically divided across two chapters to provide clarity and depth. The chapter on sustainable fuels focuses on consumable fuels and feedstocks, whereas the chapter on technologies for low-carbon power systems addresses electricity generation and grid integration, covering technologies like solar, wind, hydropower, SMRs, energy storage, and digital grid management.

In the realm of sustainable fuels, the Outlook adopts a pragmatic, technologically neutral approach that evaluates sustainability by a fuel's net carbon footprint rather than its origin alone. This encompasses a diverse portfolio of decarbonization strategies, including biofuels, hydrogen, natural gas and other fossil fuels with with carbon capture, utilization, and storage (CCUS) and other abatement technologies. The report identifies three strategic models for sustainable fuels within BRICS, shaped by national resources and economic goals. Export-oriented diversifiers, including Russia, Saudi Arabia, the UAE, and Iran, are strategically prioritizing the decarbonization of their fossil fuel industries while pragmatically integrating renewable and other low-carbon energy sources, guided by principles of economic viability. The green industrialists, such as Brazil, India, South Africa, and Indonesia, are prioritizing hydrogen and expansive biofuel programs to drive domestic development, enhance energy security, and build new export sectors. China stands as the scalable pragmatist, pursuing a comprehensive strategy across all fuel types to achieve scale, cost-reduction, and technological dominance swiftly. The report identifies natural gas, supported by its lower emissions profile and flexibility, as a key transitional fuel within the bloc, while underscoring CCUS as an indispensable technology for decarbonizing hard-to-abate industrial sectors like steel, cement, and chemicals.

Finally, the report delves into the technological advancements required for low-carbon power systems, emphasizing that the challenge has shifted from adding renewable capacity to integrating it reliably into the grid. Key to this are advancements in energy storage, from short-duration batteries to long-duration solutions like pumped hydro; grid modernization through digitalization, artificial intelligence, and market reforms that reward flexibility; and the emerging role of SMRs as a firm, low-carbon complement to variable renewables. The successful deployment of these technologies is contingent upon modernized regulatory frameworks, streamlined permitting, and financial mechanisms that reduce the high cost of capital in emerging markets.

In conclusion, the BRICS Youth Energy Outlook 2025 posits that the BRICS collective action is not only imperative for its own sustainable future but also for shaping a more just and resilient global energy system. By leveraging its collective strengths – vast resources, technological capacity, and established cooperation platforms like the BRICS Energy Research Cooperation Platform (ERCP) BRICS can accelerate a just energy transition, transform challenges into opportunities for industrial development, and assert itself as a leader in defining a pragmatic and inclusive path forward for the Global South.

Financing Energy Transitions and Ensuring Clean Energy Transition Minerals

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1. Introduction: The Urgency of the Energy Transition

The acceleration of climate change, evidenced by rising global temperatures and the intensification of extreme weather events, imposes unprecedented urgency on the global energy transition. The structural transformation of economies is inseparable from climate action, as the capacity to mitigate climate risks depends directly on advancing toward low-carbon energy systems. In 2024, global energy demand increased by 2.2%, a pace exceeding the 1.4% annual average observed over the last decade (IEA 2025a). Emerging and developing economies accounted for over 80% of this growth, with notable contributions from China and India (IEA 2025a).

Electricity demand has risen even more sharply, driven by cooling needs, transport electrification, and the expansion of data centers, outpacing both overall energy demand and Gross Domestic Product (GDP) growth (IEA 2025a). However, the energy matrix of the BRICS countries remains predominantly based on fossil fuels (BRICS 2023a), representing a significant challenge to just and inclusive energy transitions and to the reduction of Greenhouse Gas (GHG) emissions.

The BRICS countries face a triple challenge: reconciling socioeconomic development goals, ensuring energy security and sufficiency, and decarbonizing their productive systems. The relevance of the BRICS bloc to the world economy places its coordination efforts at the center of addressing this challenge. Despite different national strategies, complementarities among BRICS members enable robust cooperation to strengthen energy security and promote sustainable development (BRICS 2023a). This transition is unprecedented, as it requires investments in infrastructure, the development of new supply chains, and the mobilization of financing on a scale that surpasses mere energy source substitution.

One of the pillars of this transformation is the growing demand for critical minerals such as copper, lithium, nickel, cobalt, graphite, and rare earths. These materials are fundamental to the development of low- and zero-carbon energy technologies, including electric vehicles (EVs), batteries, renewable energy systems, and electricity networks (IEA 2025b). Although an electric vehicle emits roughly half the lifetime emissions of a conventional vehicle (IEA 2024d), its material intensity is six times greater (IEA 2021b). This increase in material demand signals new ecological pressures and the need to promote material substitution and design for sufficiency.

Additionally, growing geopolitical tensions, marked by export controls on key materials and technologies (IEA 2025b), threaten the resilience of low-carbon energy and critical mineral supply chains. Refined material production is highly concentrated among a few suppliers (IEA 2025b), which has led BRICS countries to commit to promoting resilient and sustainable supply chains of such minerals to ensure benefit sharing, value addition, and economic diversification in resource-rich countries, while fully preserving sovereign rights over mineral resources and public policy objectives (BRICS 2025a).

Beyond material and geopolitical challenges, a significant financing gap persists. Decarbonizing the global economy will require annual investments of several trillion dollars (World Economic Forum 2025). The Climate Policy Initiative (CPI) estimates that the funding needed to meet transition goals will reach $9 trillion annually by 2030 and is expected to surpass $10 trillion each year from 2031 to 2050 (Buchner et al. 2023). Although global capital is available, structural barriers continue to disproportionately hinder developing countries' access to affordable financing (BRICS 2025b). In this context, the development of innovative financing mechanisms within South-South cooperation becomes imperative, particularly mechanisms that emphasize non-discriminatory access to markets and low-interest finance (BRICS 2025a).

1.1. The Financing Nexus of the Energy Transition

The global energy transition, necessary to achieve net-zero targets, hinges upon the secure and sustainable supply of critical minerals such as lithium, cobalt, and rare earth elements. The transition to a clean energy system is inherently more mineral-intensive than its fossil-fuel-based counterpart, driving a significant increase in demand for a wide range of mineral resources (IEA 2022; UNECE 2024). The accelerating deployment of low-carbon technologies is projected to significantly boost mineral requirements, with demand for clean energy applications expected to quadruple by 2040 in a scenario aligned with the Paris Agreement goals (IEA 2022). This surge highlights the growing importance of both critical and strategic minerals, which are essential for manufacturing technologies such as batteries, solar panels, and wind turbines (IEA 2022). However, the supply chains for these minerals are marked by price volatility, geopolitical risks, and high geographic concentration (IEA 2025b; IEA 2022; UNECE 2024).

Consequently, accelerating the energy transition is inextricably linked to the rapid and strategic deployment of innovative sustainable finance mechanisms. Governments are increasingly deploying public funding through loans, grants, and strategic partnerships to fast-track project development and enhance access to finance (IEA 2025b). In parallel, structured market-based mechanisms are being introduced to attract private capital by mitigating key market uncertainties (IEA 2025b). These include price-stabilization schemes, such as contracts-for-differences, and volume-guarantee mechanisms that provide greater demand certainty for new projects (IEA 2025b). When combined with international co-investment and shared de-risking frameworks, these strategies are crucial for building the resilient and diversified supply chains required to support technological autonomy (IEA 2025b). In recent years, the concept of transition finance has emerged as a new frontier within the broader sustainable finance framework, driven by the increasing need for an orderly and timely transition to net-zero across all sectors (BRICS 2025b).

2. Definition and Classification of Minerals

Critical minerals are broadly defined by their high economic importance for key technologies, especially low-carbon technologies, and by potential supply constraints due to factors like market concentration, geopolitical risks, and a lack of viable substitutes (UNECE 2024; IEA 2022). Globally recognized examples include lithium, cobalt, and rare earth elements, which are indispensable for producing batteries and high-performance permanent magnets used in EVs and wind turbines (UNECE 2024; IEA 2022).

In contrast, the term strategic minerals refers to materials vital to a nation's broader economic and geopolitical interests, encompassing applications beyond the energy sector, such as defense, aerospace, and advanced manufacturing, even if they are not globally scarce (IEA 2025b). Niobium, for instance, is considered strategic for Brazil due to its role in industrial competitiveness and export leadership, while platinum group metals (PGMs) hold similar importance for South Africa, the world's leading supplier (UNECE 2024).

It is important to note that the designation of a mineral as critical or strategic is widely considered a political one, reflecting national security and economic priorities rather than purely geological characteristics (UNECE 2024). Understanding these distinct but interconnected concepts clarifies the need for holistic and integrated policy approaches that address the entire lifecycle of these materials, thereby ensuring that mineral resources act as an enabler, rather than a bottleneck, for the global energy transition (IEA 2025b; UNECE 2024).

2.1. The Critical Minerals Value Chain

The mineral value chain comprises four interdependent stages. The first is extraction, which provides the primary feedstock for all subsequent processes (UNECE 2024). This stage is characterized by long lead times, with an average of over 16 years from mineral discovery to first production, creating a potential mismatch with rapidly accelerating demand (IEA 2022).

Following extraction, the raw ore undergoes refining and processing, where it is converted into the high-purity inputs required by technology manufacturers through methods like pyrometallurgy and hydrometallurgy (UNECE 2024; IEA 2022). This midstream segment is marked by extreme geographical concentration, which poses a significant risk to supply security.

The final stage in the linear production process is manufacturing, where these refined materials are transformed into essential components for clean technologies, such as batteries and high-performance permanent magnets (UNECE 2024). This stage is also highly concentrated and is critical for capturing domestic and regional economic value and enabling the large-scale deployment of clean energy technologies (IEA 2025b; UNECE 2024).

Closing the loop is the fourth stage, which involves recycling and circularity, and entails the recovery of valuable materials from end-of-life products (UNECE 2024; IEA 2022). Scaling up recycling could reduce pressure on primary supply, potentially cutting the need for new mining activity by 5-30% by 2040 (IEA 2025b). However, the recycling industry for many energy transition minerals, such as lithium and rare earth elements, is still in its early stages compared to established practices for bulk metals like copper (IEA 2022). While circularity is an essential framework for sustainable resource management, it is widely acknowledged that secondary supply will not eliminate the need for continued investment in primary production (IEA 2022; UNECE 2024).

Currently, investment in the critical minerals sector is heavily concentrated at the upstream extraction stage, with a significant portion of capital directed toward mining projects (IEA 2025b). This focus has led to the comparative neglect of midstream and downstream segments, such as refining, manufacturing, and recycling, which are essential for supply chain security and value creation. Given that market forces alone are considered insufficient to foster the necessary diversification and resilience, integrated policy support and financing mechanisms spanning the entire value chain are deemed essential to de-risk new investments and ensure a secure supply (IEA 2025b).

Given this global context of supply chain concentration and vulnerability, the strategic position of BRICS countries becomes particularly significant. BRICS countries occupy a pivotal position in the global distribution of natural resources essential to the energy transition, collectively holding vast reserves and significant production capacity across several key commodities. China and Brazil together hold about 48% of the world's graphite reserves, and, when India is included, the three countries account for 73% of global production (Kowalski and Legendre 2023). Russia ranks as the second-largest cobalt producer, with a 4.3% share of global output (Kowalski and Legendre 2023). In the case of manganese, South Africa possesses the largest reserves (32.1%), followed by Brazil (13.6%), and is also the leading producer with 28.2%, ahead of China, which contributes 15.8% (Kowalski and Legendre 2023). Indonesia and Brazil together account for 36% of global nickel reserves (Kowalski and Legendre 2023), while Indonesia leads global production, responsible for nearly 45% of total output (IEA 2025b). This dominance has been reinforced by national policy: since 2022, Indonesia has gradually restricted nickel ore exports, mandating that extraction be followed by domestic processing before the material can be sold abroad (IEA 2024e). Figure 1 illustrates the BRICS share of reserves and production for these minerals.

BRICS Share of Global Critical Mineral Reserves

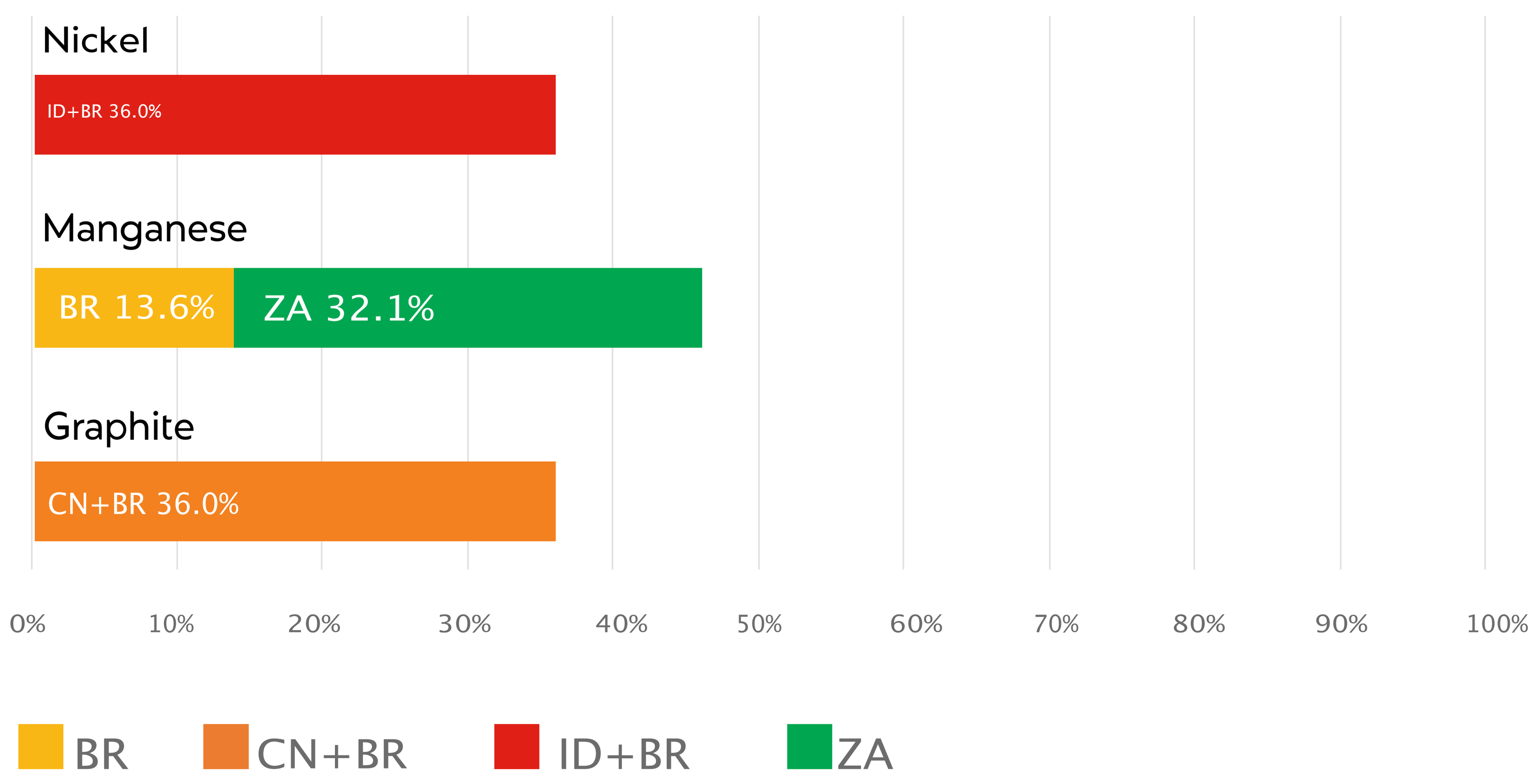

Figure 1 **BRICS members share global reserves for graphite, manganese, and nickel.**

Note: Blue bars represent single-country data; orange bars indicate multi-country aggregates.
Country codes: BR=Brazil, CN=China, ZA=South Africa, ID=Indonesia. Graphite: CN+BR (48%); Manganese: ZA (32.1%) + BR (13.6%); Nickel: ID+BR (36%). Cobalt reserve data not available.
Sources: Kowalski and Legendre 2023; IEA 2024d; IEA 2024e; IEA 2025a-f.

In addition to these resources, China dominates rare earth elements, representing nearly 70% of global production and 87% of global refining production (U.S. Geological Survey 2025; Natural Resources Canada 2023).
Figure 3 further demonstrates the extent of BRICS concentration across key energy transition minerals, including rare earths. Together, these figures illustrate how BRICS countries have become central to the supply of critical minerals underpinning clean energy technologies, granting the bloc growing influence over the pace and security of the global energy transition.

BRICS Share of Global Critical Mineral Production

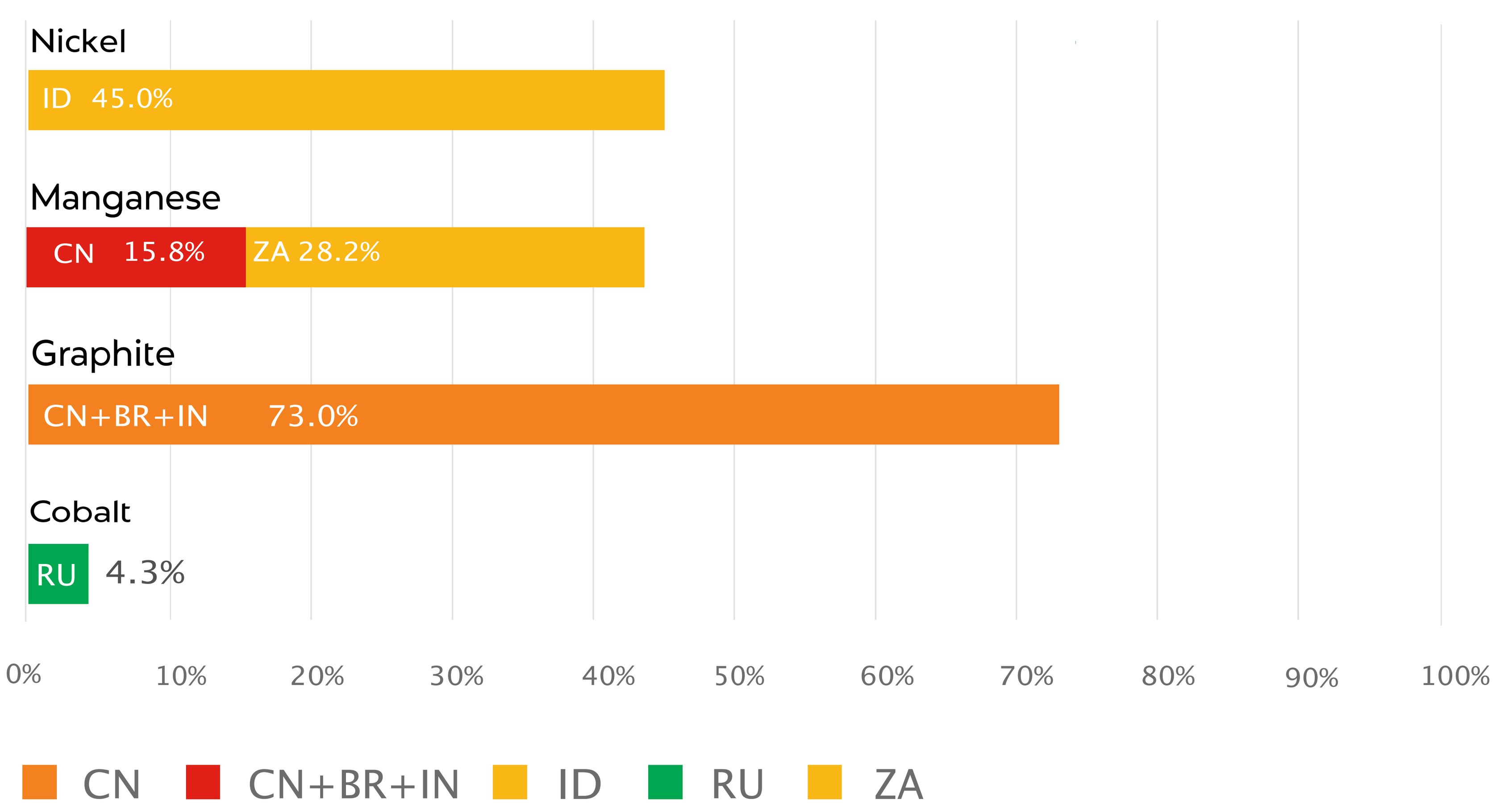

Figure 2 **BRICS members share global production for graphite, manganese, nickel, and cobalt.**

Note: Blue bars represent single-country data; orange bars indicate multi-country aggregates.
Country codes: BR=Brazil, RU=Russia, CN=China, ZA=South Africa, ID=Indonesia, IN=India. Graphite: CN+BR+IN (73%); Manganese: ZA (28.2%) + CN (15.8%); Nickel: ID (45%); Cobalt: RU (4.3%).
Sources: Kowalski and Legendre 2023; IEA 2024d; IEA 2024e; IEA 2025a-f.

Market share of BRICS countries across six critical mineral categories. China's concentration in rare earth elements is particularly striking, controlling 87% of global refining and 70% of production. BRICS also holds significant shares in graphite production (73%) and nickel production (45%), while cobalt production (4.3%) represents a strategic gap.

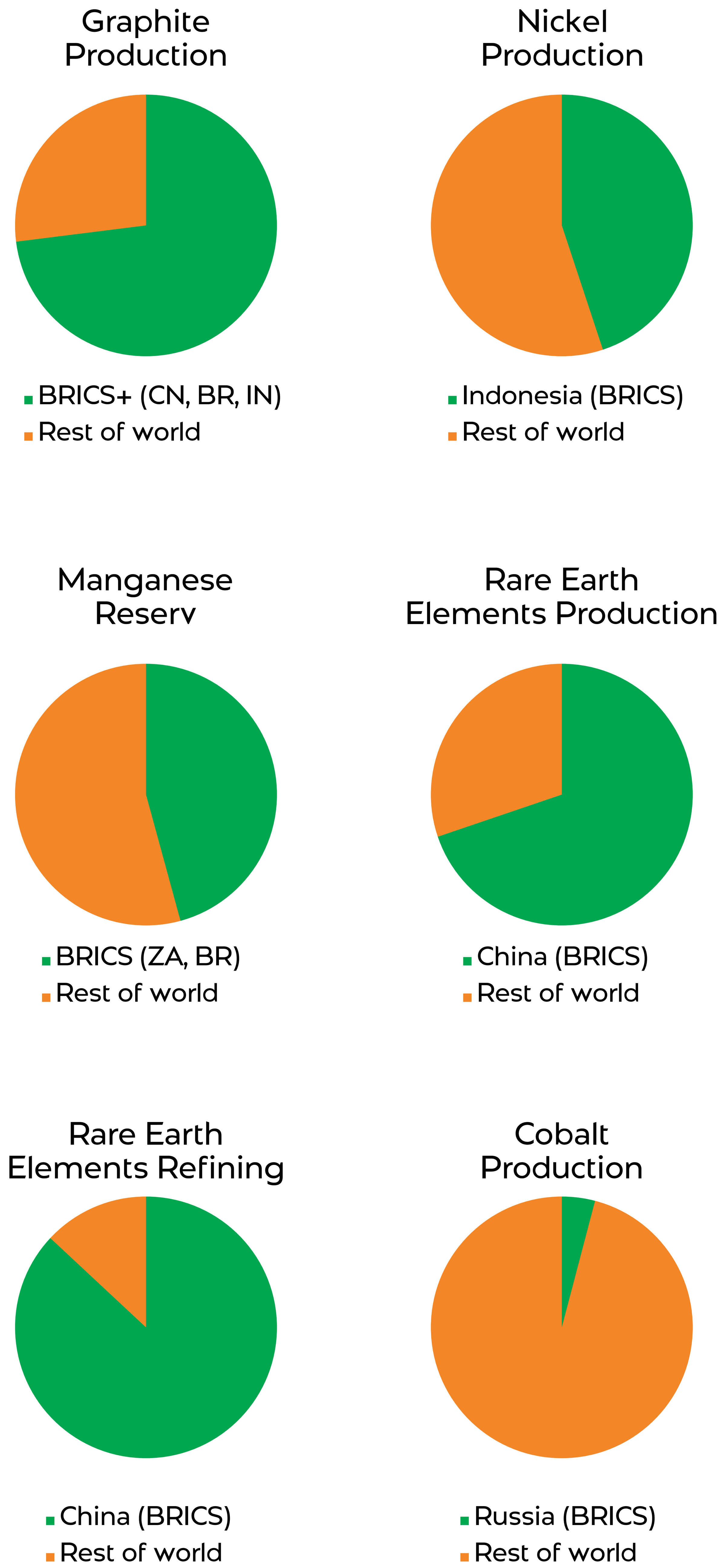

Figure 3 **BRICS members' concentration on key energy transition minerals.**

Sources: Kowalski and Legendre 2023; IEA 2024d; IEA 2024e; IEA 2025a-f; Natural Resources Canada 2023; USGS 2025.

3. National Energy Transition Strategies of BRICS Countries

BRICS countries, while sharing common principles for the energy transition, such as increasing the accessibility and reliability of energy supply and viewing energy efficiency and energy security as powerful tools for enhancing productivity, economic growth, and reducing emissions, adopt distinct national strategies that reflect their socioeconomic realities and resource endowments.

Brazil focuses on expanding its already predominantly renewable energy matrix (~50% total, ~90% electricity), with the modernization of its transmission infrastructure including ultra-high voltage lines and smart grid technologies. The country is developing advanced biofuels as part of its diversified energy transition strategy (BRICS 2024). It seeks to attract private investments for clean energy projects, utilizing auctions and market mechanisms to ensure competitiveness.

Russia, in turn, supports a balanced and pragmatic approach to the energy transition, which allows for the continued development of all energy sources in line with national circumstances. It positions itself as a leader in both traditional and renewable energy resources. The Russian approach includes hydrogen energy development, carbon capture and storage (CCS) technologies, while modernizing its energy sector to improve operational efficiency and reduce emissions (BRICS 2024).

India is highly dependent on fossil fuel imports, with fossil fuels representing 84% of its primary energy mix. In 2023, the country imported over 40% of its primary energy requirements, worth over USD 90 billion annually. To address this, the country has introduced various market instruments to stimulate renewable energy, including the National Green Hydrogen Mission, which aims to establish India as a global hub for green hydrogen production, with targets of 5 million metric tonnes of annual production and 125 GW of associated renewable energy capacity by 2030 (BRICS 2024).

China approaches the green transition by adhering to the people-centered approach and exploring the synergy between environmental protection and economic development, job creation and poverty eradication (BRICS 2024). In 2024, significant policy developments advanced China's green finance ecosystem. The National Development and Reform Commission (NDRC) finalized the Green and Low-Carbon Transition Industry Guidance Catalogue (2024 Edition), which includes traditional industries requiring resources for green transition. The People's Bank of China (PBoC) completed the compilation of transition finance standards for the first batch of four high-emission sectors – steel, thermal power, construction materials, and agriculture – and piloted them in some regions. Furthermore, the State Council released the Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development in April 2024 (Yue and Nedopil 2025). The country is expanding cooperation on renewable energy with countries participating in the Belt and Road Initiative (BRI). In 2024, China's green energy engagement in the BRI reached a record high of approximately USD 11.8 billion, representing about 30% of its total energy sector engagement for the year (Nedopil 2025).

South Africa has a significant number of jobs in the coal mining industry. In 2022, coal was the third largest employer in the national mining industry, directly employing 89,548 people or 20.48 percent of total mining industry employment (BRICS 2024). The country is highly dependent on coal production in many areas. The energy transition is seen not only as a necessity, but also as a process that requires managing significant socioeconomic impacts and social risks. The Just Transition Framework supports the decarbonisation of the mining and energy sectors in a socially acceptable manner that contributes to the economic development of the country, focusing on the issues related to workers in the coal value chain and specifically coal miners (BRICS 2024).

The new BRICS members, including Iran, the UAE, Egypt, Ethiopia, and Indonesia, are at different stages of decarbonization. Oil-exporting countries such as the UAE are diversifying into renewables and hydrogen. Meanwhile, Egypt and Ethiopia emphasize transitioning their energy production to hydro and solar power (BRICS 2025b).

3.1. Hard-to-Abate Sectors in BRICS Countries

Energy-intensive industries account for about 25% of total CO_2 emissions globally, of which 66% are from the industrial sector. The three sectors of steel, chemicals, and cement are the most significant industrial CO_2 emitters, with shares within the industrial sector reaching 27%, 25%, and 14%, respectively (UNECE 2022).

Steel production depends heavily on coal, which is used as a reducing agent to extract iron from iron ore and to provide the carbon content needed in steel (IEA n.d.-d). In the case of cement, more than half of the emissions are process-related. These emissions are associated with making clinker, an extremely carbon-intensive primary component that accounts for 90% of overall emissions from cement (IEA 2024b). In the case of chemicals, the emissions are largely due to the fact that around half of the chemical sector's energy input is consumed as feedstock, which is fuel used as a raw material input rather than as a source of energy (IEA n.d.-c).

BRICS countries are among the world's largest producers in hard-to-abate sectors, making the decarbonization of these industries a strategic priority. In steel, for example, China, India, and Russia rank among the top five producers, together accounting for roughly 65% of global output (World Steel Association 2025). A similar dominance is evident in cement and chemicals, where BRICS economies hold substantial production shares. This scale of industrial activity underscores the need for a coordinated BRICS roadmap to drive low-carbon transitions in these critical sectors.

Steel

As of 2021, the iron and steel sector accounted for about 6.1% of global greenhouse gas emissions (Ge et al. 2025). In the near term, reductions can be pursued through energy-efficiency upgrades and expanded scrap collection to increase the share of scrap-based production. These options, however, face inherent limits as efficiency gains are incremental, and scrap supply is constrained by collection systems and the availability of end-of-life steel (IEA n.d.-d). Achieving deep decarbonization over the long term will require a structural shift away from coal-based blast furnaces toward electric arc furnaces (EAFs) powered by clean electricity, using either recycled scrap or direct reduced iron (DRI) produced with zero-carbon feedstocks such as green hydrogen (Zhang, Nilsson, and Baxter 2025). Green steel is essentially the manufacturing of steel without any fossil fuels. Estimates suggest that a USD 1.4 trillion investment is required to green the steel value chain by 2050, which entails existing steelmaking infrastructure, operational emissions, and investment in carbon offset measures, such as Carbon Capture, Utilization and Storage (CCUS) (Wu, Vora, and Chaudhary 2022).

Cement

As of 2021, the cement sector accounted for about 3.4% of global greenhouse gas emissions (Ge et al. 2025). In cement production, the majority of emissions are process-related, stemming from the calcination of limestone, with the remainder linked to energy use. Decarbonization strategies therefore extend beyond energy substitution. The use of alternative cementitious materials to partially replace clinker can significantly lower carbon intensity (Barbhuiya et al. 2024). CCS will also be essential, as it can address the process emissions that cannot be eliminated otherwise. At the same time, improving energy efficiency and integrating clean energy into manufacturing through process optimization, waste heat recovery, and advanced energy-efficient technologies remains critical (Barbhuiya et al. 2024). Some estimates highlight that up to USD 300 billion in additional funding will be required by 2050 to decarbonize the cement sector (United Nations Industrial Development Organization 2024).

Chemicals Sector

As of 2021, the chemical and petrochemicals sector accounted for about 6.4% of global greenhouse gas emissions (Ge et al. 2025). The chemical sector can consider CCUS and the deployment of electrolytic hydrogen for decarbonization and integrating direct electrification technologies, such as high-temperature heat pumps, since approximately 30% of the required process heat is below 200°C (IEA n.d.-c). Material efficiency measures can also be instrumental for reducing overall chemical demand. These include increased plastics recycling, more efficient use of ammonia fertilizers, and efforts to limit single-use plastics (IEA n.d.-c). Estimates mention that the new clean capacity and retrofits for lower emissions in the chemicals and petrochemicals sector will require an additional USD 759 billion compared to business-as-usual capacity growth (BloombergNEF 2022).

Apart from the three sectors discussed, if we consider all hard-to-abate sectors like steel, aluminum, cement, primary chemicals, oil and gas, aviation, shipping, and trucking, USD 30 trillion in additional capital will be required across these sectors to achieve the net-zero transition (World Economic Forum 2024). Their decarbonization is particularly complex, requiring breakthrough technologies, large-scale infrastructure shifts, and substantial capital investment. The pathways are both technology- and finance-intensive, underscoring the need for coordinated action. Financing hard-to-abate sectors also presents numerous challenges because of the significant capital needs, long payback periods, and high technology risk. Some of the financing avenues that can be considered by the BRICS nations are as follows:

1) Strengthening South-South Technology Cooperation Amongst the BRICS: South-South collaboration within BRICS can be transformative in accelerating access to affordable green technologies, especially in incremental innovation areas such as energy efficiency, green hydrogen, and industrial process optimization. Over the past decade, China, Brazil, and India have made notable progress in clean energy technologies and industrial innovation. Leveraging this progress through joint Research and Development (R&D) platforms, knowledge-sharing mechanisms, and coordinated technology transfer could help other BRICS members adopt decarbonization pathways at lower cost. Such cooperation would also lessen dependency on Northern technologies and intellectual property regimes, thereby building greater technological self-reliance in the Global South.

2) Empowering the New Development Bank (NDB) for Transition Finance: The NDB, established by BRICS, is uniquely positioned to address the financing barriers in hard-to-abate sectors. A clear mandate to focus on hard-to-abate sectors could enable the NDB to serve as a catalyst for industrial decarbonization. This would involve providing concessional loans, equity investment tools, blended finance structures, and de-risking facilities tailored to the high capital costs and technology risks of the sector. By absorbing part of the risk and providing concessionality, the NDB could unlock large-scale private investment and support first-mover projects across BRICS.

3) Innovative Financing Instruments: A market for transition bonds and sector-specific Sustainability-Linked Bonds (SLBs) should be promoted that can lower financing costs when linked to credible, verifiable decarbonization milestones (e.g., percentage scrap use, percentage clinker substitution, CO_2 per ton of steel). Clear, BRICS-aligned transition taxonomies and standards (as recommended in the BRICS roadmap) are necessary to avoid greenwashing and attract institutional investors. To ensure that the funds also move to credible and effective projects, scale up technical assistance and early-stage grant funding to develop bankable project pipelines (feasibility, permitting, commercial models) should be provided by Multilateral Development Banks (MDBs) like NDB, World Bank, and others.

4. Financial Challenges and Opportunities

The energy transition in emerging markets and developing economies (EMDEs) faces significant financial obstacles. EMDEs account for two-thirds of the global population but only around 15% of clean energy investment (IEA 2025d). Mobilizing the private sector depends fundamentally on reducing the cost of capital.

4.1. Financial Challenges

Currently, EMDEs face higher capital costs than advanced economies, which result from two sets of risks: country and macroeconomic risks, and project- or sector-specific risks (IEA 2025c). High interest rates and inflationary pressure affect the cost of capital (Weighted Average Cost of Capital (WACC)), making it difficult to generate attractive risk-adjusted returns and hindering long-term capital access (IEA 2024b). Many EMDEs have limited space to increase government debt due to fiscal constraints (IEA 2025d), while Multilateral Climate Funds (MCFs) provided an average of USD 780 million in financing per year between 2015 and 2024 (IEA 2025f).

Meanwhile, countries in Emerging Markets continue to invest in fossil fuels. Investment in coal is set to increase by 4% to an all-time high in 2025. China and India were responsible for almost all of the growth in coal investment in 2024 and 2025 (IEA 2025c). Commodity price volatility has strained producers' financial capacity; adjusted for cost inflation, real investment growth in 2024 was just 2% (IEA 2025c).

Transition finance is another key point for EMDEs in achieving energy security. It helps mitigate the risks of financial carbon leakage, where strict regulations, narrow definitions of Paris Agreement alignment, and a lack of clarity on credible hard-to-abate transition pathways lead to divestment and capital shifting to less-regulated regions or sectors, such as private debt markets that are harder to monitor (IEA 2025c). Beyond debt markets, other types of general-purpose finance, such as equity investments, are needed. Private Equity and Venture Capital could play a much more prominent role, for example, in financing breakthrough low-emission innovations (OECD 2022).

4.2. Financial Opportunities and the Role of the NDB

BRICS countries are central to the global energy transition as major energy consumers and critical mineral producers (BRICS 2025a). Data from the International Monetary Fund (IMF) (2025) shows that only China mobilizes green bond capital above the global average, indicating significant room for improvement across BRICS.
The NDB, established by the original BRICS members in 2015, has evolved beyond its founding structure. While historically closely aligned with BRICS, the NDB currently does not include all BRICS members following the bloc's expansion, and it has also admitted non-BRICS countries such as Bangladesh as members. This institutional configuration presents both constraints and opportunities. On one hand, it may limit the NDB's direct reach within the expanded BRICS membership. On the other hand, it positions the NDB as a broader Global South development institution, potentially facilitating operations and partnerships across a wider range of emerging and developing economies beyond the BRICS framework.

The NDB can strengthen its role as an anchor investor through four strategic actions:

1) Risk Reduction: Commodity price volatility and country risk premiums increase financing costs in BRICS (Simon 2025; Kaltenbrunner et al. 2024). The NDB can provide guarantees, risk insurance, and political risk coverage to reduce costs and encourage private participation.

2) Creating New Investment Products: The NDB can develop multimarket funds, exchange-traded funds, and transition bonds for sectors requiring gradual decarbonization, while blended finance structures can scale investment by lowering risks for private investors (IEA 2025c).

3) Expanding Local Currency Financing: With over 75% of the NDB's portfolio in U.S. dollars (Godinho and Mattos 2025), expanding local currency financing can reduce exchange rate risks and strengthen domestic capital markets, aligning with BRICS efforts to reduce dollar dependence.

4) Developing a Framework for Transition Finance: The NDB can design a BRICS-wide transition finance framework integrating fragmented taxonomies (IEA 2025c) while addressing social dimensions, particularly for communities dependent on carbon-intensive industries (International Labour Organization 2022; United Nations Framework Convention on Climate Change Standing Committee on Finance 2022). A BRICS Transition Finance Framework was introduced in the BRICS Business Council Annual Report 2023/24, providing a foundational approach for mobilizing capital for low-carbon transition activities.

By reducing risks, backing new investment products, supporting local currency finance, and building a coherent transition finance framework, the NDB can mobilize resources at scale while ensuring development and social concerns remain central to the BRICS energy transition.

5. Socio-environmental Dimensions of Mineral Extraction

The global shift to clean energy is not only a technological transformeation but also a structural one, from a fuel-intensive to a material-intensive system. EVs, wind turbines, and solar panels require vast quantities of lithium, cobalt, copper, nickel, and rare earth elements. These minerals are indispensable for decarbonization. Yet the rapid expansion of mining brings profound social, environmental, and geopolitical challenges. Unless addressed directly, the transition risks reproducing the inequities of the fossil fuel era, undermining its own moral and ecological foundation.

5.1. Social, Environmental, and Geopolitical Challenges in Mineral Extraction

A central challenge is obtaining and maintaining a Social License to Operate (SLO), which goes beyond a government permit. It is built on trust, transparency, and fair benefit-sharing with local communities. Many mining projects face opposition not because residents reject clean energy, but because they bear the immediate burdens such as land disruption, pollution, and cultural loss while the benefits are externalized. Without genuine community engagement, projects encounter protests, delays, and shutdowns, threatening the reliability of critical mineral supply chains (Cosbey et al. 2016).

Disproportionate impacts on Indigenous peoples and local communities are another major concern. Critical mineral deposits are often located on or near the lands of Indigenous peoples and vulnerable communities. For them, land is not only a resource but also a basis of cultural identity and survival. Mining can lead to land dispossession and restricted access to traditional livelihoods, cultural loss including destruction of sacred sites, and marginalization, as promised jobs and revenues often prove short-term or unevenly distributed. International frameworks, such as the principle of Free, Prior and Informed Consent (FPIC) enshrined in the UN Declaration on the Rights of Indigenous Peoples, provide guidance but are frequently overlooked (United Nations General Assembly 2007). A just transition must therefore extend protection not only to fossil fuel workers but also to those on the frontlines of mineral extraction, ensuring that the costs of the transition are not borne by the most vulnerable (Business & Human Rights Resource Centre 2002).

Intensive water use and pollution represent a critical vulnerability. Lithium and copper extraction often occurs in arid regions, such as the salt flats of the Atacama Desert. Brine extraction for lithium is highly water-intensive, lowering water tables and threatening local agriculture and ecosystems. This creates a stark paradox: technologies designed to combat a global crisis, climate change, may exacerbate local crises such as water scarcity and contamination. Responsible water management, monitoring, and investment in less water-intensive processes are urgent priorities (Moran et al. 2022).

Waste and tailings risks are immense. Mining is inherently waste-intensive. Ores contain only a small fraction of usable material, generating vast quantities of waste rock and chemically treated tailings. These residues may include heavy metals and radioactive substances. Inadequate storage or failure of tailings dams, as tragically demonstrated by the 2019 Brumadinho disaster in Brazil, can devastate communities and ecosystems (Thompson et al. 2020). Furthermore, rare earth processing produces toxic and radioactive by-products, requiring stringent long-term management often lacking in resource-rich but regulation-poor jurisdictions.

Finally, the geopolitical concentration of refining extends risks beyond extraction. The refining of critical minerals is highly concentrated, with China dominating approximately 90% of rare earths processing, 65% of cobalt refining, and 85% of lithium processing. This concentration adds another layer of risk to supply security and highlights the need for diversification across the entire value chain.

5.2. Building Resilient and Sustainable Mineral Supply Chains

Building resilient and sustainable mineral supply chains requires a multi-faceted approach. BRICS countries possess complementary strengths that, if strategically linked, could form a self-reinforcing value chain from raw-material extraction to advanced manufacturing. Brazil's abundant niobium and lithium, Russia's nickel and palladium, South Africa's platinum-group metals and manganese, and Indonesia's nickel and copper reserves position them as key upstream suppliers. China remains the hub of refining and component manufacturing, while India has rising capabilities in cell manufacturing and electrochemistry research (IEA 2025b; BRICS 2023a). Midstream refining is highly concentrated, with China dominating 90% of rare-earth processing, 65% of cobalt refining, and 85% of lithium refining (IEA 2025b). To reduce this vulnerability, BRICS coordination could prioritize regional joint ventures. For example, Brazil could supply lithium concentrate for refining in China, while India co-develops cathode production lines through shared industrial parks. This cross-integration would strengthen supply security while capturing more value locally.

A parallel strategy involves scaling circular supply and recycling. A BRICS circular-economy strategy can reduce raw-material dependence and price exposure. The IEA estimates that without secondary supply, mining investment requirements would be 30% higher to 2040 (IEA 2025b). Recycling and recovery could meet 20-30% of lithium, nickel, and cobalt demand by 2040, easing extraction pressures and supporting regional manufacturing resilience. To operationalize this potential, BRICS members should: (i) align minimum recycled-content standards in batteries and permanent magnets; (ii) harmonize end-of-life collection rules (IEA 2025b); and (iii) establish a "BRICS Re-Minerals Facility" blending concessional and commercial finance for hydrometallurgical recycling plants in Brazil, India, and South Africa. Such coordination would deliver both economic and environmental returns.

Furthermore, enhancing digital traceability and transparency is crucial. Digital traceability can increase market confidence and compliance while reducing Environmental, Social, and Governance (ESG) risk premiums. The IEA's The Role of Traceability in Critical Mineral Supply Chains 2025 report highlights that upcoming regulatory regimes, such as the European Union (EU) Battery Passport, will require cradle-to-gate traceability of origin, custody, and ESG data (IEA 2025e). Similarly, the United Nations Transparency Protocol (UNTP) pilot on critical minerals emphasizes interoperability across digital systems to enable data exchange among multiple jurisdictions (UNTP 2024).

A BRICS traceability framework could adopt common data schemas covering origin, custody, emissions, and social metrics, alongside shared blockchain-based registries. This approach would both improve lender due diligence and streamline export compliance for battery and electric vehicle manufacturers.

Concurrently, local-content programs and community development must be advanced. Local-content programs (LCPs) should go beyond procurement quotas to foster technology transfer, skills, and ownership. As shown in the International Institute for Sustainable

Development (IISD)/Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGFMMS) report Local Content Policies in the Mining Sector (2018), definitions of "local" that emphasize value addition rather than headcount create longer-term industrial spillovers and supplier capabilities (IISD and IGFMMS 2018). The report further notes that supplier-development programs and public-procurement linkages can increase domestic value capture by 15-25% (IISD and IGF 2018). For BRICS nations, LCPs should define clear geographic and value-added thresholds, link LCP requirements to skills training and supplier certification, and embed LCP targets within community benefit agreements. Such integration ensures that the economic gains from critical-mineral projects reach local communities and Indigenous peoples, not just national elites.

The implementation of these measures requires dedicated financing mechanisms for community development. The World Bank's Mining Community Development Agreements Source Book underscores that community development agreements (CDAs) enhance participation, clarify obligations, and align expectations between companies and communities (World Bank 2012). For BRICS members, such agreements should be anchored in the principle of FPIC as outlined in the International Finance Corporation (IFC) Performance Standard 7: Indigenous Peoples (IFC 2012). Financing mechanisms could include royalty-linked trust funds, CDA-tied procurement clauses, and sustainability-linked loans with Key Performance Indicators (KPIs) for local employment and recycled-content shares. Blended finance and political-risk insurance provided through the NDB can reduce the cost of capital for projects that meet these criteria (IEA 2025c).

Finally, the adoption of robotics and digitalisation is key to reducing costs and risk. Technological innovation constitutes a core strategy for cost reduction and risk mitigation across the mining value chain. A BRICS Mining 4.0 initiative could develop shared standards for robotic drilling, remote operations, and sensor integration, accompanied by training programs to upskill local workers. This ensures digital technologies complement, rather than displace, employment, aligning efficiency gains with social objectives.

The integration of BRICS value chains, expansion of recycling capacity, deployment of digital traceability, and inclusive financing can together build a resilient and just critical-minerals ecosystem. Recycling reduces capital needs by up to 30%; traceability lowers risk premiums for lenders; LCPs and CDAs ensure that local communities share benefits; and robotics improves efficiency and safety. Such a coordinated approach would allow BRICS to transition from a resource-supplier to a technology- and value-creation bloc within the global clean-energy economy.

6. Conclusion and Recommendations

Financing the energy transition and developing resilient, sustainable critical mineral value chains represent one of the most complex and urgent challenges for BRICS countries. The analysis demonstrates that the transition is both an imperative necessity for climate action and an unprecedented opportunity for industrial development and geopolitical reconfiguration. However, the success of this endeavor depends on overcoming significant structural barriers, from mobilizing capital at scale to responsibly managing the socio-environmental impacts of mineral extraction.

BRICS countries are uniquely positioned to lead this process. As major energy consumers, holders of vast mineral reserves, and representatives of a significant portion of the global population and economy, their cooperation is essential. South-South cooperation, facilitated by institutions such as the NDB, emerges as a fundamental pillar for building a more inclusive, resilient financial architecture aligned with sustainable development objectives. Based on the analysis presented, the following recommendations are proposed:

Strengthen the Role of the NDB as an Anchor Investor: The NDB should intensify its action in mitigating investment risks through guarantees and insurance, developing new financial products adapted to the needs of emerging markets, expanding local currency financing to reduce currency exposure, and leading the creation of a common transition finance framework for BRICS.

Promote Local Value Addition in Critical Mineral Chains: Investments should be strategically directed toward developing midstream refining and processing capacities in producing countries. This approach enables the capture of greater economic value, the creation of skilled jobs, and the reduction of dependence on a limited number of processing countries, increasing the resilience of the global supply chain.

Integrate Just Transition Criteria in All Financing: It is imperative that mining and energy projects be evaluated not only for their economic viability but also for their social and environmental performance. The implementation of robust safeguards, respect for the principle of FPIC, and the guarantee of fair benefit-sharing with local communities must be non-negotiable conditions for financing.

Harmonize Taxonomies and Sustainable Finance Standards: BRICS countries should collaborate to develop taxonomies and transition finance standards that are specific to their contexts, recognizing enabling activities for the energy transition and avoiding the application of restrictive standards that may lead to capital flight. The harmonization of these frameworks will facilitate cross-border investment and capital mobilization at scale.

The just and sustainable energy transition requires more than the application of financial instruments developed in advanced economies. It requires innovative approaches that reduce risks, strengthen domestic financial systems, and integrate development concerns with climate action. By adopting a strategic cooperation agenda, BRICS countries can not only accelerate their own transition but also shape a more equitable and resilient global energy system.

Energy Access in Addressing Energy Poverty with Affordable Solutions

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1. Introduction

Universal energy access is a cornerstone for sustainable development and social equity. The United Nations' Sustainable Development Goal 7 (SDG 7) explicitly calls for ensuring access to affordable, reliable, sustainable, and modern energy for all by 2030. However, energy poverty remains a critical barrier for nearly one billion people worldwide, who either lack access to electricity altogether or rely on severely deficient energy services.

This chapter explores strategies to close this gap, with particular attention to addressing energy poverty in underserved communities.

The scope of analysis includes a technologically neutral portfolio of decentralized energy systems, in line with BRICS Just Energy Transition principles (BRICS 2024). This encompasses renewable solutions like solar mini-grids and geothermal energy, transitional fuel-based systems such as natural gas microgrids and hybrid biofuel solutions, as well as advanced nuclear options like small modular reactors (SMRs). The analysis also examines innovative business models, such as pay-as-you-go schemes, and policies designed to make clean energy affordable and reliable. To illustrate practical applications, the discussion incorporates case studies of successful implementations across BRICS countries and comparable regions.

1.1. Energy Access and Development Linkages

The period from 2000 to 2023 marked a significant global convergence in electricity access, yet it revealed two distinct pathways for human development among BRICS nations. While the global electrification rate increased from 78.2% to 91.6% (World Bank 2023a), the relationship between this progress and improvements in the Human Development Index (HDI) was not uniform. For countries like Ethiopia and India, which started with low initial access, the massive expansion of electrification was a transformative force, directly correlated with dramatic HDI increases of 70% and 37%, respectively. In contrast, members like China, Russia, and Brazil, which began the period with near-universal access, achieved further HDI gains through advancements in health, education, and governance, demonstrating that energy access is a foundational enabler whose developmental impact is most profound when it addresses a fundamental deficit. This highlights energy access as a critical enabler of human development, particularly in countries with historically low levels of access

Table 1: Progress in Electrification Access and Human Development Index (2000–2023).
Source: (World Bank 2023a; UNDP 2025)

Country	Access to electricity (in %)		Human Development Index (HDI)	
	2000	2023	2000	2023
Brazil	94.4	99.8	0.690	0.786
China	96.7	100	0.598	0.797
Egypt	97.7	100	0.639	0.754
Ethiopia	12.7	55.4	0.293	0.497
India	60.3	99.5	0.501	0.685
Indonesia	86.3	99.4	0.600	0.728
Iran	97.9	100	0.710	0.799
Russia	97.8	100	0.750	0.832
Saudi Arabia	100	100	0.737	0.900
South Africa	72.4	87.7	0.618	0.741
UAE	100	100	0.790	0.940
World	78.2	91.6	0.651	0.756

However, despite the above achievements in electricity access, energy poverty remains deeply entrenched. Almost one billion people still lack reliable or affordable modern energy, and even those connected to the grid often endure unstable supply or limited productive use. Importantly, electricity access alone does not capture the full picture of deprivation. Energy poverty is multidimensional, closely linked to a lack of clean cooking, safe water, sanitation, and decent housing (Alkire et al. 2021). These overlapping deprivations reinforce each other and trap households in cycles of poverty.

This persistence of multidimensional energy poverty, even amid rising electrification, reveals a deeper development challenge. Access to electricity is necessary, but not sufficient to break the poverty cycle. The next section examines how the lack of clean fuels and affordable, modern energy services continues to act as a structural development trap for millions, particularly in low-income and rural communities.

The relationship between increased access to electricity and HDI (2000 - 2023)

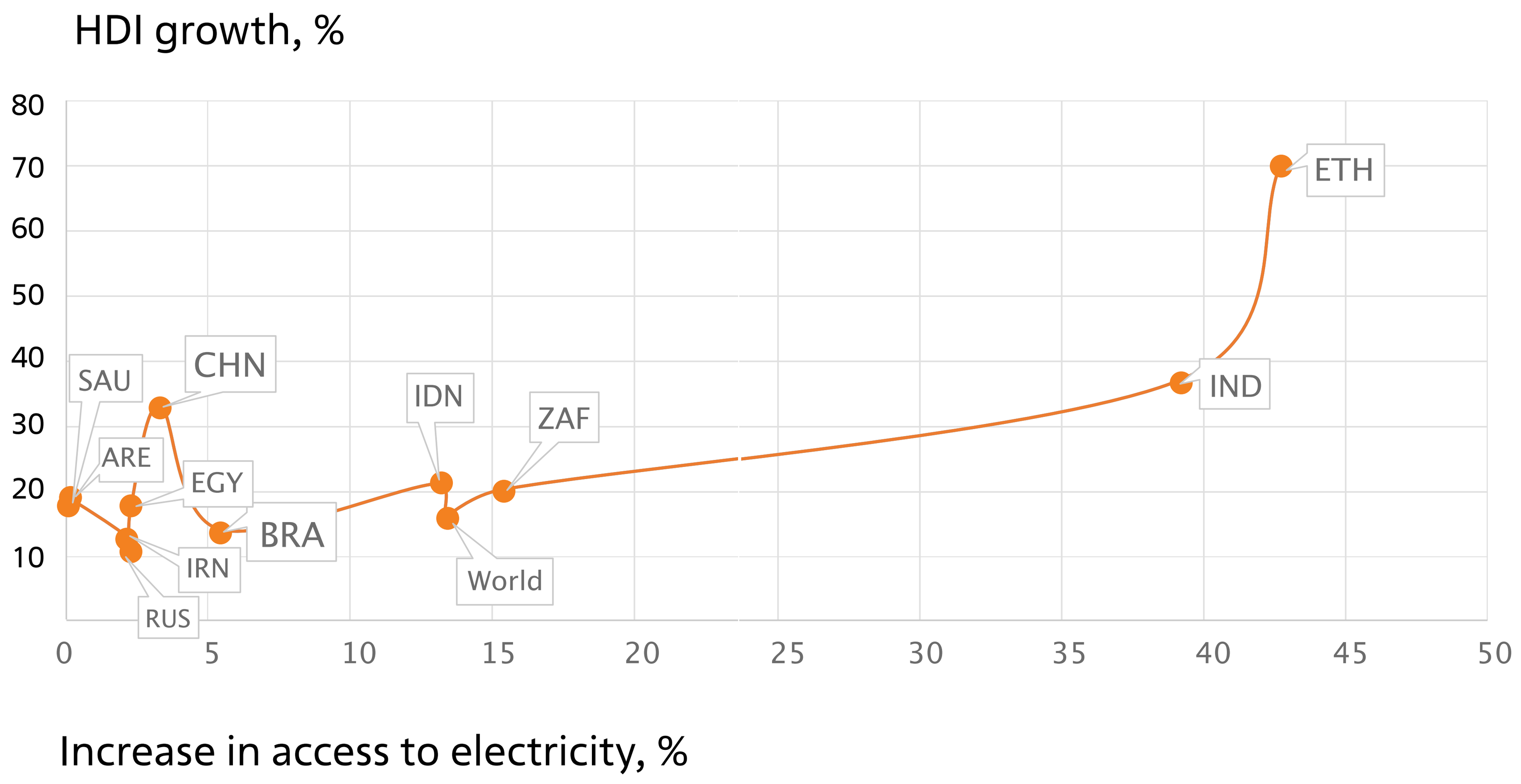

Figure 4 **The relationship between increased access to electricity and HDI (2000-2023)**

Sources: (World Bank 2023a; UNDP 2025).

1.2. Energy Poverty as a Multidimensional Trap

As highlighted by the International Energy Agency (IEA), "modern energy is a basic condition for social and economic inclusion" (IEA 2022). Populations without access to sustainable fuels remain trapped in a cycle of dependence on traditional biomass, which exacerbates inequalities and has significant environmental and health impacts. From a social perspective, unequal access to clean cooking technologies perpetuates gender and public health injustices. In 2022, among the BRICS countries, Ethiopia was the only one with access to clean cooking fuels well below the global average of 74%, with only 8.8% of its population using such technologies, as shown in Figure 5 (World Bank 2023a; World Bank, WHO et al. 2023)

This asymmetry in clean fuel access highlights the varying levels of energy development within these emerging economies. Although BRICS is often presented as a cooperative bloc of rising powers across economic, political, and technological dimensions, the data reveals significant disparities in clean fuel consumption among its members.

BRICS access to clean fuels and technologies for cooking in 2022 (%)

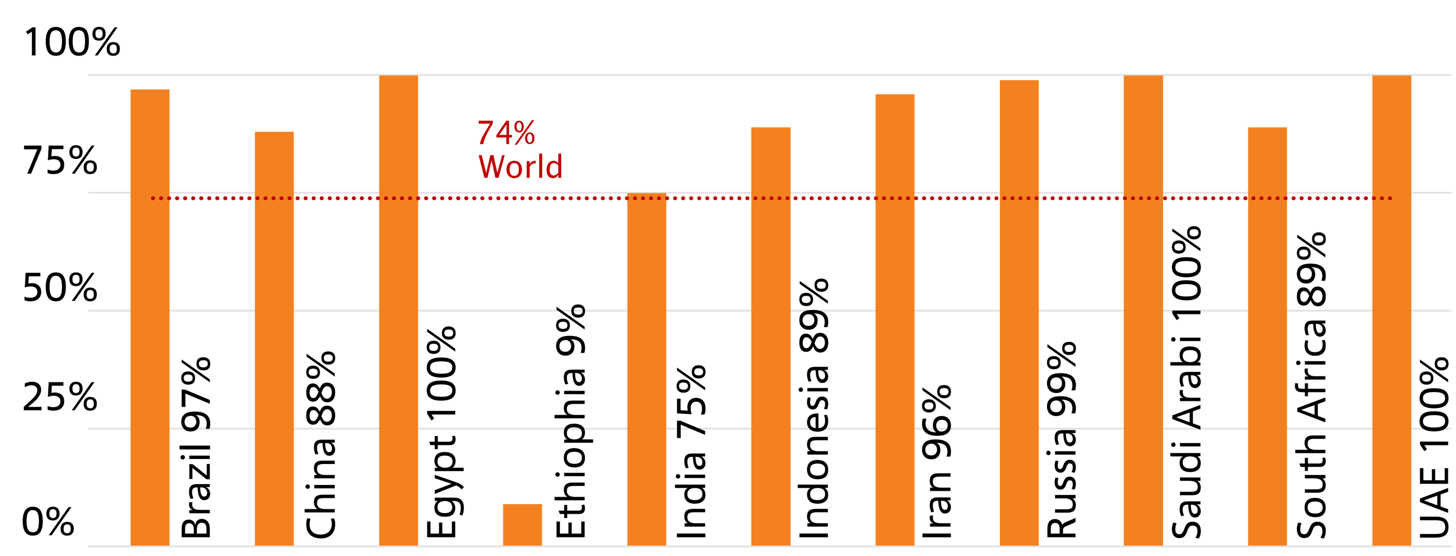

Figure 5 **BRICS access to clean fuels and technologies for cooking in 2022 (%)**

Sources: World Bank 2023

Table 1: Progress in Electrification Access and Human Development Index (2000-2023)
Source: (World Bank 2023a; UNDP 2025)

Country	The relationship between increased access to electricity and HDI (2000-2023)		The relationship between increased access to electricity and HDI (2000-2023)	
	2000	2023	2000	2023
Brazil	94.4	99.8	0.690	0.786
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Ethiopia	12.7	55.4	0.293	0.497
India	60.3	99.5	0.501	0.685
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Saudi Arabi	100	100	0.737	0.900
South Africa	72.4	87.7	0.618	0.741
UAE	100	100	0.790	0.940
World	78.2	91.6	0.651	0.765

1.3. Operational Definitions and Scope

Addressing this challenge requires a multidimensional approach that recognizes the diverse dimensions of access: capacity, duration, reliability, power quality, legality of connection, and safety. In addition, the scope of energy access must include clean cooking, given that reliance on traditional fuels such as firewood and kerosene continues to compromise health, exacerbate gender inequalities, and limit opportunities for human development (Teixeira 2024).

BRICS countries represent over 40% of the world's population and illustrate sharp contrasts in energy access, ranging from near-universal electrification in China and Russia to persistent reliability crises in South Africa's coal-dependent grid (BRICS Brazil 2025).

The challenges of accessing energy differ markedly depending on the type of settlement: in urban areas, affordability and reliability are key concerns, with load-shedding forcing dependence on costly backup generators. In peri-urban zones, informal settlements are often excluded from safe and legal connections. In rural regions, the high costs and logistical difficulties of grid extension leave many with limited, low-quality, or no access. And in remote territories, populations rely primarily on decentralized renewables such as solar photovoltaic home systems or hybrid mini-grids.

From a social perspective, energy poverty deepens inequality. Women and girls face time and health burdens from fuel collection and indoor pollution, while vulnerable groups (low-income households, children, the elderly, and indigenous peoples) remain disproportionately affected. Therefore, ensuring inclusive access demands policies that explicitly prioritize these groups, ranging from the deployment of decentralized renewable energy sources in remote villages to the provision of targeted subsidies for the urban poor.

Some countries with robust public policies to combat energy poverty encounter geographical constraints as their primary barrier. According to Brazil's EPE, approximately 76% of the population that primarily uses biomass for cooking lives in rural areas (EPE 2025). The situation is even more critical in the Amazon, where riverine populations, although eligible for energy poverty alleviation programs, often cannot effectively access them due to geographical isolation. Even though these communities may already be partially electrified, they still depend on small combustion-powered boats to cross rivers and reach urban centers to purchase basic goods such as LPG, medicines, and other essentials. Furthermore, the fossil fuel used in these vessels is often adulterated and purchased from informal or illegal markets, exacerbating economic and environmental vulnerabilities.

Therefore, energy access programs should be integrated with complementary social and mobility policies to ensure that these populations can benefit fully from public initiatives. Local geography directly shapes energy poverty dynamics, extending the challenge beyond electricity provision alone. In remote or isolated areas, particularly in riverine communities, geographical barriers such as difficult terrain, vast distances, and a lack of infrastructure must be systematically addressed in policy design to achieve truly equitable energy access.

1.4. Analytical Framework and Method

This report applies the World Bank's Multi-Tier Framework (MTF), which treats energy access as a spectrum rather than a binary "connected/unconnected" condition (World Bank 2015). Access is assessed across six attributes: capacity, duration, reliability, quality, affordability, and formality. This tiered analysis enables a precise diagnosis of the energy poverty gaps, ensuring recommendations are targeted and effective. To situate this analysis within the broader energy transition, we align with the energy Trilemma framework, which seeks to balance the three often competing goals of energy security (reliable supply), energy equity (accessibility and affordability), and environmental sustainability (decarbonization). The MTF directly addresses the "equity" pillar, while our analysis of technological solutions and policies engages with "security" and "sustainability".

2. Current Issue Overview and Recent Technologies Globally

The countries analyzed have diverse experiences with rural electrification and decentralized energy solutions, each aimed at overcoming specific barriers, from geographical inaccessibility and low levels of reliability to economic limitations and inequalities of access. The analysis of flagship projects in BRICS countries provides valuable insights into recurring patterns, lessons learned, and effective strategies for delivering reliable and sustainable energy in diverse contexts. Each initiative was assessed according to its main challenges, key characteristics, business models, and outcomes, which were classified based on MTF levels. The MTF levels were estimated following the methodology proposed by the World Bank (World Bank 2015). This framework allows for a more comprehensive understanding of energy access, considering not only the presence or absence of electricity, but also the quality, reliability, and diversity of its uses. The levels are defined as follows:

Table 2 *MTF tiers explanation.*
Source: World Bank 2015.

Tier	Description
1	Corresponds to minimum service, with enough energy to light one or two lamps and occasionally charge a smartphone;
2	Reflects an advance in terms of continuity of supply, with stable lighting, regular cell phone charging, and operation of small appliances, but still without the capacity for TV or more powerful tools;
3	The available energy not only enables lighting and communication, but also the operation of televisions and small equipment used in both educational activities and small businesses, thereby expanding the social and economic impact;
4	Marks a transition to more robust uses, including light refrigeration, water pumps, and higher-capacity tools, allowing community services and small businesses to operate more stably and efficiently;
5	Corresponds to full supply, with high reliability and power capable of serving multiple appliances, more intensive refrigeration, and even small industrial enterprises, a level generally achieved only by well-dimensioned, hybrid, or large-scale storage-supported networks.

2.1. Technological Portfolio for Decentralized Electrification

The countries analyzed have diverse experiences with rural electrification, each aiming to overcome barriers from geographical inaccessibility to economic limitations. It is evident that many flagship projects adopt similar technological solutions, mainly the combination of photovoltaic (PV) and battery systems in areas with geographic constraints, and grid expansion in regions closer to urban centers (Uruchi et al. 2023; Tata Power 2023). Nevertheless, each country applies distinct strategies reflecting its socio-economic and institutional context. In line with the principle of technological neutrality, a successful and secure energy transition must leverage a diverse portfolio of solutions (BRICS 2024). No single technology is a panacea; rather, the local context, resource availability, and development stage should dictate the optimal mix. The following overview presents key technologies suitable for decentralized generation across the BRICS nations, assessed through the lens of the MTF.

The pay-as-you-go (PAYG) model in India and the financing structure of Brazil's Luz para Todos program illustrate approaches that could inspire hybrid solutions adapted to Ethiopia's reality, where geographic and economic barriers to energy access persist (Karamov et al. 2021; AfDB 2024). Even countries with high electrification rates continue to face local challenges to achieve universal access. In Brazil, the Centro de Eficiência Energética da Amazônia (CEAMAZON/UFPA) has developed integrated energy and mobility solutions combining PV+battery systems with zero-emission electric boats to serve riverine communities (EEA 2021; C40 Cities 2024). These projects aim to be replicable and overcome the geographical barriers typical of the region.

These initiatives demonstrate that localized and context-specific solutions can effectively expand electrification policies and contribute to reducing energy poverty in different regions (Uruchi et al. 2023; Renewables Now 2021).

Solar Photovoltaics (PV) and Battery Storage (BESS)

A dramatic decline in costs has established solar PV coupled with battery storage (BESS) as a cornerstone of decentralized electrification. According to IRENA, the global weighted average levelized cost of electricity (LCOE) for solar PV fell by approximately 90% between 2010 and 2024, while the installed cost of utility-scale BESS plummeted by 93% over the same period (IRENA 2025). This trend is particularly pronounced within BRICS, where countries like India have seen cost reductions of up to 91%, and China, a global manufacturing leader, maintains among the world's lowest LCOEs (IRENA 2025).

This cost-competitiveness makes hybrid PV+BESS systems viable for providing reliable, off-grid power in areas where grid extension is prohibitively expensive or unreliable. The key technological challenge remains the inherent intermittency of solar generation, which necessitates storage or backup generation to ensure a stable power supply. However, the primary constraint for scaling these solutions is now shifting from hardware costs to financing. In high-interest environments, the weighted average cost of capital (WACC) becomes the dominant factor. Competitiveness therefore hinges on creating stable revenue frameworks – such as power purchase agreements (PPAs) and regulated tariffs – to lower risk and unlock investment.

Best practices across the bloc demonstrate the successful application of this formula. Saudi Arabia's Red Sea Global project, an isolated resort powered entirely by solar farms and a 1.3 GWh battery system, achieves near-Tier 5 reliability (Huawei n.d.). In Brazil, the Tunui-Cachoeira Microgrid in the Amazon uses a solar-battery-diesel hybrid system to modernize isolated grids, providing Tier 3 access to remote communities while reducing diesel consumption (Uruchi et al. 2025). Similarly, Ethiopia's Mini-Grid Directive promotes solar mini-grids operated by local cooperatives, expanding access to Tier 3-4 levels in remote areas (UNDP Ethiopia 2023). These examples underscore that pairing low technology costs with low WACC through stable contracts is the core formula for scaling decentralized energy access.

Geothermal Energy

Geothermal energy offers a critical advantage for the energy trilemma: it provides stable, baseload power, independent of weather conditions, thereby enhancing energy security. It is ideal for regions with significant geothermal potential, such as parts of China, Indonesia, Russia and Ethiopia. The primary barrier is high upfront exploration and drilling costs, though it boasts very low operating costs and a small physical footprint once operational (IEA 2022). Indonesia, home to nearly 40% of the world's geothermal reserves, is actively developing this resource. The Ulubelu Unit 3 & 4 geothermal power plant expansion in Lampung, for instance, adds 110 MW to the grid, providing reliable, clean power and supporting regional development (ThinkGeoEnergy 2017). In Russia, the Mutnovsky Geothermal Power Plant in Kamchatka, with a capacity of 50 MW, has been pivotal in powering the isolated Kamchatka peninsula, reducing its dependence on imported diesel fuel and providing a stable, low-carbon energy source (RusHydro n.d.). Ethiopia, which has an estimated geothermal potential of 10 GW is seeking to develop its first commercial projects in the Rift Valley (Benti et al. 2023).

Natural Gas and Hybrid Systems

Natural gas, particularly in liquefied (LNG) or liquefied petroleum gas (LPG) form, serves as a crucial transitional fuel for decentralized energy. Natural gas micro-turbines or LPG systems can provide reliable, dispatchable power with lower emissions than coal or diesel, making them ideal for hybrid systems that complement intermittent renewables. This enhances grid stability and energy security while reducing the carbon footprint during the transition. The key consideration is that while it reduces emissions, it is not zero-carbon, and its deployment requires a secure fuel supply infrastructure. Iran has successfully leveraged its vast natural gas reserves for a massive rural gasification program, connecting over 90% of its rural population to the natural gas network and significantly reducing reliance on polluting fuels for heating and cooking (Manara Magazine 2024). In Russia, a large-scale national gasification program has achieved a coverage level of approximately 74%, leveraging natural gas as the cleanest fossil fuel to reduce greenhouse gas emissions and mitigate environmental impact (TASS 2025). In Egypt, the government has promoted the use of LPG micro-grids in remote tourist lodges and settlements in the Western Desert, providing a cleaner and more reliable alternative to diesel generators (Kamel and Dahl 2005). China is exploring the next step by piloting projects that blend hydrogen with natural gas in existing pipeline networks, testing a pathway for further decarbonization of gas-based systems (Zhao 2025).

Small Modular Reactors (SMRs)

Small Modular Reactors represent a promising frontier for providing dense, zero-emission, baseload power to remote, high-energy-demand sites, such as large mining operations or isolated industrial communities. They are particularly relevant for regions where renewables are challenged by geography or climate. SMRs are currently in early deployment stages and require robust regulatory frameworks, significant capital, and broad social acceptance to be viable. Russia is the global leader in this domain with the Akademik Lomonosov, the world's first floating nuclear power plant, which provides up to 70 MW of power to the remote port town of Pevek in the Arctic Circle, replacing a aging coal-fired plant (Rosatom n.d.). China has also connected its first SMR, the Linglong One (ACP100), to the grid in Hainan province, with the stated goal of demonstrating a technology suitable for powering isolated islands and dense inland regions (Global Energy Prize 2025). While other BRICS nations are in earlier stages, countries like Saudi Arabia are actively conducting feasibility studies with international partners to assess SMRs as part of their long-term, low-carbon energy mix (Al-Salhabi et al. 2024).

Bioenergy and Waste-to-Energy

Bioenergy utilizes agricultural waste, dedicated crops, or municipal solid waste to generate dispatchable power, addressing both energy access and waste management issues. This is especially relevant in agricultural powerhouses like Brazil, India, and South Africa. Key considerations involve avoiding land-use conflicts with food production and ensuring the sustainability of the feedstock supply chain. Brazil's success with sugarcane-based bioethanol is world-renowned, but its application in decentralized power is also significant. Many sugarcane mills are energy self-sufficient, selling surplus biogas and bioelectricity to the grid, creating a distributed generation model. In South Africa, the eThekwini Municipality's Durban Landfill-Gas-to-Electricity project captures methane from landfill sites to generate electricity, reducing greenhouse gas emissions and contributing to the local grid, demonstrating a viable urban waste-to-energy model (World Bank n.d.). India's Pradhan Mantri Ji-VAN Yojana initiative provides financial support for setting up commercial-scale bioethanol plants, which often include cogeneration facilities, promoting distributed bio-energy production from agricultural residues (Government of India n.d.).

2.2. BRICS Decentralized Electrification: A Comparative Assessment

Table 3 provides a consolidated overview of BRICS countries, highlighting their strategic focus in decentralized electrification and an estimated MTF level achieved through flagship initiatives assessed in previous section.

Table 3: Consolidated overview of BRICS countries estimated MTF Tier.

Country	Strategic Focus & Technological Diversity	Estimated MTF Tier
Brazil	Hybrid renewable systems for remote areas (e.g., Amazon); leadership in bioenergy from sugarcane; robust universalization policies.	Tier 4-5
China	Massive scale-up of distributed solar PV (e.g., Lingang Project); integration with the main grid; advanced digital management.	Tier 4-5
Egypt	Deployment of LPG and off-grid PV systems for remote tourism lodges and settlements in arid regions.	Tier 4-5
Ethiopia	Focus on solar mini-grids operated by local cooperatives to overcome high grid extension costs in remote regions.	Tier 2-3
India	Grid expansion combined with decentralized PAY-G solar and biomass mini-grids to address affordability and reliability.	Tier 4
Indonesia	Ambitious plans for village-scale PV and batteries; development of geothermal potential to reduce diesel dependency.	Tier 3-4
Iran	Extensive rural gasification program using natural gas pipelines to achieve near-universal household access.	Tier 5
Russia	Tailored hybrid systems (PV-wind-diesel) for the Arctic; pioneering floating SMRs (Akademik Lomonosov); geothermal in Kamchatka; large-scale gasification program.	Tier 4-5
Saudi Arabia	Giga-scale, high-reliability solar-plus-storage projects for isolated, high-demand sites like the Red Sea Global.	Tier 4-5
South Africa	Solar mini-grid and SHS pilots to address slow grid rollout and load-shedding, focusing on affordability for the rural poor.	Tier 2-3
UAE	Distributed rooftop PV and storage projects in urban areas, emphasizing 24/7 reliability and technical standardization.	Tier 4-5

The diversity of approaches captured in the Table 3 underscores that there is no single solution to decentralized electrification. The MTF evaluation, when cross-referenced with national electrification rates, reveals a clear stratification where the breadth of access fundamentally influences the potential depth of its quality.

- High-Tier Attainment (Tiers 4-5): This group consists of nations that have achieved universal or near-universal electricity access (Brazil, China, Egypt, Iran, Russia, Saudi Arabia, UAE). Their high MTF tiers reflect an advanced stage of energy development, where the focus has shifted from basic connection to ensuring high-quality, reliable, and productive power. They leverage distinct advantages: Iran's extensive gas grid provides robust service; Saudi Arabia and the UAE deploy giga-scale solar-plus-storage for high-reliability isolated systems; Russia combines grid resilience with a pioneering gasification program and advanced nuclear solutions; while China, Brazil, and Egypt demonstrate strong integration of distributed renewables within a framework of universal access.

- Mid-Tier Advancement (Tiers 3-4): Countries like India and Indonesia have achieved near-universal electrification, and their MTF tiers reflect ongoing efforts to consolidate these gains and improve quality. India's vast market for decentralized renewables addresses last-mile challenges, though variability in reliability places it solidly in Tier 4. Indonesia is actively enhancing its infrastructure through major solar and geothermal rollout plans, bridging the gap towards higher tiers of service.

- Foundational Efforts (Tiers 2-3): South Africa and Ethiopia face significant structural barriers that cap the national average tier. South Africa's progress is severely hampered by persistent load-shedding and grid instability, undermining reliability despite a relatively high access rate. Ethiopia, while demonstrating promising models with solar mini-grids, has the lowest electrification rate in the group, meaning that even successful flagship projects cannot yet elevate the national average above foundational tiers, as a large portion of the population remains without access or with only basic service.

2.3. Clean Cooking

While access to electricity is a critical development metric, the lack of access to clean cooking solutions represents a parallel and often more immediate crisis, with severe impacts on public health, gender equality, and the environment. Addressing this challenge requires a suite of technologies and policies tailored to diverse national contexts, from fossil-based transitional fuels to renewable biogas systems.

India shows how mass inclusion begins. Pradhan Mantri Ujjwala Yojana (PMUY) paired connection subsidies with upfront finance and rapid distribution build-out, delivering 100+ million beneficiary LPG connections with strong refill uptake (India, Ministry of Petroleum and Natural Gas n.d.). The lesson: lower the barrier to the first cylinder and keep refills reliably available. The remaining challenge is sustained refill affordability for the poorest, requiring targeted support and demand-side nudges.

Building from first-connection at scale to industrialized delivery, China demonstrates how coordinated industrial policy, subsidies, and infrastructure can push clean stoves and coal-to-clean conversions toward near-universal coverage by 2030 (IEA n.d.-a). The connective tissue with India is systemic design for scale. A persistent constraint remains in winter-heating regions: local fuel affordability and security. Translating national ambition into community practice, Brazil blends LPG social support (e.g., Gás do Povo) with Sustainable Solidarity Kitchens, deploying efficient, often renewables-linked solutions for community meals and training (Argus Media n.d.; Brazil, SECOM 2024). As in India and China, well-targeted subsidies work best when coupled with local clean-cooking assets that strengthen food security and dignity. Open questions include fiscal sustainability of broad fuel support and dependable logistics to remote areas. With a mature LPG retail base, South Africa offers a mixed market-policy model: functioning LPG supply, urban electric cooking, and targeted stove programs (IEA n.d.-b). The throughline with Brazil is last-mile execution, clear consumer targeting and private distribution capacity, while the hardest problems remain rural affordability and delivery into informal settlements.

Recently, South Africa led the adoption of the “Closing the Clean Cooking Gap” ministerial document during the fourth G20 Energy Transition Working Group (ETWG) meeting (Moloi, 2025). The document establishes voluntary actions for governments, industry, international partners, and civil society to expand access to clean cooking solutions, emphasizing sustainability, affordability, and inclusiveness. The initiative marks a turning point in the continent’s energy agenda, aligning with long-term goals to eradicate urban energy poverty and achieve universal access to modern energy services by 2050.

Where network infrastructure is feasible, Russia leans on rural gasification, expanding pipelines and subsidized household connections for natural gas and LPG. This reduces biomass and coal use where pipelines reach. Planning from a low baseline, Ethiopia anchors its clean-cooking effort in a national sustainable-energy strategy, setting 2030–2035 targets for improved stoves, electrification, and fuel diversification. The link back to India and Brazil is measurement, reporting, and verification (MRV) plus results-linked finance: pay for verified connections, safety, and sustained use to unlock scale in low-income, fragile-logistics settings.

Finally, where LPG or grid solutions are costly or weak, Indonesia illustrates bio-solutions. Biogas Rumah (BIRU) deploys household biodigesters that turn manure into biogas for cooking with fertilizer co-benefits. Its strengths – user ownership, local construction, ready feedstock – also mark its limits: adequate livestock density and accessible upfront finance are prerequisites (Yayasan Rumah Energi n.d.).

In summary, the BRICS case studies reveal that successful clean cooking transitions are not dependent on a single technological silver bullet. Instead, they hinge on strategically aligned policy packages that combine targeted subsidies, robust fuel distribution logistics, and context-appropriate technologies – whether LPG, natural gas, electricity, or biogas – to overcome the unique affordability and infrastructure barriers in each national and local context.

3. Challenges and Opportunities

The pursuit of universal energy access through decentralized systems presents a complex landscape of intersecting challenges and opportunities. While BRICS nations have demonstrated remarkable progress in electrification rates, the multidimensional nature of energy poverty requires addressing not just connectivity but also reliability, affordability, and the availability of modern energy services for productive use.

3.1. Technological Challenges and Opportunities

As outlined in Section 2, many of the implemented projects use cutting-edge technology. The modernization of energy systems has driven innovation but also exposed critical barriers to energy access, particularly in BRICS countries. Key challenges include the fluctuating nature of renewable resources, the cost and short-lived storage solutions, and the complexities of integrating local and distributed energy systems into national grids (Bonan, Pareglio, and Tavoni 2017; BRICS 2024).

In developing countries specifically, a lack of knowledge and technological infrastructure for low-carbon energy development presents a significant barrier (Chigbu and Umejesi 2024; Concessao and Gupta 2022). These barriers lead to reduced system reliability, increased costs, and slow down the transition to clean energy (Anenberg et al. 2013).

Table 4: Technological challenges in BRICS countries for universal access to energy: opportunities and mitigation strategies.

Challenge	Key Issues	Opportunities and Mitigation Strategies
Intermittency and Supply Gaps	Solar and wind generation are inherently intermittent, leading to a mismatch between production and demand, especially in areas with limited backup systems (DMRE n.d.). Without strategic storage deployment, these gaps increase operating costs for decentralized systems (Energy Trend 2024).	Deployment of hybrid systems combining RES with dispatchable sources such as diesel generators, biofuels, or natural gas. Utilization of geothermal energy for baseload capacity in suitable regions (e.g., Indonesia, Russia).
Energy Storage	Current solutions, particularly lithium-ion batteries, remain expensive, representing a significant portion of system costs, and have a limited lifespan (5-7 years), creating a financial burden for low-income households (IISD 2016).	Development of battery recycling and second-life markets, as seen in China and India, to reduce costs and environmental impact. The 93% reduction in storage costs between 2010 and 2024 creates favorable conditions for their wider adoption (IRENA 2025).
Grid Integration	Many rural and peri-urban grids in BRICS countries are outdated and incapable of handling bidirectional electricity flows from distributed sources, leading to voltage fluctuations and instability (Kanagawa and Nakata 2008; Katre, Tozzi, and Bhattacharyya 2019).	Grid modernization and the introduction of smart meters and management systems. Development of common technical standards for mini-grid integration within BRICS.
Technical Support	A shortage of qualified technicians in remote areas for system installation, maintenance, and repair is a major barrier, leading to premature project failures (Kanagawa and Nakata 2008).	Creation of local training and capacity building programs. Use of remote monitoring and diagnostic platforms to support maintenance.

3.2. Financial and Investment Landscape

The financial architecture for decentralized energy access remains inadequate despite promising innovations. The weighted average cost of capital (WACC) has become the dominant factor in project viability in high-interest environments (BloombergNEF 2025), overshadowing even hardware costs. This creates particular challenges for capital-intensive technologies like geothermal and SMRs that require patient capital with longer payback periods.

Opportunities for financial innovation are emerging through BRICS cooperation mechanisms. The New Development Bank (NDB) has demonstrated potential in supporting sustainable energy projects. In Brazil, the NDB's USD 300 million loan to Banco Nacional de Desenvolvimento Econômico e Social (BNDES) enabled lending to renewable and transmission projects, diversifying the energy mix beyond hydropower while maintaining strict environmental and social standards (NDB 2017a). In China, the Lingang Distributed Solar PV Project illustrates how NDB funding can drive industrial-scale decarbonization through distributed solar systems (NDB 2017b). These cases show that leveraging existing BRICS mechanisms, such as the NDB, offers a practical pathway to scale decentralized, inclusive, and sustainable energy access across the bloc.

3.3. Policy and Regulatory Frameworks

Policy fragmentation and underdeveloped licensing for decentralized energy systems in BRICS nations create significant investment risks and uncertainty. Specific regulatory gaps, particularly regarding "grid arrival" protocols, persist even in countries with advanced reforms. For instance, South Africa's Electricity Regulation Amendment Act (2024) fails to introduce a mini-grid licensing tier, while Brazil's robust universalization policies lack standard pathways for interconnecting or buying out private mini-grids (Republic of South Africa 2024; ANEEL 2021). This discourages private investment despite the clear need for such systems.

To overcome these barriers, a concerted effort is needed to adopt transparent tariff methodologies and codified grid-arrival protocols that define compensation and interconnection rights. The recently adopted BRICS Energy Cooperation Roadmap (2025-30) offers a critical platform for this. By aligning standards and sharing best practices – such as Brazil's service quality framework and South Africa's procurement models – member states can create larger markets, reduce costs, and finally provide the regulatory predictability required to scale decentralized energy.

3.4. Social Dimensions and Inclusive Governance

Efforts to implement innovative mechanisms of energy diffusion have led to a proliferation of experiments designed to identify effective pathways for local governance. Bottom-up approaches, sensitive to local needs and development trajectories, have shown particular success in including energy-excluded populations and decentralizing provision, thereby fostering community empowerment. At the same time, multi-partner governance models have demonstrated efficacy by mobilizing hybrid networks of actors (researchers, non-governmental organizations (NGOs), civil society organizations, and state agencies) toward collaborative energy transitions.

The social acceptance of new energy technologies varies considerably across communities and technologies. While solar systems have gained widespread acceptance, other options like nuclear and waste-to-energy face greater public skepticism, with evidence from rural communities in India (Sharma 2020) shows that communities' receptiveness to new technologies varied according to economic, political, and educational backgrounds. This case underscores the centrality of trust-building in alternative energy sources and new governance models. Community engagement can generate a "strong sense of ownership," which is essential for building effective governance structures (Katre, Tozzi, and Bhattacharyya 2019).

Gender remains a decisive factor. Persistent inequalities constrain women's participation in household and community energy governance. Programs such as India's PMUY illustrate how gender-sensitive approaches can reduce adoption barriers while enhancing agency. By granting LPG connections directly to women in low-income households, PMUY both expanded clean cooking access and strengthened women's capacity for decision-making and asset ownership (Kelkar and Nathan 2021). Such initiatives reposition women as active stakeholders across the energy value chain (ESMAP 2018).

Acknowledging the social dimension in all its complexity requires treating citizens and their social environments, encompassing culture, social norms, power relations, and community structures, not as passive recipients of infrastructure, but as protagonists of energy transitions.

4. Conclusion and Recommendations

4.1. Conclusion

This analysis confirms that addressing energy poverty requires moving beyond binary metrics of electrification to embrace a multidimensional understanding of energy access that encompasses reliability, affordability, and the capacity for productive use. The technologically neutral approach adopted in this study reveals that no single solution can address the diverse energy needs across BRICS nations – instead, a strategic portfolio of solar, wind, geothermal, transitional fuels, bioenergy, and emerging nuclear technologies must be deployed in configurations tailored to local contexts and resource endowments.

Three fundamental insights emerge from this analysis. First, energy access serves as a critical enabler across multiple development domains – from health and education to gender equality and economic opportunity. Second, technological diversification enhances energy security by reducing overreliance on single solutions and enabling resilience through complementary systems. Third, BRICS cooperation mechanisms – particularly the New Development Bank (NDB) and BRICS Energy Research Cooperation Platform (ERCP) provide ready-made vehicles to accelerate progress through coordinated action.

Despite promising advances, significant challenges remain in financing, regulatory harmonization, social inclusion, and technology integration. The persistence of multidimensional energy poverty even amid rising electrification rates underscores the need for more comprehensive approaches that address clean cooking, productive use, and regional disparities. By adopting the integrated recommendations below, BRICS nations can transform these challenges into opportunities for leadership in the global energy transition.

4.2. Recommendations

1) Foster Technological Diversification through Joint Research and Collaboration – leverage the existing ERCP workstreams to initiate joint research programs and explore opportunities for knowledge-sharing and collaboration on a diverse set of decentralized energy technologies. This should include:
- Research on hybrid systems and grid integration.
- Research on circular economy for energy storage: battery recycling and second-life applications.
- Joint feasibility studies for less-established technologies, including but not limited to geothermal energy, advanced bioenergy systems etc.

2) Strengthen Financing Mechanisms for Inclusive Energy Access – expand the NDB's mandate to include a dedicated financing window for decentralized energy access, incorporating three key elements:
- Blended finance structures that combine public capital with private investment to address the high upfront costs of diversified energy systems, particularly for storage-intensive and capital-intensive technologies.
- Technical assistance facility to help project developers prepare bankable proposals and build implementation capacity, especially for newer technologies with less established business models.
- Results-based financing components that incentivize not only energy connections but also reliability metrics and productive use applications, ensuring developmental impact beyond basic access.

3) Harmonize Regulatory Frameworks Across Technologies – accelerate the development of the BRICS Model Mini-Grid Code through the ERCP, with expanded scope to encompass the full technological portfolio:
- Technology-specific standards for interoperability and safety across solar-storage hybrids, natural gas micro-grids, bioenergy systems, and future SMR deployments.
- Transparent "grid arrival" protocols that define rights and responsibilities when main grid expansion reaches areas served by decentralized systems, protecting both investor interests and consumer rights.
- Mutual recognition of equipment certifications to create integrated BRICS markets for energy technologies, reducing costs through economies of scale while maintaining quality benchmarks.

4) Mainstream Social Inclusion and Local Capacity Building – integrate inclusive design principles across all BRICS energy initiatives, with particular attention to:
- Gender-sensitive implementation that expands on successful models like India's Ujjwala Yojana by ensuring women's participation in technology selection, governance, and economic opportunities throughout the energy value chain.
- Community engagement protocols for newer technologies like SMRs and waste-to-energy systems that incorporate local knowledge, address concerns proactively, and ensure equitable benefit sharing.
- Capacity building programs focused on developing local technical expertise for operating and maintaining diverse energy systems, creating sustainable local jobs while ensuring system longevity.

Sustainable Fuels for Energy Transitions

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1. Introduction and Scope Clarity

The global energy landscape is undergoing a profound transformation, driven by the imperative to meet climate goals under the Paris Agreement and the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). This transition involves a strategic shift towards diverse energy carriers and a critical re-evaluation of fuel sustainability. Achieving universal access to affordable, reliable, and sustainable energy, as advocated by SDG 7, is challenging due to the complex shift from traditional fossil fuels to cleaner modern technologies (BRICS, 2024).

This urgent global shift has developed over decades. Initial concerns about fossil fuel dependence came from the 1970s oil crises, which highlighted energy security risks. Later, the focus grew to include environmental sustainability, supported by global agreements like the Kyoto Protocol (1997) and the Paris Agreement (2015). Recent geopolitical tensions and technological advances have further accelerated efforts to diversify energy sources and reduce import dependence. This transition is vital not only for climate protection but also for long-term economic and geopolitical stability.

The BRICS bloc plays a key role in this transition. Together, these countries produce over 40% of the world's oil and hold 53% of its natural gas reserves (Climate Ambition BRICS 2024; Bricspolicycenter.org). Initiatives like the BRICS Energy Cooperation Plan (2025–2030) show a commitment to a just, affordable, and realistic energy transition. This plan aims to clarify rules, attract clean energy investment, and maintain competitiveness while respecting each nation's unique circumstances.

A central challenge is the absence of a common global definition for "sustainable fuels." While key criteria often include renewability, significant lifecycle greenhouse gas (GHG) reduction, and socio-economic impacts (Arias et al. 2024; Malik, Bhatia, and Srinivasan 2024; Oloyede et al., 2023), definitions vary widely. Debates continue about the boundaries of "sustainable," particularly concerning indirect land use and feedstock sourcing (Jaccard 2001; Andersson, Brynolf, et al. 2020; Hansson, Fridahl, and Bryngelsson 2019). In academic and policy discussions, these fuels are often defined by their renewable origins (Reddy, Mohan, and Tiwari 2023; Arias et al. 2024). However, a narrow focus on renewables can ignore practical transitional pathways. Many major economies use their existing fossil fuel infrastructure as part of their decarbonization strategies.

This chapter uses a broader, technologically neutral framework. In this view, a fuel's sustainability depends on how it is used and the technology that reduces its environmental impact, not just its origin. Therefore, we conceptualize 'sustainable fuels' as a portfolio of decarbonization strategies. This approach shifts the focus from a fuel's origin to its net climate impact. It also ensures the pathway does not harm national economies, regional living standards, or create uncompetitive environments.

Consequently, the category of sustainable fuels encompasses a diverse array of options, including but not limited to biofuels, synthetic fuels, hydrogen, ammonia, and critically, natural gas and other fossil fuels when integrated with carbon capture, utilization, and storage (CCUS) and other abatement technologies. The scope does not include renewable electricity sources like solar, wind, and hydropower, as these are covered in another chapter ("Technological Advancements for Low-carbon Power Systems"). Instead, the analysis focuses on consumable fuels that use decarbonization strategies.

2. Overview of Current Issue and Recent Trends

This chapter analyzes sustainable fuels through a technologically neutral lens, evaluating options based on their lifecycle greenhouse gas (GHG) emissions, cost, and applicability, rather than their origin. The core sustainable fuel families for decarbonizing the BRICS bloc are hydrogen, biofuels, and carbon-abated fossil fuels. Each family offers distinct pathways and must be understood comparatively to assess its strategic role.

The following Table 5 provides a high-level comparative analysis of these three fuel families, highlighting their relative advantages and potential niches within the complex energy systems of BRICS countries.

Table 5: Comparative analysis of sustainable fuel families for BRICS.

Feature	Hydrogen	Biofuels	Fossil Fuels with CCUS
Key Advantage	Versatility; enables decarbonization of hard-to-abate sectors (industry, heavy transport).	Drop-in solution for liquid fuel infrastructure; utilizes organic waste streams.	Leverages existing fossil assets and infrastructure for a lower-carbon transition.
Key Challenge	High infrastructure costs for transport & storage; low energy density by volume.	Land-use concerns; feedstock availability and sustainability; potential food-vs-fuel conflict.	High capital expenditure (CAPEX); long-term storage verification and liability; energy penalty for capture.
Primary Niche in BRICS Energy Balance	Industrial feedstock (refining, chemicals), green steel, heavy-duty freight, seasonal energy storage.	Road transport fuel blending, aviation (SAF), maritime, decentralized power generation.	Decarbonizing existing power plants, cement and steel production, blue hydrogen production.

2.1. Hydrogen

Hydrogen is increasingly seen as a key part of the global shift to sustainable energy. It is important because it can store and deliver clean energy, making it a transformative solution for reducing fossil fuel dependence (Hydrogen Council 2017). Many sectors can use hydrogen to decarbonize, including long-haul transport, shipping, aviation, utilities, and the metal industry. Hydrogen systems offer several advantages, such as very low emissions, versatile applications, and lower storage costs compared to batteries (Aris and Shabani 2015).

Conventional methods for producing hydrogen, like steam methane reforming (SMR) of natural gas (producing "grey" hydrogen) and gasification of coal (producing "brown" or "black" hydrogen), are well-established (Nikolaidis and Poullikkas 2017), but have a significant carbon footprint. To reconcile this high emissions profile with climate goals, newer pathways and classifications have emerged, as shown in Figure 6.

Newer production pathways have emerged to align with the broader definition of sustainable fuels. These newer methods integrate renewable electricity or carbon abatement technologies. For example, green hydrogen is produced via electrolysis using renewable energy, offering a zero-carbon option. Blue hydrogen uses traditional reforming combined with CCUS to cut emissions. Therefore, the sustainability of hydrogen depends on its overall lifecycle emissions and the technology used to reduce its impact, not just the production method.

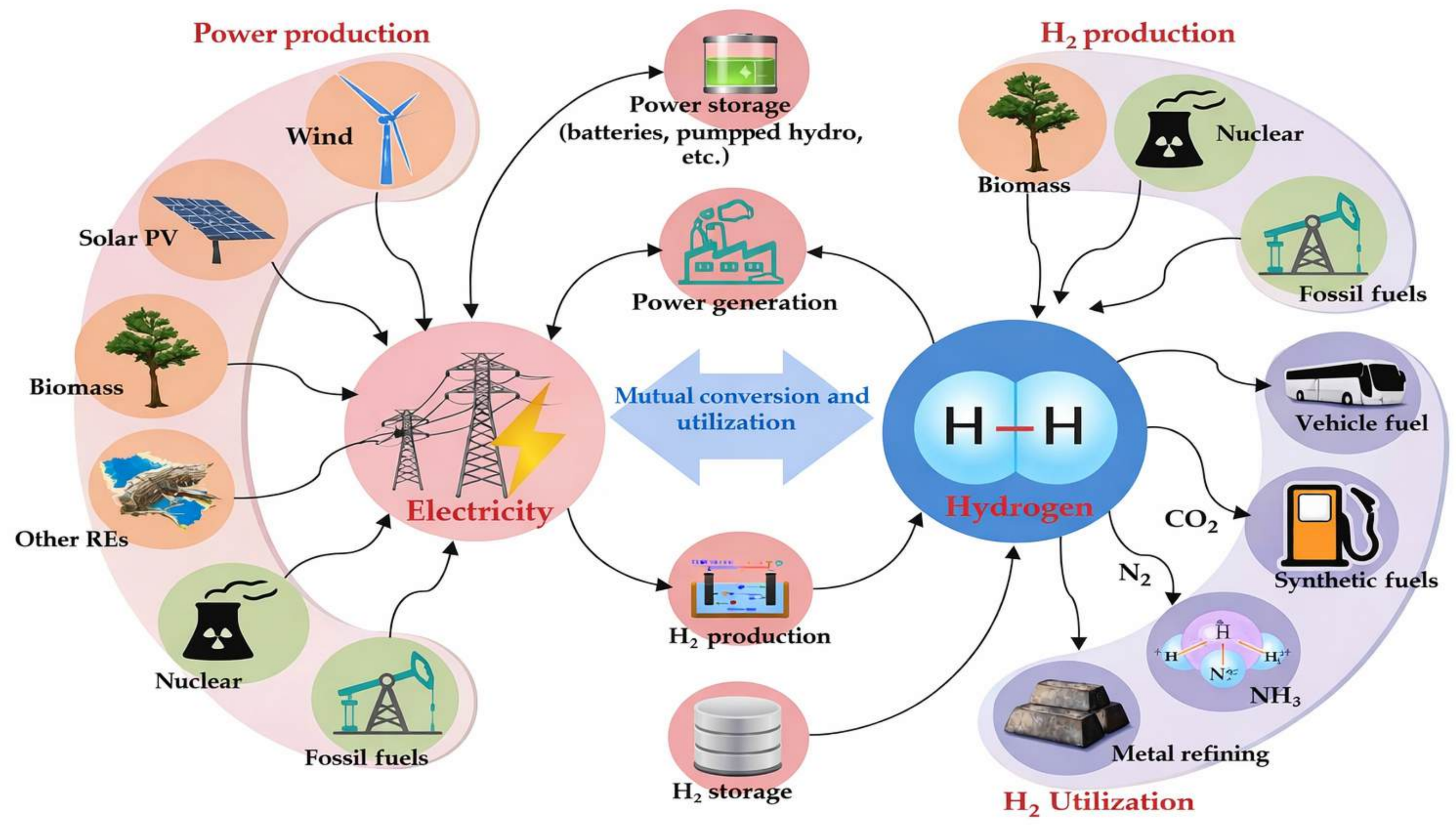

Figure 6 **Hydrogen Cycle.**

Sources: Nikolaidis and Poullikkas 2017.

A comparative analysis of national hydrogen strategies within the BRICS in Table 6 reveals fundamentally divergent pathways, shaped by each country's unique resource endowment, economic structure, and geopolitical goals.

Table 6: BRICS Hydrogen Strategies Overview.
Source: Abdoos et al., 2025; Aziz et al. 2024; BRICS 2024; Benziane and Zaghdoud 2025; DSI South Africa 2021; Egypt Oil & Gas n.d.; Ministry of Energy and Mineral Resources, Indonesia 2023; Indonesia Ministry of Energy and Mineral Resources 2025; Ministry of Energy and Infrastructure, UAE 2023; Ministry of Energy of the Russian Federation 2021; Ministry of Mines and Energy of Brazil 2022; Ministry of New and Renewable Energy, India 2023; Naranjo-Silva 2025; NDRC and NEA 2022.

Country	Vision	National Strategy	Potential Niche in Energy Balance	Country Conclusion
Brazil	Competitive low-carbon hydrogen economy.	National H2 Program promotes R&D, market growth, and global cooperation. Focus on green H2.	Decarbonizing fertilizers & chemicals; green ammonia for export; biofuels refining.	Aims to use its vast clean energy potential; prioritizes market development and collaboration.
China	Hydrogen for energy security and climate goals.	2021–2035 plan for transport, storage, and industry integration. Mix of green, blue, and by-product hydrogen.	Clean transportation; industrial feedstock; balancing renewable grid.	Focuses on scaling low-carbon hydrogen to support energy security and deploy 50,000 hydrogen vehicles by 2025.
Egypt	Regional clean hydrogen exporter.	2024 Low-Carbon Hydrogen Strategy for industrial and transport use.	Export of green hydrogen/ ammonia to Europe; decarbonizing domestic industry and transport.	Plans to use solar and wind for export-oriented hydrogen, boosting GDP and creating jobs by 2040.
Ethiopia	Use renewable potential for green hydrogen.	Policy taskforce developing national framework.	Leveraging hydropower for domestic industrial decarbonization and potential export.	Uses hydropower to enter the hydrogen market; has issued its first national hydrogen license.
India	Energy-independent global hydrogen hub.	National Green Hydrogen Mission for exports, sector decarbonization, and local manufacturing.	Refining, fertilizers, heavy industry; replacing grey H2 in existing uses.	Seeks to become a global hub by 2030, generating jobs and investment through low-cost production.
Indonesia	Self-sufficient, net-zero (2060), major hydrogen player.	Hydrogen & Ammonia Roadmap 2025–2060 (3 phases).	Export of green ammonia; using geothermal and biomass; domestic industry decarbonization.	Implements a phased roadmap, targeting significant annual production and job creation.

Country	Vision	National Strategy	Potential Niche in Energy Balance	Country Conclusion
Iran	Leverage renewable resources for a sustainable hydrogen economy.	No formal strategy yet. Research focuses on green H_2 from solar/wind, with blue as transitional.	Export-oriented green hydrogen/ammonia; decarbonizing industry; leveraging existing infrastructure.	Possesses solar potential but faces regulatory gaps, high costs, and sanctions.
Russia	Leader in hydrogen export and low-carbon industry.	2021 roadmap to 2050 for export diversification. Focus on blue and yellow hydrogen.	Export to Europe and Asia; decarbonizing gas via H2 blending; domestic refining.	Leveraging fossil fuel infrastructure and nuclear capacity for an export-oriented sector.
Saudi Arabia	Global hydrogen superpower and export leader.	Part of Vision 2030 and the Saudi Green Initiative. Strategy includes green and blue hydrogen.	Export of green ammonia; decarbonizing operations; producing synthetic fuels.	Aims to be a top supplier by leveraging resources, capital, and location.
South Africa	Key part of energy transition and decarbonization.	Hydrogen Society Roadmap for exports, clean power, and transport.	Green ammonia for export; synthetic fuels; decarbonizing mining sector.	Vital to its just energy transition, targeting significant green hydrogen production by 2030.
UAE	Net-zero 2050 cornerstone.	Hydrogen Strategy 2050 positions UAE as major producer by 2031.	Export of green hydrogen/ ammonia; decarbonizing operations and heavy industry.	Aims to become a leading low-emission supplier with clear production goals.

The analysis identified 3 distinctive approaches of BRICS countries to the hydrogen development:

One clear pathway is that of the Export-Oriented Diversifiers, such as Russia, Saudi Arabia, and the UAE, with Egypt also aligning with this model. These nations are leveraging their existing fossil fuel infrastructure, financial capital, and strategic location to maintain their status as global energy suppliers. Their focus on blue hydrogen (from natural gas with carbon capture) and, in Russia's case, yellow hydrogen (from nuclear power), allows for a rapid market entry by decarbonizing existing energy exports like natural gas and oil, thereby managing the risk of stranded assets.

In contrast, the Green Industrialists – including Brazil, India, South Africa, Indonesia, and Ethiopia – are betting on green hydrogen as a tool for economic development and energy security. For countries like India and Brazil, it is a means to reduce costly fossil fuel imports and decarbonize heavy industry (e.g., fertilizers, refining, steel). For South Africa and Indonesia, it is central to a "just transition" and net-zero goals, aiming to create hundreds of thousands of jobs and build a new industrial export sector centered on green ammonia and synthetic fuels.

China stands out as the Scalable Pragmatist, pursuing a characteristically comprehensive strategy. By developing green, blue, and hydrogen from industrial by-products, it aims to achieve scale and cost-reduction in the shortest time possible. Its primary drivers are energy security and technological dominance, using its massive domestic market – including a target of 50,000 hydrogen vehicles by 2025 – to bootstrap its entire hydrogen value chain. Meanwhile, Iran's situation highlights the critical role of governance; despite immense solar potential, its progress is paralyzed by a lack of a formal strategy and severe external constraints like sanctions.

Underlying this divergence is a core strategic dilemma: the choice between a transitional pathway that leverages existing assets for faster market entry versus a transformative, green-focused pathway that builds a new energy system for long-term leadership. The collective efforts of these nations will significantly shape the global hydrogen landscape, with their success hinging on forging new technological partnerships and creating vibrant, interconnected markets for low-carbon energy.

2.2. Biofuels

Bioenergy is a form of renewable energy generated from burning biomass. Biomass includes organic materials like wood, animal waste, and agricultural residues. The main technologies for processing biomass are: combustion, fermentation, gasification, anaerobic digestion, and pyrolysis. These processes create different types of biofuels for various applications. Biofuels fall into three main categories: solid, liquid, and gaseous (IEA Bioenergy 2024).

Globally, about 105 billion tons of organic waste are generated each year, but only 2% is currently processed. The World Biogas Association estimates that the biogas industry could reduce global greenhouse gas (GHG) emissions by up to 10% by 2030, showing its key role in fighting climate change. Furthermore, bioenergy can be produced locally from existing biomass (World Biogas Association 2023). This provides rapid access to energy without needing extensive infrastructure or large capital investment. This makes bioenergy a viable and cost-effective solution for rural communities with limited access to centralized energy. Currently, bioenergy provides about 6% of global energy, but according to IEA Net Zero Scenario, this share could reach 20% by 2050 (IEA 2023a).

As Table 7 below shows, the trajectory of biofuel development in the BRICS bloc is not uniform.

Table 7: BRICS Biofuel Strategies Overview.
Source: AbdelMeguid et al. 2023; ANP 2024; IEA Bioenergy n.d.; IESR 2024; India, MNRE 2023; Kononova, Mineeva, and Sladkovskii 2023; Mekonnen, Beyene, and Melesse 2016; RREDA 2024; South Africa, DMRE 2007; Li 2024; UAE, The Cabinet n.d.

Country	Biofuel Vision & Strategy	Feedstocks & Policy Levers	Potential Niche in Energy Balance	Country Conclusion
Brazil	Global leader in liquid biofuels; competitive low-carbon economy.	National Strategy: RenovaBio; Fuel of the Future Law. Feedstocks: Sugarcane, corn, soybeans, 2G from bagasse, biomethane. Mandates/Incentives: E30, B15; tax benefits.	Displacing gasoline in light-duty transport; aviation (SAF); biodiesel for trucks.	Aims to maintain global leadership, leveraging agro-industrial base to decarbonize transport and expand into new markets.
China	Scale up biofuels for energy security and environmental goals.	National Strategy: 14th Five-Year Plan; Action Plan for Carbon Peaking. Feedstocks: Corn, cassava; shifting to cellulosic biomass, waste oils, MSW. Mandates/Incentives: E10 regionally; incentives for 2G sources.	Waste-to-energy; reducing emissions in road transport; bio-jet fuel.	Focuses on utilizing waste streams and scaling production to reduce emissions in large transport market.
Egypt	Develop domestic biofuel sector for waste management and energy diversification.	National Strategy: Egypt Vision 2030; Waste Management Law. Feedstocks: Molasses, sugarcane, UCO, agri residues. Mandates/Incentives: Supportive green investment environment; no mandate yet.	Decentralized power generation; waste management for biogas; reducing agricultural waste.	Has significant potential from agricultural residues, but development is at early stage.
Ethiopia	Leverage agriculture for energy access and economic development.	National Strategy: National Biofuel Strategy (2024). Feedstocks: Agricultural residues, sugarcane, jatropha. No nationwide mandate yet.	Rural energy access; decentralized power generation; reducing reliance on imported fuels.	Emerging player with strong biomass potential, using biofuels for rural development and energy security.
India	Achieve energy independence and reduce oil import bills.	National Strategy: National Green Hydrogen Mission; Ethanol Blended Petrol Programme. Feedstocks: Non-food crops, UCO. Mandates/Incentives: E20; 5% biodiesel by 2030; excise duty exemptions.	Reducing oil import dependence in road transport; managing agricultural waste.	Rapidly growing biofuel market, using policy to create demand and manage waste.
Indonesia	Maximize palm oil resources for energy security and export.	National Strategy: National Energy General Plan; Biofuel Development Roadmap. Feedstocks: Palm oil, agricultural residues. Mandates/ Incentives: B30; B40 from 2025; price support, VAT exemptions.	Domestic energy security via biodiesel; export of biofuels and derivatives.	World leader in biodiesel with strong resource-based strategy, facing sustainability challenges.
Iran	Explore biofuels for energy diversification and waste valorization.	No formal national biofuels strategy yet.	Rural and off-grid heating; power generation from agricultural waste.	Possesses theoretical potential but hampered by lack of strategic framework and regulatory barriers.
Russia	Unlock vast biomass potential for decarbonization and industry development.	National Strategy: Biofuels in state industrial development program (2024). Feedstocks: Agricultural and forest residues; wood pellets. Mandates/ Incentives: State support for producers; no nationwide mandate.	Decarbonizing remote heat and power generation; potential for biodiesel and biomethane.	Enormous resource potential but late-mover, with strategy in infancy focusing on pilot projects.
Saudi Arabia	Diversify energy sources and explore circular carbon economy.	National Strategy: Vision 2030. Feedstocks: Used Cooking Oil (UCO). Mandates/Incentives: No nationwide mandate or publicized tax incentives.	Waste-to-energy initiatives; potential production of Sustainable Aviation Fuel (SAF).	Initial focus on waste-derived feedstocks, with potential to scale up pending stronger policy.
South Africa	Foster just transition and rural development through biofuels.	National Strategy: Biofuels Industrial Strategy (2007). Feedstocks: Sugar, oilseeds, livestock waste. Mandates/ Incentives: Fuel excise exemption for ethanol; 50% biodiesel levy rebate; no mandate.	Rural energy access; waste management; potential for sustainable aviation fuel (SAF).	Progress slow due to policy uncertainty but retains potential for just transition.
UAE	Position as hub for advanced green fuels, including biofuels.	National Strategy: National Policy on Biofuels (2024); Net Zero 2050 Strategy. Feedstocks: Imported UCO. Mandates/ Incentives: Proposed export tax on UCO; no domestic mandate.	Export of advanced biofuels; decarbonizing aviation and maritime transport.	Aiming to become key trading and production hub for advanced biofuels.

The comparative analysis of BRICS national strategies in biofuel energy reveals three clear and distinct development models within the BRICS bloc, each defined by a unique interplay of agricultural resources, policy maturity, and strategic focus.

- Established Biofuel Giants (Brazil, Indonesia): These nations have built powerful, export-oriented biofuel industries rooted in highly efficient agricultural production. Brazil, producing 22% of global liquid biofuels, supplies 25% of its transport fuel through robust frameworks like RenovaBio. Indonesia's biodiesel industry exemplifies advanced policy implementation, leveraging its palm oil resources for both domestic energy security and export..

- Large-Scale Domestic Markets (India, China): The strategy here is primarily inwardly focused. Biofuels are leveraged as a strategic tool to enhance energy security and reduce import dependency. India, the world's third-largest ethanol producer, has achieved major progress through its Ethanol Blended Petrol (EBP) Programme, which reduces oil imports and manages agricultural waste. China's biofuel sector, while currently contributing less than 1.5% of transport fuels, is pursuing growth under its 14th Five-Year Plan, focusing on waste streams like MSW and used cooking oil.

- Emerging Players with Potential (South Africa, Saudi Arabia): This group possesses significant feedstock resources but has developed more slowly. South Africa's Biofuels Industrial Strategy from 2007 has seen slow implementation, while Saudi Arabia's initial focus remains on used cooking oil (UCO) as part of its Vision 2030 diversification agenda. Their future success is critically dependent on implementing consistent and supportive regulatory frameworks to unlock this latent potential.

In summary, the trajectory of biofuel development in the BRICS bloc is a function of the synergy between national resource endowments and the quality of the policy environment. While some countries are already reaping the economic and environmental benefits of mature industries, others are still in the process of building the necessary foundations to capitalize on their natural advantages.

2.3. Best Practices in Fossil Fuel Decarbonization across BRICS

Adhering to the principle of technological neutrality is crucial when evaluating pathways to a sustainable energy future. Fossil fuels currently form the backbone of many BRICS economies, providing energy security and supporting critical industries. A pragmatic transition strategy, therefore, focuses not on immediate abandonment but on active decarbonization, leveraging technologies to mitigate environmental impact while maintaining economic stability. For example, China's "Two Capabilities and One System" approach to energy security exists alongside a significant coal sector, which is being modernized through "smart" coal mines and clean coal use, with coalbed methane extraction reaching nearly 12 billion m³ in 2023 (BRICS 2024). In India, energy transition pathways are set against a backdrop where the country is rapidly scaling up renewable capacity but also continues to navigate its relationship with coal, a historical mainstay for power generation (BRICS 2024).

The Strategic Role of Natural Gas as a Transition Fuel

A key pillar of this pragmatic approach is the increased use of natural gas. Forecasts, including those from the Gas Exporting Countries Forum (GECF) in 2024, indicate global gas demand is expected to rise by 32% by 2050, with gas becoming the world's second-largest energy source (GECF 2025).

This growth is driven by gas's abundance, affordability, and environmental advantages, notably its lower capital intensity versus renewables. Natural gas provides reliability and flexibility for seasonal and peak demand balancing, which is essential for supporting the integration of variable renewable sources like wind and solar. Furthermore, it offers decarbonization pathways for hard-to-abate sectors such as heavy transport (including maritime), industry (steel, cement), and residential heating, where direct electrification remains challenging. Consequently, several BRICS nations are strategically expanding gas infrastructure and consumption as a core component of their energy transition strategies, often using it to displace more carbon-intensive fuels like coal and oil.

Brazil's Ten-Year Energy Expansion Plan (PDE 2032) forecasts natural gas production reaching about 323 million m³/day in ten years (BRICS 2024). The "Gas for Employment" program promotes domestic natural gas use, aiming to increase supply and integrate natural gas into the national energy transition strategy (BRICS 2024). The Brazilian Energy Research Company (EPE) identifies natural gas as crucial for grid flexibility and security, especially after the 2021 water crisis, where its share in electricity generation reached 12.8% (BRICS 2024). The sector sees natural gas as superior for replacing more polluting sources and as a transition fuel for biogas, biomethane, and low-carbon hydrogen (BRICS 2024).

While rapidly expanding renewables, China has also significantly increased its domestic natural gas production, which exceeded 230 billion m³ in 2023, growing for seven consecutive years (BRICS 2024). The country views natural gas as a key component of its "Two Capabilities and One System" approach to enhance energy security (BRICS 2024).

Egypt has made a strategic commitment to natural gas as a cleaner fuel. Following gas self-sufficiency in 2018, consumption has more than tripled since 1999/2000 (BRICS 2024). Infrastructure rollout has connected 15 million households (62 million citizens) to the gas network, with 1.2 million connections per year recently (BRICS 2024). Furthermore, about 540,000 vehicles have been converted to run on CNG, displacing petroleum products (BRICS 2024). The role of gas is also pivotal in Egypt's ambition to become a regional energy hub and reducing consumption of petroleum products in favor of decarbonized natural gas (BRICS 2024).

India's energy strategy focuses on achieving energy independence by 2047, with diversification of energy resources as a key pillar (BRICS 2024). This diversification includes a role for natural gas as a cleaner fossil alternative.

Indonesia is pursuing strategies to increase natural gas use primarily to meet growing domestic demand and enhance energy security. While complete replacement of coal with gas faces challenges, the country is developing gas infrastructure and exploring coal-to-gas conversion (ACE 2022).

As a major holder of hydrocarbon reserves, Iran's position emphasizes technological neutrality and facilitating investment in energy infrastructure (BRICS 2024). The country defends its right to develop its gas resources as part of a just transition.
Russia supports a "balanced and constructive approach" to the energy transition, allowing continued development of all energy sources (BRICS 2024). The strategic expansion of natural gas, particularly as a lower-carbon alternative to coal, is a logical component of this approach.

Facing high dependence on coal, South Africa's Just Energy Transition (JET) framework represents a comprehensive approach to addressing climate change, energy security, and affordability (BRICS 2024). Natural gas is likely to be considered crucial for grid stability and phasing out coal, though the report calls for access to financial capital and technology (BRICS 2024).

The UAE, led by ADNOC, is expanding its natural gas role, with current production around 3.2 million barrels of oil equivalent per day and ambitions to reach 5 million bpd by 2027 (InfoBRICS 2025).

In conclusion, the BRICS bloc demonstrates a strong, pragmatic reliance on natural gas as a strategic transition fuel. It is actively used to enhance energy security, provide. grid flexibility for renewables, and directly displace coal and oil, thereby serving as a key tool for immediate decarbonization within a diverse energy portfolio

Carbon Capture, Utilization, and Storage (CCUS) as a Key Enabler

For existing coal and gas infrastructure, Carbon Capture, Utilization, and Storage (CCUS) is an indispensable technological solution for deep emissions reductions. CCUS development involves a four-stage process: capture, transport, utilization, and storage, which includes liquefaction, conditioning, and injection into geological formations. Its implementation is complex and depends on global demand, storage availability, and supportive policies.

The scale of the challenge underscores CCUS's critical role. According to the International Energy Agency (IEA 2021a), under the Net Zero Emissions (NZE) scenario, global CO_2 emissions in 2025 are still projected at around 30 gigatonnes (Gt), highlighting the massive reductions required in subsequent decades.

Global deployment of CCUS is accelerating significantly. The Global CCS Institute reports a 54% increase in the number of operational facilities in 2025. Between 2023 and 2024, the number of facilities in early development doubled, while operational facilities remained relatively stagnant (Global CCS Institute 2025). Among major players, China, a BRICS member, ranked among the global top five CCUS leaders in 2024, marking a significant step in global deployment. Global carbon capture capacity has continued to grow since 2019, with approximately 57% of total capacity still under construction (Global CCS Institute 2025).

Readiness for CCUS varies across the bloc. In 2024, several BRICS countries introduced new CCUS regulations; India and China are pursuing incentives, while Brazil, Indonesia, Saudi Arabia, and Egypt are developing regulations for CCUS hubs. Among emerging economies, Brazil and China are the most advanced, with Technology Readiness Levels (TRLs) between 6–9, indicating relatively stronger industry readiness.

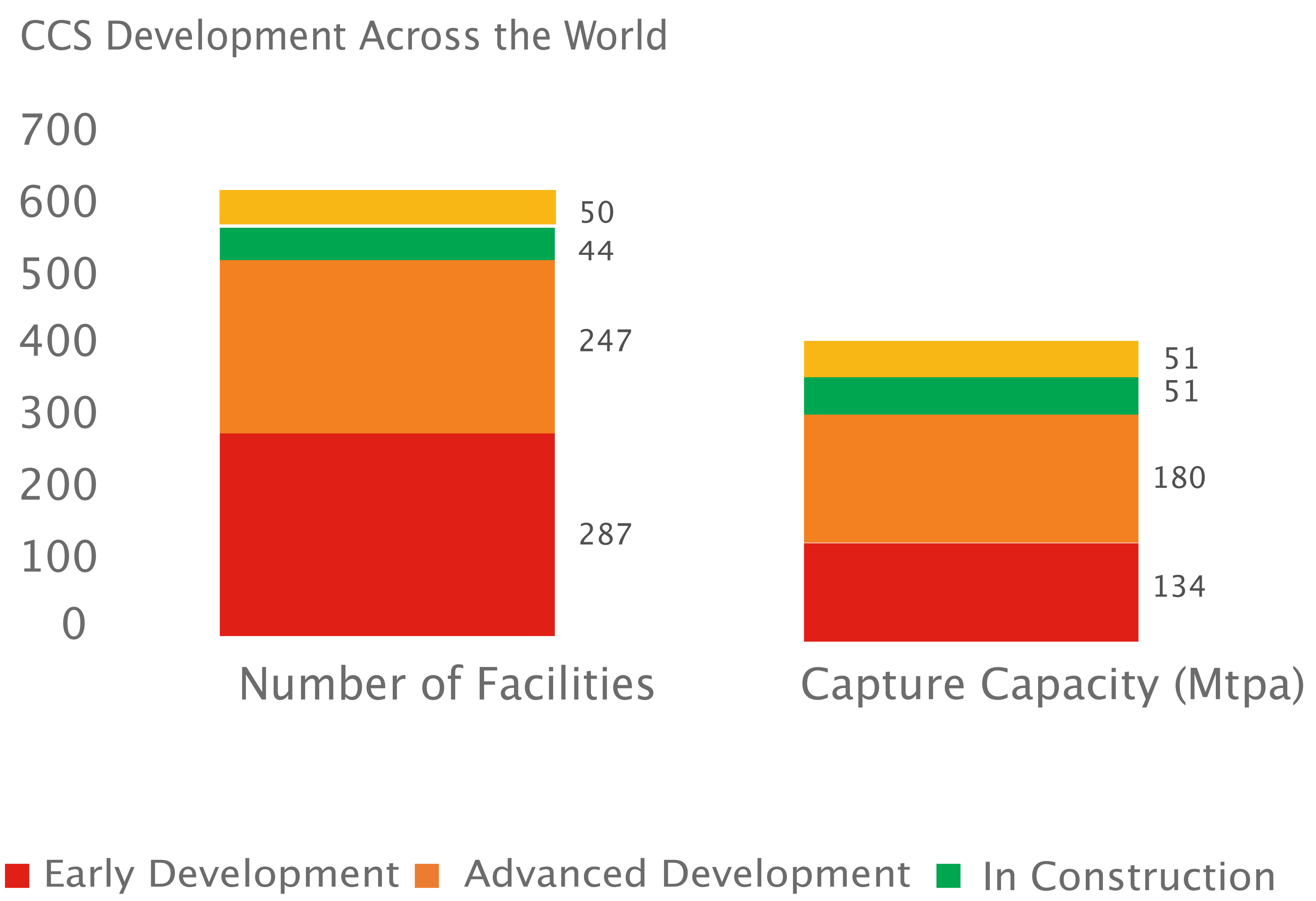

Figure 7 **CCS Development across th world**

Sources: Global CCS Institute 2024

The BRICS report provides specific evidence of this technological push. In Brazil, a significant portion of CO2 from pre-salt offshore production is re-injected, reaching 53% of gross production volume in 2023. This practice is used as a solution for removing high levels of CO2, enhancing oil recovery, and maintaining reservoir pressure (BRICS 2024). Furthermore, Brazil's Energy Research Company (EPE) has identified CCUS as a key low-carbon solution to be integrated into the national energy transition strategy, with over 1 billion reais allocated for R&D in 2024 alone for projects related to carbon capture, among other technologies (BRICS 2024).

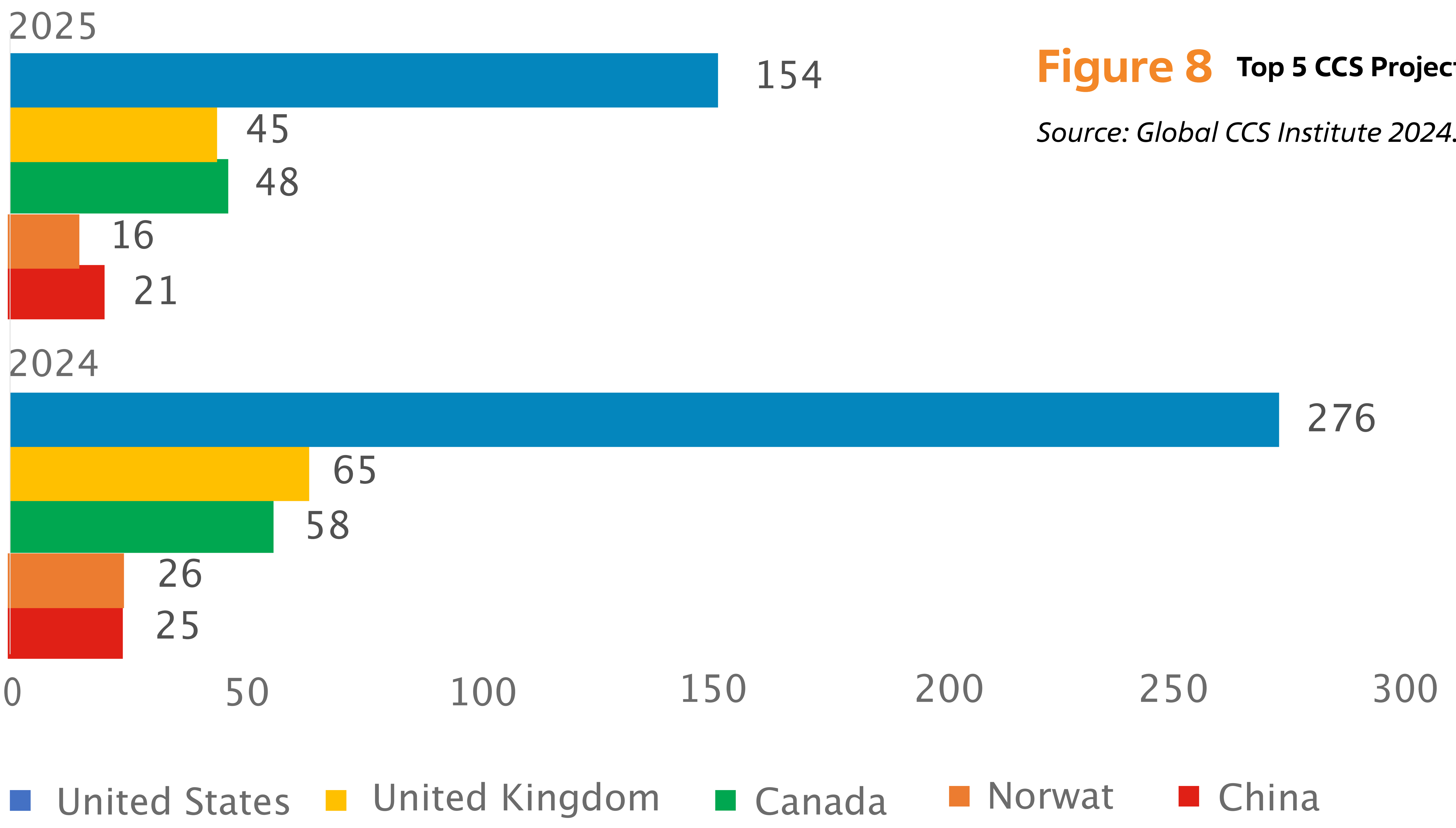

Figure 8 **Top 5 CCS Projects in the World.**

Source: Global CCS Institute 2024.

Table 8. CCS Readiness across BRICS Countries.
Note: The ranging based on commercial, transport, utilization, using BRICS 2024; IEA 2023b; Nkundukize Prime, Moyo, and Govender 2023; OGC 2021.

Country	Policy	Legal & Regulatory Framework	TRL Level (Range)*
Brazil	✓	✓	6-9
China	✓	✓	6-9
Egypt	✓	(✓)	5-7
Ethiopia	(✓)	(✓)	4-8
India	✓	✓	4-8
Indonesia	✓	✓	4-7
Iran	(✓)	(✓)	2-6
Russia	(✓)	(✓)	5-9
Saudi Arabia	✓	✓	3-7
South Africa	(✓)	(✓)	6-9
UAE	✓	✓	8-9

Moreover, BRICS countries are actively moving from planning to implementation, deploying a diverse portfolio of projects that extend beyond CCUS to include fuel switching, operational improvements, and innovative coal processing, as shown in table below.

Table 9. Decarbonization Case Studies in the Fossil Sector across BRICS.
Source: BRICS 2024; Shanxi Daily 2025; NITs Kuzbass 2025; Sharma et al. 2025; Tehran Times 2025; Petrobras 2023.

Country	Policy	Policy	Sector	TRL Level (Range)*
Brazil	Pre-Salt CO2 Reinjection	Oil & Gas	Re-injecting CO_2 from offshore pre-salt fields, achieving a 53% re-injection rate of gross production in 2023 for EOR and storage	Leveraging existing oil expertise for emissions reduction; leader in bioenergy and hydropower. Actively funding R&D for CCUS technologies.
China	"Green" and Low-Carbon Transition	Coal & Industry	Developing "smart" coal mines and escalators, and promoting clean and efficient coal use. Coalbed methane extraction reached nearly 12 billion m^3 in 2023	Global leader in renewables deployment, using technological upgrades and CCUS to decarbonize its vast industrial and coal-based energy sector.
Egypt	Fuel Switching & Flaring Reduction	Oil, Gas & Power	Strategic shift to natural gas, connecting 15 million households and converting 540,000 vehicles to CNG. Active development of a national low-carbon hydrogen strategy to leverage its renewable potential	Reducing energy waste and emissions from oil products; aiming to become a regional gas and green hydrogen hub as part of its energy transition.
India	Tata Steel CCUS Pilot	Steel	Capturing CO_2 from blast furnace gas, a first-of-its-kind pilot in India	Aiming for energy independence; rapidly scaling renewables while tackling emissions from heavy industry.
Iran	South Pars Flaring Reduction	Oil & Gas	Investing in infrastructure to capture and utilize associated gas instead of flaring	Reducing energy waste and emissions; developing renewable potential amid fossil fuel dependency.
Russia	Clean Coal - Green Kuzbass	Coal	Scientific and technical program focused on safe mining, processing, digital solutions, and ecological protection for the coal industry	Focusing on gas expansion and low-carbon hydrogen exports; using technology to maintain fossil export competitiveness.

The findings confirm that by simultaneously advancing the use of lower-carbon natural gas, accelerating the deployment of CCUS technologies, and implementing a wide array of sector-specific decarbonization projects – from Brazil's CO2 reinjection and Egypt's mass fuel switching to gas, to China's smart coal mining – the bloc is positioning itself to manage the dual imperatives of economic development and climate mitigation. Their progress underscores that a diverse portfolio of solutions, tailored to national circumstances, is essential for a realistic and effective path toward a sustainable energy future.

3. Challenges and Opportunities

3.2. Challenges

BRICS countries face multiple challenges in adopting sustainable fuels, linked to their economic structures, infrastructure, and the need for a just transition. A key overarching challenge is the lack of a universally accepted, technologically neutral regulatory framework that equitably supports the entire portfolio of sustainable fuels, from renewables-based options like green hydrogen to carbon-abated fossil fuels with CCUS. Figure 9 shows the main challenges and their impact level.

Main challenges faced by BRICS countries:

1 - Dependence on international technologies
2 - Lower range and efficiency when compared to diesel vehicles
3- Complex conditions for transportation and storage
4 - Limited variety of energy supply
5- High land-use impact
6 - Water stress
7 - Lack of national and BRICS policies
8 - Economic dependence on fossil fuels exports
9 - Displacement of labour and the lack of inclusive planning
10 - Lower affordability and accessibility for communities
11- Lower public awareness and cultural acceptance
12 - Lack of production and distribution infrastructure
13 - Higher production and consumption costs

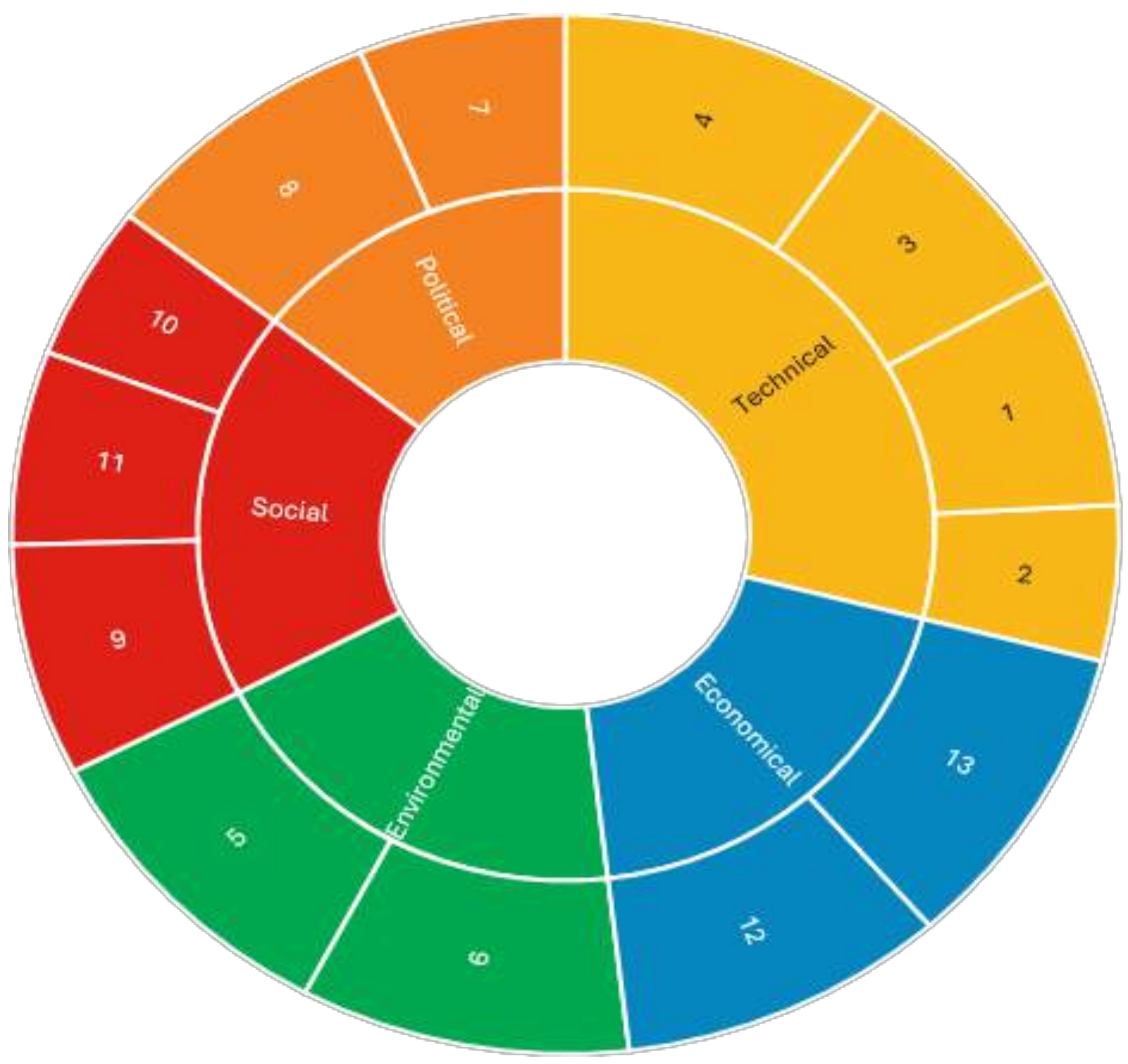

Figure 9 **Key Challenges for BRICS in Implementing Sustainable Fuels.**

Note: impact level is shown through the width of each cell.

Social challenges amidst JET affect many communities dependent on traditional energy sectors. These communities face a higher risk of losing their livelihoods as energy systems change. Rural populations also face logistical problems, highlighting persistent inequalities. Furthermore, a lack of inclusive governance often causes resistance, slowing the transition. This is particularly relevant for regions with high dependence on fossil fuels, where a transition must ensure socio-economic benefits for all citizens (BRICS 2024).

Political and Regulatory challenges are significant. These include a lack of certifications for sustainable fuels, unclear fuel blending policies, and a lack of technology-neutral frameworks. This affects Russia, India, China, Indonesia, Saudi Arabia, and the UAE (UNFCCC 2022). In 2017, fossil fuel revenues accounted for 17.8% of government revenue in India, and 6.8% in both Brazil and South Africa (Beyond Fossil Fuels: Fiscal Transition in BRICS 2024). This fiscal dependency underscores the need for a managed transition that leverages, rather than abruptly abandons, existing energy assets through decarbonization.

Technological challenges include dependence on a limited variety of feedstocks for biofuels and reliance on international technology in Russia, Brazil, and India. Overcoming these requires international collaboration (FUNDEP 2024; Natural Gas Society 2025; Gubiy et al. 2025; EPE 2025). Furthermore, key technologies like CCUS face hurdles such as high capital expenditure and the need for long-term storage verification (Global CCS Institute 2025).

Infrastructure challenges have a high impact. Countries like China, South Africa, and the UAE have limited available land for large-scale biomass cultivation and renewable energy projects (UNFCCC 2022; IEA Bioenergy 2024a). The high costs of building new production and distribution infrastructure for hydrogen and other advanced fuels pose a significant barrier. However, the strategic expansion and future repurposing of existing natural gas infrastructure, as seen in Egypt and Brazil, presents a critical opportunity to mitigate this challenge (BRICS 2024).

Finally, environmental costs and risks remain high. Countries like Brazil, India, Iran, and South Africa struggle with deforestation, biodiversity loss, soil degradation, and water scarcity from fuel production (IEA Bioenergy 2024).

3.2. Opportunities

Joint Research & Development on a Technologically Neutral Portfolio

New technologies create R&D opportunities. In early 2025, BRICS created a Roadmap for BRICS Energy Cooperation 2025–2030 leveraging BRICS Energy Research Cooperation Platform (ERCP) to the new level. These platforms can accelerate development for the entire fuel portfolio. This includes collaborative R&D on minimizing the energy penalty of CCUS, improving biofuel feedstock sustainability, and developing efficient hydrogen storage. BRICS countries can exchange knowledge and experiences. For instance, advanced CCUS projects of Brazil and China, coal decarbonization programmes of Russia, China and India offer valuable case studies for fossil fuel decarbonization. Finally, sustainable fuels allow for joint research to improve energy security, waste management, and support industries like chemicals and enhanced oil recovery (UNFCCC 2022; NITI Aayog 2022).

Shared Infrastructure for a Diverse Fuel Mix

Adopting sustainable fuels offers a major opportunity to build shared infrastructure. One promising area is cross-border transport corridors, such as expanding South Africa's Hydrogen Valley into a Southern African Hydrogen Corridor. Another is co-investing in regional refining hubs for biofuels, hydrogen, and ammonia. Furthermore, joint development of transnational CO2 transport and storage networks can create regional CCUS hubs, turning one country's storage potential into a regional asset. Digital infrastructure, like smart-grid platforms and digital marketplaces for carbon credits, is also critical (Asif, Singh, and Li 2024).

Green Job Creation and Skills Training for a Just Transition

The adoption of sustainable fuels could create 13 million green jobs by 2040 in countries like Brazil, South Africa, and India (APROBIO 2025; NITI Aayog 2022). This requires skill development for roles in CCUS operation, hydrogen production, biofuel refining, and the maintenance of modernized gas infrastructure. BRICS initiatives, such as the BRICS Network University (BRICS NU) and BRICS ERCP "Skills for Energy Transition" workstream are vital for this retraining, ensuring a just transition for workers in fossil-fuel-dependent regions.

Leveraging the BRICS Development Bank for a Diverse Portfolio

The BRICS New Development Bank (NDB) is a key platform for funding sustainable fuel projects. Its 2022–2026 strategy prioritizes clean energy and climate resilience. For BRICS, the NDB is strategic for financing the entire technology spectrum, from green hydrogen and advanced biofuels to carbon-abated fossil fuel projects, including CCUS deployment. NDB is not just a financier but a partner in a just energy transition.

Positioning BRICS as Global Leaders in a Pragmatic Energy Transition

The global energy transition opens opportunities for new leaders. BRICS, with its collective strengths in traditional energy, renewables, and technological capacity, is uniquely positioned to advocate for a pragmatic, technologically neutral transition pathway. A strong, cohesive energy branding strategy that leverages this diversity is essential. By offering equitable access to a full suite of clean energy solutions – from green to blue hydrogen, and from advanced biofuels to decarbonized fossil fuels – BRICS can reshape global energy relationships and advance its own interests, turning the bloc into a coordinated force that defines the future of international energy cooperation.

4. Conclusion and Recommendations

4.1. Summary of Findings

Sustainable fuels are crucial for global decarbonization, especially in hard-to-abate sectors. Within BRICS nations, their role is defined by a pragmatic, technologically neutral approach, where the strategic use of carbon-abated fossil fuels is leveraged alongside green alternatives to ensure energy security and a realistic transition. The bloc's strengths – vast resources, technological capacity, and large markets – provide a solid foundation. However, barriers remain, including unaligned policies, insufficient infrastructure, and slow technology diffusion. A coordinated strategy is essential to make sustainable fuels a tool for climate action, industrial competitiveness, and social inclusion.

4.2. Recommendations

Governments

- Align policy tools like carbon pricing and fiscal incentives to consistently support all sustainable fuels within national plans, based on their net carbon footprint rather than their origin.

- Harmonize rules across BRICS to ease cross-border investment and trade in low-carbon fuels, including certified carbon-abated fossil fuels.

- Improve infrastructure planning using BRICS platforms to integrate sustainable fuels, while strategically planning for the repurposing of existing fossil fuel infrastructure.

- Expand retraining programs to include women and youth in the entire sustainable fuels value chain, from CCUS to renewables.

- Develop technology-neutral certification systems that recognize the decarbonization benefits of both renewable and carbon-abated fossil fuels.

Civil Society

- Boost involvement in tracking the social and environmental effects of all sustainable fuel projects.

- Use consultation mechanisms to ensure just distribution of benefits like jobs and cleaner air.

- Advocate for inclusive decision-making that considers communities affected by both new renewable projects and the decarbonization of existing fossil fuel infrastructure.

BRICS Bloc, Global South, and Global Cooperation

- Improve coordination by combining R&D and commercialization efforts for the entire fuel portfolio through the BRICS

Industry

- Use sectoral alliances to increase technology adoption for the full fuel portfolio, including pilot plants for CCUS and blue hydrogen.

- Strengthen supply chains by streamlining certification, trading, and logistics for all sustainable fuels.

- Developing CO_2 transport networks to enable CCUS hubs, learning from case studies like Brazil's CO_2

Academia

- Enhance partnerships through BRICS NU and ERCP to research system integration and efficiency for all sustainable fuel pathways.

- Focus research on minimizing the energy penalty and cost of CCUS, improving the sustainability of biofuel feedstocks, and developing efficient hydrogen storage solutions.

- Lead interdisciplinary research on the social and environmental impacts of all sustainable fuel pathways, including carbon-abated fossil fuels.

ERCP

- Enhance South-South cooperation to fund shared innovation clusters and infrastructure, including CCUS hubs and hydrogen corridors.

- Continue joint knowledge-sharing on fossil fuel decarbonization, focusing on best practices for gas flaring reduction, coal mine methane capture, and CCUS.

- Collectively advocate in international fora for the recognition of technological neutrality and the role of carbon-abated fossil fuels as a legitimate part of the global energy transition, reflecting the diverse national circumstances of BRICS and other Global South nations.

Technological Advancements for Low-carbon Power Systems

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1. Introduction

1.1. Background

Global environmental risks and Paris Agreement commitments have made the transition to low-carbon power systems urgent. Countries are pursuing this shift at different speeds, reflecting their economic conditions, policy frameworks, and development goals. The common constraint has moved from "adding capacity" to integrating variable renewables reliably and affordably – a theme that is especially salient for BRICS, where electricity demand is rising alongside decarbonization imperatives.

BRICS countries account for nearly half of the world's population and over 48% of carbon dioxide emissions, a share expected to increase as their contribution to global Gross Domestic Product (GDP) grows (Global Energy Monitor 2025a). Power systems remain fossil-heavy in several members, but the share of fossil-fuel power capacity has been declining, with non-fossil additions overtaking planned coal, oil, and gas projects in 2024; China's fossil capacity share has fallen roughly twice as fast as other members over the past five years (Global Energy Monitor 2025b). This underscores a system in motion: solar and wind scale-up, hydropower and pumped storage as flexible backbones, batteries for fast services, emerging long-duration energy storage (LDES) for multi-day balancing, and firm low-carbon complements such as small modular reactors (SMRs).

At the same time, BRICS face distinct structural constraints: legacy grid codes not designed for high shares of inverter-based resources; thin or missing flexibility products; limited Distributed Energy Resources (DER) and Virtual Power Plant (VPP) aggregation; slow permitting and interconnection; and high capital costs in several markets. Yet these are also opportunities: modernized grid standards, capability-based procurement (e.g., grid-forming services, fast frequency response (FFR)), revenue stacking for storage, and blended-finance instruments can make the transition investable and reliable. As Brazil's energy transition leadership notes, the task is to balance energy security, sustainable development, and decarbonization – and to use the transition as a generational opportunity for inclusive growth (Ministry of Mines and Energy Brazil 2024).

The broader digital transformation amplifies both challenges and opportunities. Artificial Intelligence (AI)-assisted forecasting and dispatch, topology-aware state estimation, digital twins, and dynamic line rating are revolutionizing power system planning and operations. Meanwhile, the surge in data-center demand and cybersecurity risks necessitate robust governance frameworks. BRICS experiences illustrate this duality: for example, Egypt's Benban solar complex and supporting reforms signal ambition to expand utility-scale renewables with system integration and investment partnerships, turning transition goals into grid-level capabilities.

This report therefore examines how BRICS can leverage advances in low-carbon generation and modern grid tools to deliver reliable, secure, and affordable low-carbon electricity, moving from capacity additions to system capabilities. It sets the stage for the analysis that follows in Current Issues and Recent Trends and Challenges and Opportunities.

1.2. Definition and Scope

For this chapter, low-carbon power refers to electricity generated with zero or significantly reduced lifecycle greenhouse-gas emissions relative to conventional fossil generation. The analysis focuses on:

- Generation-side advances and dispatchable clean complements: Solar photovoltaic (PV), wind, geothermal, hydropower, and SMRs with attention to hybridization (e.g., PV/wind co-located with storage) and operational flexibility.
- Grid integration and the flexibility stack: Energy storage (short-duration batteries; pumped-storage hydropower (PSH) and other LDES options), modern transmission (high-voltage direct current (HVDC), flexible AC transmission systems (FACTS)), grid-forming inverter capabilities, DER/VPP aggregation, and market products (e.g., FFR, ramping, congestion relief, capacity).
- Digital and AI-enabled operations: forecasting, state estimation, digital twins, dynamic line rating, and secure data/telemetry frameworks that enable reliable high-variable renewable energy (VRE) grids.

The scope explicitly excludes fuels and emission-reduction retrofits on conventional plants (covered by the "Sustainable Fuels for Energy Transitions" Chapter). The emphasis throughout is on integrating diverse low-carbon resources into modern grids, turning technology potential into system reliability, emissions reductions, and investable projects, thereby aligning BRICS' growth trajectories with a resilient low-carbon future.

2. Current Issues and Recent Trends

2.1. Generation Advances

BRICS nations and their partners have diverse energy profiles, but all are trending toward greater renewable adoption. Brazil already derives about half its energy from renewable sources (mainly hydro and biofuels). China leads the world in added renewable capacity (with over 1 TW of hydro, wind, and solar by 2023) and now generates roughly one-third of its electricity from renewables (wind and solar provide 16%) (Ember 2025). India is rapidly expanding renewables toward a target of 500 GW of non-fossil capacity by 2030 (up from ~140 GW of solar and wind today) (Press Information Bureau 2025). Russia, with most of energy mix covered by natural gas, already has over 20% of its installed capacity from renewables including large hydro, and over one-third from low-carbon sources when nuclear is included. In contrast, South Africa remains heavily reliant on coal but aims to boost renewables from ~12% to 25% soon. New BRICS entrants such as Egypt have ambitious renewable goals (42% by 2035), and the United Arab Emirates (UAE) is diversifying with solar (8% of capacity) and nuclear (7%).

Solar PV and Wind

By late 2024, the BRICS bloc was a key driver of global solar and wind growth. Attention has shifted from simply cutting costs to ensuring high shares of VRE can be integrated reliably. China's massive deployment push accelerated solar and wind adoption, and India, Brazil, and South Africa expanded capacity as well. Advances making it feasible to handle more solar and wind include improved technologies (higher-efficiency panels and larger turbines capturing more energy) and new tools for grid stability. For example, grid-forming inverters let renewables help regulate frequency and voltage, and hybrid projects that pair solar or wind with batteries or hydrogen production provide steadier power and reduce curtailment (Press Information Bureau 2025). A mix of storage is also crucial: fast lithium-ion batteries for short-term smoothing, and resources like pumped hydro for overnight or seasonal backup (LDES Council 2024).

Grids are being strengthened with new transmission lines and smarter controls for forecasting and dispatch (IEA 2024a), and existing thermal/hydro plants are operated more flexibly to fill renewable gaps (Ember 2025). China and India's efforts offer lessons on integrating renewables at scale. Brazil's hydropower provides flexibility, but it still needs investments in hybrid projects and grid upgrades to support more wind and solar. South Africa and Russia, starting from low VRE levels, will need major upgrades in grid-forming equipment and storage as they add renewables. Policies are adjusting too: auctions now often reward projects that offer grid support (not just lowest cost), and standards ensure new solar and wind are grid-friendly (Ember 2025).

Advanced Nuclear and SMRs

Numerous countries are revisiting nuclear power as a cornerstone of low-carbon strategy, and SMRs are at the forefront of this trend. SMRs are nuclear reactors up to ~300 MWe that can be factory-built in modules and assembled on-site, reducing construction risks and allowing incremental capacity additions (IAEA 2020). Mass production could drive SMR costs down to rival large reactors (BEIS 2016). They are also designed for operational flexibility (load-following), making them suitable to complement intermittent renewables and to serve smaller grids that large reactors cannot.

BRICS countries are increasingly interested in SMRs for energy security and decarbonization. Russia and China are global leaders, hosting the only SMRs currently in operation. Russia's floating 70 MWe SMR plant has powered a remote Arctic town since 2020, and China's 200 MWe high-temperature SMR (HTR-PM) began feeding the grid in 2023. Both nations are constructing new SMRs (Russia a 50 MWe land-based unit due ~2028, China a 125 MWe ACP100 by 2026) and developing further designs. India is in early talks to deploy SMRs, potentially to replace aging coal plants as a means to add distributed nuclear capacity. South Africa is revisiting modular reactor plans (such as a 100 MWe pebble-bed design) to bolster its grid with clean, firm power (Black, Shropshire, and Araújo 2023). Egypt is constructing its first nuclear power plant at El Dabaa, with four reactors totaling 4.8 GW. Construction began in 2022 and completion is expected by 2028, but the country has not yet formally explored SMRs (Tariq, Johansson, and Moss 2025). Brazil is at a preliminary stage, conducting feasibility studies and exploring partnerships for SMRs (World Nuclear News 2025). Ethiopia is actively exploring the integration of nuclear energy into its energy portfolios. These moves indicate that nuclear energy, in particular SMRs, is becoming part of BRICS energy transition strategies, offering a pathway to reliable low-carbon power (Black, Shropshire, and Araújo 2023).

Hydropower and Pumped Storage

Hydropower remains a cornerstone of renewable electricity and also serves as critical storage via pumped hydro. Globally, about 1.4 TW of hydro capacity is installed, including roughly 180 GW of pumped storage acting as the world's largest grid battery (IEA 2024b). Hydroelectric plants are prized for their flexibility – they can rapidly adjust output to balance fluctuations in wind and solar generation, making hydropower a key enabler for high renewable penetration. However, large dams can pose environmental and social challenges, so careful planning is needed (IEA 2024b).

BRICS countries collectively account for nearly half of global hydropower capacity, led by China and Brazil. They are investing in new projects, especially PSH, to add flexibility to renewable-heavy grids. China alone has a majority of the world's PSH projects under construction, and members like India and South Africa also plan new PSH capacity. South Africa, for example, intends to add about 1.5 GW of PSH. New BRICS members are also leveraging large-scale hydro power to strengthen their domestic energy security. For example, Ethiopia has recently commissioned the largest hydro power plant in Africa and continues to prioritize hydropower development as a central economic pillar of its growth strategy (IEA 2024b). This trend reflects a consensus that leveraging water power, both for generation and storage, is crucial to integrating more solar and wind while keeping electricity supply reliable.

Green Hydrogen

Green hydrogen, produced by electrolysis using renewable electricity, is emerging as a bridge between the power sector and other sectors. Modern electrolyzers can ramp quickly to absorb surplus solar or wind power without destabilizing the grid (IEA 2025h). Gigawatt-scale pilot projects have shown that excess renewable power can be converted to hydrogen and stored, then later used to generate electricity via turbines or fuel cells when needed (NREL 2025). In effect, green hydrogen can function as long-duration storage, shifting energy from times of oversupply to times of deficit. With improving efficiency and smart controls, electrolyzer facilities are even able to provide grid services while producing hydrogen. Recognizing this potential, many governments are investing in scale-up of electrolysis. The result is a shift from static hydrogen production to dynamic, grid-integrated hydrogen systems that boost renewable utilization and cut fossil fuel use in other areas.

Overall comparative situation in BRICS

Table 10: Energy source trends in the BRICS countries.

Country	Dominant Energy Source	Key Trend	Climate Goals
Brazil	Hydro (60%, Renewables)	↑ RE & Hydro, ↓ Oil/Gas/Coal	37% GHG reduction by 2025; Net zero by 2050
China	Coal & Renewables	↑ Coal, Hydro, Nuclear, RE	Net zero by 2060; Improve energy efficiency
Egypt	Natural Gas	↑ Gas, Nuclear, RE ↓ Oil	Developing nuclear; Expand solar and wind
Ethiopia	Hydro, Biofuels	↑ RE	Electricity rural areas; Export surplus
India	Coal (72%)	↑ Hydro, RE	500 GW RE by 2030; Nuclear expansion
Indonesia	Coal & Natural Gas	↑ Solar, Geothermal, EVs ↓ Coal (planned)	Net zero by 2060; 23% RE in energy mix by 2025
Iran	Gas & Oil	↑ Gas	Diversify energy
Russia	Gas, Oil, Coal	↑ Nuclear, RE	30% CO2 reduction by 2030; Net zero by 2050; RE and nuclear expansion
Saudi Arabia	Oil & Gas	↑ RE, Solar, Hydrogen ↓ Oil (domestic)	Net zero by 2060; 50% renewable energy by 2030
South Africa	Coal (86%)	↓ Coal	Green transition strategy; Increase RE; Modernize coal
UAE	Gas & Oil	↑ Nuclear, RE ↓ Oil	Net zero by 2050; Triple RE by 2030

The table above highlights that most BRICS countries have set clear goals for achieving carbon neutrality. These energy strategies show that they all share one common feature: a focus on reducing CO_2 emissions, increasing the share of renewable energy sources, diversifying energy sources, and improving energy efficiency (Emishyan and Guliev 2025).

2.2. Energy Storage

Storage Portfolio

To integrate variable renewables, a mix of energy storage technologies is needed. Short-duration storage (seconds to a few hours) is typically provided by batteries dominated by lithium-ion today, thanks to falling costs and maturing supply chains. Across BRICS, battery farms are already deployed to supply FFR and intra-day energy shifting, preventing renewable curtailment. For longer durations (many hours to days), the main solution is PSH. China, for example, has rapidly added PSH capacity to help meet evening peaks (International Hydropower Association 2024). Where PSH isn't viable, emerging long-duration options (novel batteries, thermal storage, etc.) are being trialed to handle overnight and seasonal lulls (LDES Council 2024).

BRICS approaches vary: China aggressively scales both batteries and PSH; India is initiating large battery and PSH projects; Brazil's extensive hydropower means less urgency for batteries (though it's adding some to solar and wind farms); South Africa is deploying big batteries to improve reliability; and Russia remains in the pilot stage. In addition to utility-scale plants, distributed storage is growing. Home and commercial battery systems and even electric vehicles (EVs) with vehicle-to-grid capability can be aggregated via VPP platforms to perform grid services. Pilot programs in India and South Africa show that pooled behind-the-meter batteries can participate in energy markets and bolster resilience (World Bank 2023a). Encouraging such efforts through policy (e.g., easing market access for aggregated resources) will further expand the flexibility available to the grid.

Capacity and Investment

Global investment in energy storage is surging. In 2025, storage investment is projected to be around $65–70 billion, over 20% higher than in 2023 (IEA 2025c). Worldwide installed storage capacity now exceeds 250 GW, led by PSH, but battery systems are growing fastest as costs have plummeted (~80% drop for Li-ion batteries since 2015

) (IRENA 2025). Policymakers and lenders increasingly view storage as essential infrastructure. The World Bank urges integrating storage into national power plans and supports projects with blended financing (World Bank 2024). Market rules are evolving too: allowing storage to stack revenues from energy, capacity, and ancillary services, and recognizing its carbon benefits through incentives (OECD 2025), are making storage projects more bankable. These trends firmly establish energy storage as critical for a reliable, decarbonized power system.

2.3. Grid Integration and Market Dynamics

Achieving high renewable penetration also requires market reforms to reward flexibility. BRICS countries are introducing new mechanisms to maintain grid stability amid rising solar and wind. FFR and fast-ramping reserves help manage rapid output swings (IEA 2024b) and are being procured in places like China, India, and South Africa to reduce curtailment and avoid blackouts (World Bank 2023b). For longer gaps (nighttime or multi-day lulls), expanding long-duration storage such as PSH is key. Market reforms that let these facilities earn from multiple value streams – capacity payments, energy arbitrage, and grid services – are improving their economics and attracting private investment (LDES Council 2024).

Demand-side flexibility is growing as well. Smart meters and Internet of Things (IoT)-driven platforms let consumers and distributed resources adjust usage or feed energy back in response to grid needs. Through demand response programs and aggregation into VPPs, industrial and household assets can support the grid. India's Green Open Access rules and South Africa's recent programs, for instance, enable large consumers and aggregators to trade energy or provide ancillary services (Government of India, Ministry of Power 2024; World Bank 2023b). By tapping both supply-side and demand-side flexibility, BRICS aims to maintain stability without excessive overbuilding, even as renewables supply a greater share of electricity.

2.4. Digitization

Digital technologies are transforming the energy sector, making grids smarter, more efficient, and more adaptable. Three key areas of innovation are Artificial Intelligence, Blockchain, and the Internet of Things.

Artificial Intelligence (AI) and machine learning are being deployed to optimize many aspects of energy systems. They help forecast renewable generation and electricity demand, detect equipment faults in advance, and optimize the dispatch of power plants and storage in real time. An S&P Global analysis found that AI-driven trading can significantly narrow the gap between forecasted and actual renewable output (by up to 700%), improving reliability and efficiency (S&P Global Commodity Insights 2025). All BRICS countries are investing in AI: for example, Russia and India use AI to optimize urban energy use and grid management, China plans to integrate AI across its power system by 2027 (Ideas-BRICS 2025), and South African firms apply AI for smarter grid operations (StartupResearcher 2025). The growth of AI is increasing electricity demand in data centers. Already, data centers consume about 1.5% of global power, and that could double to ~3% by 2030 at current growth rates (IEA 2025g). Developing and running advanced AI also requires skilled talent and capital. BRICS strategies must therefore address AI's energy footprint and resource needs even as they reap its benefits.

Blockchain Technology (BCT) is essentially a decentralized digital ledger that offers potential for energy applications such as peer-to-peer electricity trading and certification of low-carbon energy. In principle, it can enable secure, transparent transactions without a central intermediary. BRICS nations have conducted pilots in this area: for instance, blockchain platforms in India let prosumers trade solar power locally (Powerledger 2023), and South Africa's Fuel Switch platform uses blockchain to trade renewable energy certificates (Fuel Switch 2025). China's government is developing a blockchain system to track and trade green power, and Brazil has considered using excess renewable capacity to power blockchain-based industries like crypto mining (Fucuchima 2025). Some blockchain systems (notably those using proof-of-work consensus) are extremely energy-intensive, which runs counter to sustainability goals. Moreover, current blockchain networks can be slow and difficult to scale. Future deployments in energy will need to use more efficient, scalable blockchain designs to be effective.

The Internet of Things (IoT) involves networks of connected sensors and devices and is foundational to smart grids. IoT devices provide real-time data on everything from power plant performance to household energy use. This allows utilities to monitor grid conditions instantaneously, detect and isolate faults, and better match supply with demand. In BRICS countries, IoT technologies are being rolled out to modernize energy infrastructure. For example, Brazilian utilities use IoT sensors at hydro dams and solar farms to track operations and environmental conditions in real time (Vale S.A. 2024), and Indian power distributors are deploying smart meters and automating substations using IoT systems (GEPDEC Energy 2025). By enabling granular control and coordination of countless distributed assets, IoT makes the grid more resilient and efficient, facilitating the integration of renewable and DER.

3. Challenges and Opportunities

Building on the previous discussion of current issues and recent trends, BRICS countries face several challenges that can be turned into opportunities in the transition to low-carbon power systems. The key areas are economic and financial factors, and regulatory and market design. Addressing these hurdles through innovative financing and effective policy and market reforms will be crucial for accelerating clean energy deployment while maintaining reliable and affordable electricity.

3.1. Economic and Financial Challenges & Oppotrunities

Economic and financial factors play a central role in accelerating low-carbon power in BRICS countries. New technologies (like SMRs) carry first-of-a-kind risks that can make private investors hesitant. Large-scale projects also demand strong balance sheets from utilities and project developers, and localization requirements (domestic supply chains and workforce development mandates) add complexity and cost. However, these challenges can be overcome with creative financing solutions. Blending public and private resources, alongside risk-mitigation tools (such as guarantees and insurance), can make pioneering projects bankable despite their higher perceived risk.

In addition, energy storage presents economic hurdles. Storage is essential for integrating variable renewables, yet its revenue streams – such as payments for energy, capacity, and grid support services – often fall short of fully valuing its benefits. Without market mechanisms that properly reward these services, storage deployment can lag behind what the grid actually needs, limiting flexibility and slowing decarbonization.

At the same time, in emerging markets, high capital costs and expensive financing, compounded by perceived project risks, raise the bar for both domestic and international investors. In response, green finance tools such as green bonds and sustainability-linked loans can help fill the funding gap and support innovative low-carbon projects (Taghizadeh-Hesary and Yoshino 2020). Public awareness and engagement also play a role by stimulating demand for clean technologies and creating a more favorable investment climate (Mensah et al. 2023). For instance, green bonds have seen success in countries like China and India, raising capital specifically for renewable energy and grid projects, which shows investor appetite for low-carbon infrastructure.

In this context, blended finance, combining concessional public funds with private capital, is a promising approach to reduce first-of-a-kind risks and make transformative projects feasible. National or multilateral development banks and climate funds can provide low-interest capital, guarantees, or currency hedging to further attract private investment. For example, the BRICS-founded New Development Bank (NDB) is financing renewable energy and grid modernization initiatives among member countries, illustrating the impact of multilateral cooperation in supporting the energy transition.

Ensuring that utilities remain financially healthy and capable of expanding generation capacity is equally critical to the transition. By establishing supportive financial structures and designing revenue mechanisms that reflect the full value of flexible resources – such as energy storage or demand response, BRICS countries can lower investment risk and unlock more private capital. Coupled with public support and clear government interventions, including well-targeted regulations, tax incentives, research and development support, and international collaboration, these financial measures position BRICS nations to lead in low-carbon innovation. This demonstrates that smart financing and policy together can transform ambitious energy goals into tangible outcomes.

Looking ahead, exploring financial cooperation and currency arrangements among BRICS members offers further opportunity. For example, currency swap agreements or local-currency settlement mechanisms can reduce exposure to exchange rate fluctuations in energy projects. According to the BRICS Energy Transition Skills Report, such measures can enhance financial stability and reduce vulnerabilities to external economic shocks, reinforcing economic ties among BRICS nations and promoting greater financial resilience (BRICS 2023b). In essence, innovative funding models and cooperative financial frameworks are turning economic challenges into opportunities for sustainable energy growth.

3.3. Regulatory and Market Design Challenges & Oppotrunities

Regulatory frameworks are another critical factor in enabling the low-carbon transition across BRICS countries. In many cases, outdated grid codes, slow permitting and approval processes, and fragmented responsibilities between national and regional authorities delay the integration of renewable energy, energy storage, and smart grid technologies. At the same time, these challenges represent a clear opportunity: by streamlining bureaucratic processes, updating technical standards, and providing predictable rules, BRICS countries can accelerate renewable deployment and attract long-term investment. As Inglesi-Lotz emphasizes, renewable energy projects require political stability, effective governance, secure property rights, and clear regulatory frameworks to succeed (Inglesi-Lotz 2021). Countries that close these regulatory gaps will create a strong foundation for innovation while maintaining system reliability.

Streamlining regulatory processes can have immediate impacts. For example, South Africa recently raised the licensing exemption threshold for embedded generation projects (up to 100 MW) – a reform that has spurred private investment in new solar and wind capacity by cutting red tape. In Brazil, regulatory modernization includes Law No. 14.300/2022, which established the legal framework for micro and mini distributed generation. According to the 2025 National Energy Balance from the Empresa de Pesquisa Energética, micro and mini distributed generation reached 42,268 GWh of electricity in 2024 (EPE 2025). This framework has accelerated private participation and supported the expansion of distributed energy in the country.

Market design is another essential piece of the puzzle. Electricity markets in many BRICS nations are partially deregulated, yet their structures often do not fully reflect the realities of a modern low-carbon grid. Integrating diverse technologies without overburdening consumers requires market rules that send clear price signals, reward flexibility, and encourage investment in solutions like storage and demand response. Sustainable energy transitions depend not only on technology but also on supportive policy frameworks, attractive pricing for investors and consumers, and a facilitating regulatory environment (Wanga, Mwaura, and Nyang'aya 2020). Well-designed markets can incentivize the development of flexibility services and ensure that resources like batteries or responsive loads are valued for the stability and resilience they provide.

Some BRICS countries are already moving in this direction. India, for instance, launched a real-time electricity market and is developing ancillary service auctions to better reward flexibility, while China's energy market reforms aim to improve price signals for storage and demand response.

Looking beyond national frameworks, harmonizing regulations and standards across BRICS countries presents both a challenge and an opportunity. Diverse regulatory and policy approaches today can complicate cross-border electricity trade and investment, but they also open the door for collaborative solutions that strengthen regional integration. For instance, aligning grid codes with international best practices (such as adopting IEEE 2800 standards for inverter-based resources) would help seamlessly integrate renewables and storage at scale.

Main technical and market challenges observed across BRICS power systems include:

Table 11: Challenges and Examples technical and market challenges observed across BRICS power systems.

Gap / Challenge	Description or Example
Legacy grid codes	Existing codes are not fully aligned with modern standards (e.g., IEEE 2800 for grid stability with high renewable penetration).
Limited procurement pathways	Few mechanisms exist to procure new technologies such as grid-forming inverters that can stabilize weak grids.
Unclear rules for DER aggregation	Restricted or undefined rights for DER aggregation hinder VPPs and community energy initiatives.
Underdeveloped flexibility products	Flexibility services (e.g., FFR, peak shifting) remain nascent, limiting revenue opportunities for flexible assets.
Opaque and slow connection queues	Lengthy and non-transparent interconnection processes delay new generation and storage projects, creating uncertainty for developers.

Addressing these issues requires diplomatic engagement, sustained cooperation, and shared best practices among the BRICS countries. As noted in the BRICS Energy Security Report, coordinated efforts, such as knowledge exchange on regulatory reforms or joint development of standards, can enhance market efficiency, provide investment certainty, and accelerate the deployment of low-carbon technologies across the group (BRICS 2023a).

In summary, regulatory reform and thoughtful market design can turn challenges into opportunities. By modernizing rules, improving coordination across agencies, and designing markets that balance affordability with investment incentives, BRICS countries can effectively integrate variable renewable generation, strengthen system resilience, and lead globally in demonstrating how regulation and market innovation go hand in hand for a low-carbon future.

4. Conclusion and Recommendations

Across BRICS, the inflection point has shifted from "how fast can we add renewables" to "how well can we integrate them." The technology pieces exist: high-efficiency PV and taller, larger turbines; hydropower and pumped-storage as flexible backbones; batteries for fast services and emerging LDES for multi-day balancing; SMRs as firm, low-carbon complements; and a fast-maturing digital stack: forecasting, state estimation, digital twins, AI-assisted dispatch. The binding constraints are system integration and investability: outdated grid codes for inverter-based resources, thin or missing flexibility products (FFR, ramping, congestion relief), barriers to DER/VPP aggregation, high cost of capital, and sluggish permitting and interconnection. Country experiences diverge – China and India are already scaling transmission, storage, and market reforms; Brazil leverages hydro but needs hybridization and grid reinforcements; South Africa and Russia must pair new VRE with storage and grid-forming capabilities. In short: more capacity helps, but capability – device-level performance, modernized grids, and markets that pay for flexibility – determines reliability, emissions, and cost.

For governments and regulators, it is recommended:

- Adopt modern grid codes for inverter-based resources by a fixed date (e.g., 2027). Align with international best practice (e.g., IEEE-style performance envelopes) and mandate grid-forming capability above defined thresholds. Require certified conformance testing and staged roll-outs tied to interconnection approvals. Harmonize these efforts through the relevant BRICS Energy Research Cooperation Platform (ERCP) workstreams.

- Stand up full flexibility markets. Procure FFR, fast ramping, congestion relief, and black-start-equivalent services with transparent, technology-neutral rules. Allow revenue stacking across energy, capacity, and ancillary services to make storage and hybrids bankable.

- Plan a national "storage portfolio," not a single technology. Pair short-duration battery energy storage systems (BESS) for fast services with PSH/LDES for inter-day/seasonal needs. Run multi-duration capacity auctions with long-term contracts and clear performance metrics (e.g., Effective Load Carrying Capability (ELCC), response time).

- Accelerate transmission with modern tools. Prioritize HVDC corridors, FACTS, and dynamic line rating in integrated resource and grid plans; create one-stop permitting with statutory timelines and standardized impact assessments.

- De-risk first-of-a-kind projects (SMRs, LDES). Use sovereign/Multilateral Development Institution guarantees, currency hedges, local-currency windows, and availability-based offtake. Capitalize the NDB and national green banks to crowd-in private finance; embed localization where feasible without inflating risk.

- Enable DER and VPP participation. Create national aggregator licenses, telemetry and cybersecurity baselines, and simplified settlement so behind-the-meter storage, EVs, and flexible loads can compete in wholesale and ancillary markets.

- Foster digital and data governance through BRICS collaboration. Standardize interoperability using the ERCP as a platform for aligning on data protocols (e.g., Open Automated Demand Response / International Electrotechnical Commission profiles). Establish joint AI sandboxes for forecasting and dispatch, and set minimum information technology/operational technology security controls.

- Address the skills gap through BRICS initiatives. Utilize the 'Skills for Energy Transition' framework within the ERCP to fund rapid upskilling in power electronics and system operations, and support the annual Youth Energy Summit to build a future workforce.

For industry, utilities, and system operators, it is recommended:

- Deploy grid-forming at scale. Specify plant-level controls so a rising share of inverter-based resources can form/hold frequency and voltage on weak grids; publish annual targets for grid-forming-equipped capacity.

- Build dispatchable hybrids. Co-locate PV/wind with BESS/PSH (and, where appropriate, power-to-hydrogen) to cut curtailment, defer grid upgrades, and deliver firm products; contract on capability KPIs (ELCC, ramp rate, restoration time).

- Operationalize the digital stack. Implement high-accuracy forecasting, topology-aware state estimation, digital twins, and dynamic line rating; adopt model-governance and audit trails for AI-assisted decisions.

- Stand up VPPs. Aggregate behind-the-meter batteries, EVs, and flexible industrial loads with standardized telemetry and cybersecurity; bid into new flexibility products as rules open.

- Pilot SMRs at coal plant sites. Reuse interconnections and cooling, target load-following service, and evaluate cogeneration (process heat, district heating/desalination) to maximize socio-economic value.

- Harden supply chains and safety. Adopt best-practice battery safety codes, launch recycling/second-life programs, and qualify multiple vendors to reduce single-point risk.

For civil society, finance, and academia, it is recommended:

- Mobilize local-currency green capital. Scale green bonds, sustainability-linked loans, and utilize the NDB's localized financing facilities for projects that deliver measurable flexibility outcomes (MW of FFR, MWh of LDES, curtailment reduction).

- Make demand a flexibility resource. Promote 24/7 clean-power procurement by data centers and industry; expand time-of-use and critical-peak pricing; reward industrial demand response with clear baselines and verifiable performance.

- Co-create social acceptance. Use transparent siting, community equity or benefit funds, and environmental co-design for hydro/PSH/SMR to align projects with local priorities.

- Open data and joint testbeds through BRICS platforms. Publish anonymized grid datasets; run BRICS joint labs for grid-forming/DER/VPP interoperability to diffuse best practice quickly; align universities' curricula with grid-modernization skills.

Abbreviations

ADELE	Access to Distributed Electricity and Lighting in Ethiopia Project
AfDB	African Development Bank
AI	Artificial Intelligence
ANEEL	Agência Nacional de Energia Elétrica
BEIS	Department for Business, Energy & Industrial Strategy
BESS	Battery Energy Storage Systems
BCT	Blockchain Technology
BIRU	Biogas Rumah
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
BRI	Belt and Road Initiative
BRICS	Brazil, Russia, India, China, South Africa
C40 Cities	C40 Cities Climate Leadership Group
CCUS	Carbon Capture, Utilization, and Storage
CDA	Community Development Agreements
CEAMAZON	Centro de Eficiência Energética da Amazônia
CPI	Climate Policy Initiative
DER	Distributed Energy Resources
DMRE	Department of Mineral Resources and Energy
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EBP	Ethanol Blended Petrol
EEA	European Environment Agency
ELCC	Effective Load Carrying Capability
ELEAP	Ethiopia Electrification Program
EMDE	Emerging Markets and Developing Economies
EPE	Empresa de Pesquisa Energética
ERCP	Energy Research Cooperation Platform
ESG	Environmental, Social, and Governance
ESMAP	Energy Sector Management Assistance Program
ETWG	Energy Transition Working Group
EU	European Union
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
FAO	Food and Agriculture Organization
FFR	Fast Frequency Response
FPIC	Free, Prior and Informed Consent
GDP	Gross Domestic Product
GECF	Gas Exporting Countries Forum
GHG	Greenhouse Gas
HDI	Human Development Index
HVDC	High-Voltage Direct Current
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IFC	International Finance Corporation
IGF	Intergovernmental Forum
IGFMMS	Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development
IISD	International Institute for Sustainable Development

IMF	International Monetary Fund
IoT	Internet of Things
IRENA	International Renewable Energy Agency
JET	Just Energy Transition
KPI	Key Performance Indicators
LCOE	Levelized Cost of Electricity
LCP	Local Content Policies
LDES	Long-Duration Energy Storage
LPG	Liquefied Petroleum Gas
MCF	Multilateral Climate Funds
MDB	Multilateral Development Bank
MENA	Middle East and North Africa
MRV	Measurement, Reporting, and Verification
MSW	Municipal Solid Waste
MTF	Multi-Tier Framework
NDB	New Development Bank
NDRC	National Development and Reform Commission
NGO	Non-Governmental Organization
NZE	Net Zero Emissions
OECD	Organisation for Economic Co-operation and Development
PAYG	Pay-As-You-Go
PBoC	People's Bank of China
PGM	Platinum Group Metals
PMUY	Pradhan Mantri Ujjwala Yojana
PPA	Power Purchase Agreement
PSH	Pumped-Storage Hydropower
PV	Photovoltaic
R&D	Research and Development
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme
RES	Renewable Energy Sources
SAF	Sustainable Aviation Fuel
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All
SLB	Sustainability-Linked Bond
SLO	Social License to Operate
SMR	Small Modular Reactor
TRL	Technology Readiness Level
UAE	United Arab Emirates
UCO	Used Cooking Oil
UN	United Nations
UNDP	United Nations Development Programme
UNECE	United Nations Economic Commission for Europe
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
UNTP	United Nations Transparency Protocol
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
WACC	Weighted Average Cost of Capital
WHO	World Health Organization
WRI	World Resources Institute

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