Emerging Capacities for Knowledge Economy in BRICS Countries

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Abstract

In the context of the modern global economy, key drivers of radical change are coming to the fore – transformational transitions to a more complex model – the knowledge economy in its broadest sense. A shift of this magnitude requires new approaches to capacity building for all countries, regardless of their level of development. The emerging imperative provides a wide range of opportunities for developing countries, suggesting a new configuration of the global economic landscape and strategic alliances. The BRICS countries (China, India, Russia, Brazil, UAE, Indonesia, South Africa, Iran, Egypt, Ethiopia) represent a critical mass of players whose actions will determine the direction in which these processes will develop.

The article provides a comparative analysis of the innovative and transformational potential of the participants in this block in knowledge-intensive sectors in comparison with each other and with two developed benchmark countries – Austria and Australia. A methodology for calculating a comprehensive index of readiness for the knowledge economy is proposed. The countries under review are ranked on four levels based on the values of this indicator. Their degree of adaptation and readiness for transformational transitions to more complex levels, resource base, educational systems, indicators of patent publication activity, management efficiency, quality of human capital, infrastructure, and global integration capabilities are assessed. Recommendations are presented on policy measures for the development of intellectual economy sectors in the BRICS countries, as well as directions for future research.

Keywords: transformative capacity; sustainability transitions; dynamic capabilities; smart economy; BRICS; emerging potential; innovation; digital transformation; human capital; governance; technological transitions

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Introduction

The transition towards a smart economy increasingly defines the modern economic paradigm rooted in knowledge, innovation, and the pervasive influence of digital technologies[1]. These economies are characterized by high-tech industries, a highly skilled workforce, and a dynamic capacity to generate and commercialize new knowledge (OECD, 2024; World Bank, 2023; WEF, 2025; etc.). Global discourse is moving beyond previously dominant narratives, such as ESG (Environmental, Social, and Governance) and DEI (Diversity, Equity, and Inclusion). Renewed focus includes the development of new governance models suited for a technologically advanced era, managing transformational transitions in key sectors with relevant capacities building, laying the groundwork for the next technological regime, etc. (Loorbach, Wittmayer, 2024; Fazio et al., 2025; López-Fernández, Oliver, 2025; Broekel, Klarl, 2025).

Within this global shift, the BRICS group of nations[2] represents a critical mass of emerging economies whose trajectory will significantly shape the future global economic and technological landscape. Understanding and cultivating their potential in smart economy sectors has become a strategic imperative (Hu, 2021; Hluszko et al., 2024). The BRICS nations, with their diverse economic structures and varying developmental stages, provide a rich context for examining these persistent topics in the context of smart economy development. This is particularly important given that, according to various estimates, these countries collectively account for between 34% and 39% of global GDP[3], while their share of the world's population is close to 50%[4]. In addition, the territories occupied by the alliance members contain over 70% of the world's reserves of rare earth metals, the development of which is critical to the prospects of the high-tech sectors that form the basis of the knowledge economy[5].

This paper aims to explore how ten BRICS countries are positioning themselves to capitalize on the smart economy revolution. The primary objective is to analyze the emerging potential in these ten BRICS countries, specifically for high-tech, knowledge-intensive sectors. This involves identifying and evaluating the key components that constitute this emerging potential, including innovative output (patents, scientific publications), the adaptability and advancement of education systems, the depth and nature of digital transformation, the availability of human capital with relevant competencies, and the formation of strategic international alliances as inputs. Then we attempt a qualitative and quantitative ranking of the ten BRICS countries according to their demonstrated and emerging potential in these sectors, acknowledging different echelons of development. This potential is demonstrated through detailed comparisons with developed countries. Austria and Australia are the two developed economies that were chosen as benchmarks for our study.

This paper will begin by addressing the concept of transformative capacities itself, how it is defined in the latest literature, and what important components determine the success of transformational transitions to a smart economy. Then we define the conceptual framework of a smart economy (innovative) and outlining the key indicators used to assess emerging potential. It will then delve into a comparative analysis of the ten BRICS nations across these indicators. Following this, a discussion will synthesize these findings to propose a qualitative and quantitative ranking and elaborate on the composition of their potential. The analysis will primarily rely on qualitative and quantitative synthesis of publicly available data, academic literature, and reports from international organizations, acknowledging that the emerging nature of this potential often requires looking at diverse qualitative and quantitative metrics. The paper will conclude with policy recommendations aimed at fostering smart economy sectors within the ten BRICS nations bloc and suggest avenues for future research.

Literature Review and Conceptual Framework

Transformative capacities

The transition to sustainable development requires profound transformations, abandoning unsustainable modes of production and consumption (Isaksson, Hagbert, 2020), and overcoming the heavy inertia that constantly generates instability in a variety of forms. The concept of transformative capacity focuses on the institutional and processual aspects that can lead to transformations toward sustainable development. Transformation is not limited to a simple linear process of achieving desired futures by facilitating incremental change or by reverse-engineering (i.e. scenario or back-casting guided). Instead, it is about fostering a cultural transformation, an ongoing process of social learning through which sustainability objectives are seen as a 'moving target' and never truly accomplished (Castán-Broto et al., 2019).

The collective capacity of participants to perform change is linked to their ability to either direct resources to specific development processes or to change the rules governing the use of such resources. Transformational potential allows combine resource portfolios at different levels.). It becomes possible to meet local needs by joining international cooperation and infrastructure networks (Westley et al., 2013).

[1] The term „knowledge economy" has gained traction in academic and policy discourse to describe a stage of economic development where knowledge, innovation, and digital technologies are central drivers of growth, competitiveness, and societal well-being (Nelson, 1993; Yoshikuni et al., 2025; Liu, Lin, 2025). It goes beyond the simple introduction of advanced technologies and implies the strategic management of complex, adaptive social systems, technological effects, and, in general, different trajectories of their development.

[2] The core group of BRICS nations comprising Brazil, Russia, India, China, and South Africa, since 2024 has expanded to include Egypt, Ethiopia, Iran, Indonesia, and the UAE (hereinafter referred to as ten BRICS nations).

[3] https://www.statista.com/statistics/1412425/gdp-ppp-share-world-gdp-g7-brics/?srsltid=AfmBOorYasUr7P55XbTXzdElldweEKXyBOZTNHxMEOBYu-sIb0Z8InLWs, accessed 16.01.2026.

[4] https://www.cfr.org/backgrounders/what-brics-group-and-why-it-expanding, accessed 30.01.2026.

[5] https://brics.br/en/about-the-brics/brics-data, accessed 30.01.2026.

In recent years, researchers have responded to the relevance of the topic of transformation potential with an expanding stream of relevant publications on this topic. Recognizing the need for radical, profound changes, the literature documents an accelerated drift toward fundamental change (Avelino, Wittmayer, 2016; Hagbert, Malmqvist, 2019). Some researchers focus on transformations as a process, examining them in terms of different paths to breakthrough change (Hölscher, Frantzeskaki, 2020; Borgström, 2019), while others view transformative change primarily in terms of a policy outcome (Homsy, Warner, 2015; Kim, Yoon, 2018). In both cases, transformative potential is seen as the driving force generating breakthrough change. From an organizational perspective, transformational potential is understood as the ability to implement changes and achieve complex goals using innovative methods that an organization strategically combines to implement and achieve transformational results (Förster et al., 2021; Hagbert, Malmqvist, 2019).

The transformational potential closely relates to innovative and political potential (Borras et al., 2024). Political potential is defined as the ability of governments to mobilize resources to achieve resilience and adaptability (Wu et al., 2018). This type of capacity implies the ability of public administration to disseminate a holistic vision across all policy levels, which requires strategic, procedural, and evaluative abilities (Kim, Yoon, 2018), reflexivity, inclusivity, adaptability, and creativity (Förster et al., 2021). With regard to innovation policy, the transformative potential allows for its rethinking not in terms of incremental improvements to the established system, but rather its transformation into a genuine transformational impetus (Weber, Rohraher, 2012). This will require skills in multi-level, virtuoso coordination and deep reflection in managing such complex processes, as well as openness to alternative ideas and practices that challenge dominant paradigms that create instability. This will require enriching dominant norms, values, and rules with a culture of innovation, collaboration, and experimentation (Isaksson, Hagbert, 2020).

In conjunction with capacity, the concept of dynamic capabilities is often considered, which focuses on the ability of public organizations to act in a transformative and renewing logic (Mazzucato, Katel, 2018; Breznitz et al., 2018).

A number of authors studying transformation potential focus on the diversity of participants in transformational transitions, their ability to interact constructively, positively perceive complexity and uncertainty, identify emerging opportunities, etc. Potential is also considered in the context of dealing with the future (Moore, Milkoreit, 2020). Scenario development helps build momentum the collective potential of participants in such projects to achieve sustainable transformations (Pedde et al., 2019). Transformative capacities are not static but fluid and dynamic, and they develop cyclically and sequentially through the correct combination of three key components—the distribution of roles, resources, and competencies — in the process of transformative transition to sustainable development (Borras et al., 2024). One may possess the necessary resources (financial, human, data, political mandate, etc.) and well-established procedures, but without a clear definition of roles and specific tasks aimed at achieving profound change, these assets may prove useless for the transition to sustainable development. Conversely, one may have limited resources and capabilities, but a clear distribution of roles can ensure transformational change by mobilizing these limited resources and (rapidly) restructuring procedures. Roles are necessary conditions, while resources and capabilities are sufficient conditions for an organization's transformative capacity. Moreover deep transformations take time and inevitably face a significant number of obstacles.

The BRICS Core Context: Opportunities and Challenges

Despite the differences between the core BRICS countries (China, India, Russia, Brazil, South Africa), they share common aspirations for technological progress, economic transformation, and the realization of their potential in a wide variety of ways (OECD, 2021). Numerous publications in recent years have been devoted to issues related to their development. Many journals, both academic and industry-specific, publish special issues devoted to various aspects of the BRICS countries' activities. For example, *Computer Law & Security Review* in 2024 published an issue on digital transformation[6], and *Sustainability* in 2025 published an issue on sustainable transport and tourism[7]. It is also worth noting a special issue of the World Education Research Association magazine on the diversity of the educational context in the countries under consideration[8]. Institutes associated with BRICS form their own ratings of the alliance's member countries on various dimensions [9,10,11]. The organizers of one of the world's leading university rankings, QS, maintain a separate subsection for ranking educational institutions in the countries belonging to the alliance[12]. A number of developed countries have special research structures that focus on assessing the potential and dynamics of the BRICS countries. These include a specialized laboratory at the Massachusetts Institute of Technology (USA)[13] and the UK Parliament's Commons Library[14].

[6] https://www.sciencedirect.com/special-issue/10VRL9GGMQG, accessed 30.01.2026.
[7] https://www.mdpi.com/journal/sustainability/special_issues/G772R7K43D, accessed 30.01.2026.
[8] https://weraonline.org/call-for-papers-special-issue-educational-mosaic-understanding-brics-states/, accessed 30.01.2026.
[9] https://brics-ratings.org/rating, accessed 30.01.2026.
[10] https://brics.world/tpost/9xapygabg1-the-pilot-ranking-of-brics-universities, accessed 30.01.2026.
[11] https://mosiur.org/ranking_brics_2024/, accessed 30.01.2026.
[12] https://www.topuniversities.com/university-rankings/brics-rankings/, accessed 30.01.2026
[13] https://bricslab.mit.edu, accessed 14.01.2026.
[14] https://commonslibrary.parliament.uk/research-briefings/cbp-10136/, accessed 30.01.2026.

A comprehensive comparative assessment of the innovative potential of the BRICS countries was undertaken in a study by Zhao et al. (2025). According to this study, China has achieved leadership in most areas of the relevant rankings thanks to its strategy of accelerated innovative development. Russia, India, and Brazil, with active state support, are also working to realize their own innovation potential, which, however, is niche in nature. Efforts are focused on developing broad partnership networks within the framework of multilateral and bilateral agreements on international scientific and technological cooperation. South Africa, despite its "trailing" position among the core BRICS countries, has managed to build the most advanced innovation ecosystem in Africa and has gained regional leadership in certain technological areas.

Other members of the alliance are also working on their potential, but at different speeds and with varying degrees of readiness for a complex development model. In their case, the key barriers on this path are: infrastructure deficits (although in some of them the situation is rapidly improving), insufficient quality and accessibility of education, low efficiency of institutional and management systems, and other factors (AlRaeesi, Rahman, 2018; et al.). Thus, the paths to a knowledge-based economy are not uniform for different countries, and capacity building is characterized by constant changes and opportunities for leaps in development.

Conceptual Framework

Our conceptual framework can be theoretically anchored in the concepts of Endogenous Growth Theory (Romer, 2011), Quadruple/Quintuple Helix Models (Carayannis, Campbell, 2012; Muñoz-Hermoso et al., 2025; Abdullah-Kaiser, 2024), Smart Governance (Almulhim, Yigitcanlar, 2025; Gatzweiler, 2014) and Institutional Complementarity (Helveston et al., 2019). Based on the directive for this paper and established literature, the emerging potential of BRICS countries in smart economy sectors will be analyzed using the following key indicators:

- Patents and Scientific Publications,
- Transformation of Education Systems
- Human Capital Development,
- Dynamics of Digital Transformation,
- Strategic Alliances and International Collaboration,
- Governance and Enabling Environment.

The proposed conceptual framework provides a structured lens for analyzing the emerging potential of ten BRICS countries along with two developed economies (Austria and Australia) that were chosen as benchmarks in advancing smart economy sectors due to the fact that the authors are familiar with their contextual specifics. At its core, the model identifies the Smart Economy as the dependent construct, influenced by a set of critical enablers grouped under two broad domains: Frontier Technology Readiness Factors (FTRF)[15], and Governance Factors (GF). FTRFs encapsulate the essential technological, educational, and trade-related capacities that underpin a country's readiness to transition toward smart economic paradigms. In turn, Governance factors pertain to the enabling institutional and policy frameworks that shape strategic decisions around technology adoption, regulation, and inter-sectoral coordination. These influence how effectively nations can deploy and regulate frontier technologies and steer their economies toward sustainable, inclusive, and innovation-driven outcomes.

These domains collectively shape the trajectory, scalability, and sustainability of smart economic initiatives across ten BRICS nations and two developed benchmark nations. By integrating both FTRF and GF, the model captures the multidimensional nature of smart economy development in ten BRICS nations and two developed nations. The framework reflects how interdependencies between human capital, infrastructure, global linkages, and governance capacity can either accelerate or constrain the transition toward a smart economy. It also implicitly supports comparative analysis across the ten BRICS members, facilitating the identification of policy gaps and scalable practices. This framework positions the ten BRICS members grouping as a collective yet diverse testbed for smart economy transformation, offering pathways that balance indigenous capabilities with global partnerships. It thus serves as a valuable analytical tool for policymakers, investors, and academic researchers seeking to understand or influence smart sector evolution within emerging economies.

Methodology

This study employs a qualitative & quantitative, comparative analytical approach to assess the emerging potential of ten BRICS countries for smart economy sectors. The research design is primarily based on the synthesis of secondary data and existing literature, focusing on identifying trends, capabilities, and strategic orientations within each nation. The core of the methodology involves assessing each of the ten BRICS nations against the key indicators of smart economy potential identified above. The findings for each indicator will be synthesized across the ten BRICS nations to draw out comparative insights and identify patterns of convergence or divergence in their approaches and achievements. Based on the comparative synthesis, a qualitative and quantitative ranking or categorization of the ten BRICS nations and two developed countries into echelons will be proposed. This ranking will be based on both a rigid quantitative index and a holistic assessment of the qualitative evidence, reflecting the emerging potential rather than a static snapshot of current development levels.

We first highlight the overarching qualitative insights that lay the foundation for the quantitative analysis. We provide a detailed discussion of the ten BRICS countries' positioning in terms of emerging smart economy potential based on such indicators such as patents, scientific publications,

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[15] Among these are: Digital Infrastructure Access; Tertiary Education Enrolment and Attainment; Investment in Tertiary Education R&D and Human Resources; Global Student Mobility and Collaboration; Global Trade in High-Tech Sectors & ICT; Macroeconomic Factors (Wu, Fang, 2024; Shields, 2019; Galindo-Martin et al., 2025; Boonman et al., 2023; Karbalaei et al., 2025).

Table 1. **Correlation Matrix**

	Patents	R&D Expenditure	Scientific Publications	Education Enrollment	Digital Infrastructure	Governance Effectiveness
Patents	1.00	0.24	0.57	-0.02	-0.08	0.41
R&D Expenditure		1.00	0.29	0.30	0.24	0.45
Scientific Publications			1.00	-0.09	-0.19	0.26
Education Enrollment				1.00	0.73	0.35
Digital Infrastructure					1.00	0.29
Governance Effectiveness						1.00

Source: authors.

R&D investment, and education systems. These qualitative insights help us understand the foundational factors shaping each country's readiness to transition.

The quantitative analysis, which is presented further, builds upon these qualitative observations by providing specific numerical values and indicators that allow for a more precise, data-driven assessment. The use of Principal Component Analysis (PCA) and the subsequent classification of countries into four performance clusters (L1 to L4) further refines the qualitative rankings. The choice of the methods mentioned is based on several reasons, which are explained in more detail in Appendix 1. We believe that the combination of these two methods allows for a more comprehensive analysis of the smart economy transition dynamics within the BRICS countries, addressing both the deterministic aspects of development and the probabilistic uncertainties inherent in such complex systems.

Data

The variables selected for the analysis were chosen based on their relevance to the key dimensions of a smart economy, which include innovation, digital transformation, education systems, governance, and infrastructure. Specifically, the following variables were included: Patent activity, Scientific output and research publications, Well-educated and skilled workforce, Development of digital infrastructure, Strong governance, Linkages to global high-tech markets. The selected variables represent a comprehensive set of output and input indicators that capture the multi-dimensional nature of a smart economy, aligning with the theoretical framework we propose.

Table 1 reveals several key insights into the relationships between the variables influencing smart economy readiness in the BRICS countries. A moderate positive correlation (0.57) between patents and scientific publications suggests that countries with more research output tend to file more patents, indicating a strong link between knowledge generation and innovation. R&D expenditure shows weak correlations with patents (0.24) and scientific publications (0.29), implying that while investment in R&D supports innovation, the impact on patents and publications may vary depending on factors like commercialization and research infrastructure.

A strong positive correlation (0.73) between education enrollment and digital infrastructure indicates that countries with better educational systems are more likely to develop advanced digital infrastructure, which is crucial for a smart economy. Similarly, governance effectiveness positively correlates with R&D expenditure (0.45), highlighting that strong governance facilitates R&D investment and innovation. However, the weak negative correlation between digital infrastructure and scientific publications (-0.19) suggests that digital infrastructure alone does not necessarily drive higher scientific output, pointing to the importance of research-focused environments.

These correlations emphasize the interconnectedness of education, governance, R&D, and digital infrastructure in shaping the development of smart economies, underscoring the importance of a holistic approach to fostering innovation and technological advancement.

Qualitative Analysis

This section provides a comparative analysis of the ten BRICS countries across the key indicators of smart economy potential (Table 2).

Transformation of Education Systems and Human Capital Development

Across BRICS, core 5 BRICS nations recognize the critical importance of human capital for a smart economy and are undertaking reforms in their education systems. This includes efforts to expand access to higher education, enhance the quality of STEM (Science, Technology, Engineering, and Mathematics) education, promote digital literacy, and cultivate skills such as critical thinking and problem-solving. *China & India* produce a vast number of STEM graduates annually. The focus is now shifting towards improving the quality of education and aligning curricula with the needs of emerging high-tech industries.

China's education system has achieved an optimal balance between basic, secondary specialized, and higher education, which promotes innovation. Plans are in place to transform the country into a global education hub by 2035. Education is linked to the "great rejuvenation of the Chinese nation" and is seen as the driving force behind national modernization and ethical renewal (Anthony, 2025).

Brazil, Russia and South Africa have established higher education systems but face challenges in ensuring equitable access, quality, and relevance of skills for the smart economy. For example, in South Africa, the emphasis is on epistemic pluralism and inclusiveness: universities are seen as instruments for restoring historical justice. Soft governance has been implemented: coordination without coercion through architecture, but with clear, legally binding requirements for

Table 2. **Snapshot of Smart Economy in studied countries**

Country	R&D Expenditure (% of GDP)	Total Patent Applications (Office Filings, 2022)	Scientific Publications (Total Documents, 2023)	Tertiary Gross Enrollment Ratio (%)	Individuals using the Internet (% of Population, 2023)	Government Effectiveness (Percentile Rank, 2022)
Two developed Benchmark Countries						
Austria	3.2 (2022)	2,047	34272	94.5 (2022)	95.3	89.62
Australia	1.86 (2022)	32,409	121008	128.3* (2022)	97.1	93.87
Five Core BRICS countries						
Brazil	1.16 (2021)	24,759	107,399	56.7 (2022)	84.3	43.8
Russia	1.0 (2022)	26,924	143,248	81.8 (2021)	88.2	51.9
India	0.64 (2021)	77,068	275,368	29.4 (2022)	48.7	53.8
China	2.4 (2021)	1,600,000	1,023,153	61.1	77.5	77.4
South Africa	0.6 (2020)	13,990	36,051	24.9 (2021)	74.7	58.7
Five New countries (Members) who joined BRICS in 2022-24						
Egypt	0.72 (2019)	2224 (2021)	36,192	39.0	71.9	24.0
Ethiopia	0.2 (2019)	82 (2023)	8,362	10.5 (2018)	29.3	24.5
Iran	0.83 (2017)	10,791 (2021)	82,989	66.8 (2022)	77.9	16.3
Indonesia	0.28 (2020)	8800 (2021)	61334	45.14	69.2	69.81
UAE	1.49 (2021)	2,423 (2021)	19,052	47.9 (2021)	100.0	85.1

*The percentage can exceed 100% due to factors like early entry, grade repetition, or students enrolled outside the official age range.
Sources: World Bank (2023), UNESCO (2021), WIPO (2024), Scimago Journal & Country Rank (https://www.scimagojr.com/, accessed 17.12.2025).

inclusiveness and the restoration of historical justice. Adaptability in the face of constraints comes first, promoting localized innovation but at the same time reproducing inequality of opportunity (Ustyuzhantseva, 2025).

Newer BRICS members are making significant investments in education infrastructure and curriculum reform, particularly in the Gulf states, aiming to upskill their national workforces. Egypt and Ethiopia are focused on expanding educational access and improving foundational skills.

Patents and Innovation Ecosystems

China demonstrates a remarkable lead in global patent filings, particularly in areas such as AI, and renewable energy technologies. Its innovation ecosystem is increasingly robust, driven by significant R&D investment, a dynamic tech private sector, and strong government support. *India* shows growing patent activity, particularly in software, pharmaceuticals, and IT-enabled services. The Digital India initiatives aim to bolster domestic innovation[16]. Challenges persist in translating research into commercially viable patents and strengthening university-industry collaborations. *Brazil* possesses notable innovative capabilities in specific fields like agriculture technology and, aerospace. *Russia* has a strong legacy in fundamental sciences and engineering, leading to innovation in areas like nuclear technology, aerospace, and certain software domains. However, translating this into broader commercial patents and fostering a vibrant private-sector-led innovation ecosystem presents ongoing challenges, even more so given the geopolitical situation. *South Africa* leads in Africa in terms of patent filings in certain areas and has a relatively well-developed research infrastructure. Strengths can be seen in biotechnology, mining technologies, and some areas of ICT.

As to *Newer BRICS Members*, these nations present a more varied picture. The UAE is making significant investments to diversify its economy towards knowledge-based sectors, with a focus on AI, smart cities, and renewable energy, leading to an uptick in related innovative activities. Iran has demonstrated indigenous innovation in various tech fields despite sanctions. Egypt and Ethiopia are in earlier stages, but both show a commitment to developing their ICT sectors and fostering innovation.

Scientific Publications and R&D Landscape

China has become a world leader in the volume of scientific publications, with an increasing emphasis on quality and impact in strategic fields such as AI, materials science, and engineering. R&D spending is substantial and growing. *India* possesses a large scientific workforce and produces a significant number of publications, particularly in computer science, mathematics, and medical sciences. *Brazil & Russia* maintain strong traditions in scientific research, with notable contributions in specific fields. *South Africa* has the most impactful research output in Sub-Saharan Africa, with strong international collaborations. *Newer BRICS members* are investing heavily in research institutions and attracting international talent to enhance their scientific output, particularly in areas aligned with their economic diversification plans. Iran and Indonesia have a notable activity in producing scientific publications.

Digital Transformation

China is a global frontrunner in digital transformation, evidenced by its leadership in e-commerce, mobile payments, AI applications (e.g., facial recognition, smart cities), and a rapidly expanding digital infrastructure. *India* has a thriv-

[16] https://www.digitalindia.gov.in/, accessed 07.10.2025.

Table 3. **Summary of output (Smart Economy Readiness Index) and Inputs (X1 to X8) carried out through Principal Component Analysis (PCA)**

Country	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	SERI (Y)
UAE	0.81	0.98	0.71	0.91	0.88	0.88	0.99	0.72	0.88
Australia	0.94	0.77	0.77	0.96	0.76	1	0.96	0.77	0.87
Austria	0.91	0.83	0.84	0.75	0.9	0.74	0.87	0.89	0.85
China	0.88	0.75	0.66	0.96	0.78	0.74	0.78	0.95	0.79
Russia	0.73	0.8	0.76	0.73	0.53	0.85	0.88	0.79	0.76
Brazil	0.72	0.66	0.77	0.68	0.77	0.92	0.86	0.95	0.75
Indonesia	0.7	0.86	0.77	0.88	0.82	0.73	0.9	0.94	0.72
India	0.62	0.7	0.72	0.68	0.85	0.65	0.7	0.8	0.71
Iran	0.8	0.69	0.83	0.72	0.6	0.66	0.69	0.64	0.68
South Africa	0.78	0.41	0.49	0.64	0.89	0.88	0.78	0.42	0.68
Egypt	0.66	0.43	0.58	0.46	0.31	0.9	0.81	0.15	0.55
Ethiopia	0.39	0.46	0.47	0.65	0.88	0.26	0.13	0.21	0.45

Variables: SERI – Smart Economy Readiness Index (output-Y); X_1 – Governance Index; X_2 – Frontier Technology Readiness Index; X_3 – Investment in Tertiary Education, R&D & HR index; X_4 – Digital Access Index; X_5 – Tertiary Education Enrolment & Attainment Status Index; X_6 – Global Student Mobility (Inbound & Outbound) & Collaboration Index; X_7 – Global Trade in High Tech Sectors and ICT; X_8 – Macroeconomic index). PCA Sub-components of inputs X_1 to X_8 and output Y are detailed in Annex 1.

Source: authors.

ing digital economy, driven by its IT sector, a large internet user base, and government initiatives like Digital India. Rapid adoption of mobile technologies and digital services is evident. The development of a robust digital infrastructure across the vast country remains a priority. *Brazil, Russia, and South Africa* are making strides in digital transformation, with increasing adoption of digital technologies in various sectors. The UAE is demonstrating similar activity by investing heavily in smart government, AI, and digital infrastructure. Digital transformation agendas are central part of the Emirates national visions (e.g., UAE Centennial 2071)[17].

Strategic Alliances and International Collaboration

The BRICS forum itself promotes cooperation in science, technology, and innovation. Initiatives exist for joint research projects, academic exchanges, and policy coordination. *China* actively engages in international science and technology (S&T) cooperation and has formed numerous strategic alliances, particularly through initiatives like the Belt and Road Initiative (BRI), which has digital components. *India* has a strong tradition of international collaboration in IT and R&D and is increasingly seeking partnerships in emerging technologies. Other BRICS nations also participate in various bilateral and multilateral S&T agreements. The extent and focus of these alliances vary. For instance, Brazil's aerospace success often involves international partnerships.

Quantitative Analysis

The integration of both qualitative and quantitative methods allows for a well-rounded understanding of each country's potential and trajectory, ensuring that the results are both nuanced and backed by solid data as evidence. We begin the quantitative section by revisiting the insights from previous section, where we discussed the qualitative categorization of the countries based on their smart economy potential. We then quantitatively validate these categorizations using data-driven methods such as PCA and K-means clustering, which produce the Smart Economy Readiness Index (SERI) values for each country.

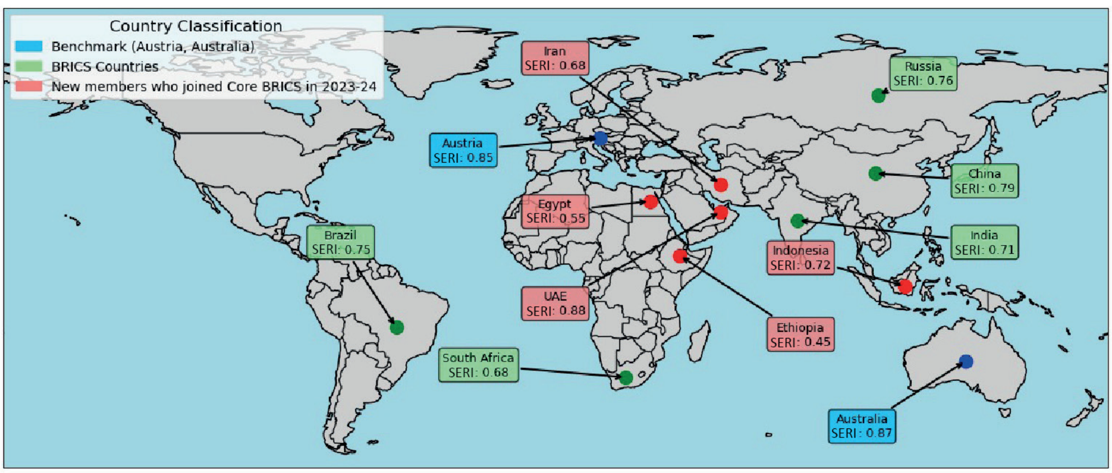
The SERI represents a composite readiness indicator derived from PCA of multi-dimensional inputs encompassing technology, governance, human capital, global integration, and macroeconomic capacity. Unlike traditional technology maturity indices, SERI reflects the principle of integrating technological aspects into a management system with a focus on the transition period. In our study, it serves as an output indicator (Y).

It is important to note that SERI values are not simple averages but are composite PCA scores of the indicators reported in Appendix 2. All variables were directionally harmonized and normalized to a [0,1] scale prior to PCA. The resulting SERI reflects weighted principal component scores, where indicator contributions are determined endogenously by variance structure and factor loadings. Consequently, countries with asymmetric strengths across dimensions (e.g., Indonesia, Ethiopia) may exhibit SERI values that differ from raw indicator means.

Table 3 summarises the principal component analysis (PCA) carried out on each of the inputs and outputs to reduce dimensionality of these variables. Figure 1 visually compares each country across the smart economy output (SERI) derived from PCA of all 8 inputs. Analysis of Table 4 and Figure 1 are discussed in following subsections. These values reflect the various dimensions of smart economy readiness identified in the qualitative analysis and serve as a precise means of quantitative classifying countries into their respective echelons (L1–L4).

[17] https://u.ae/eu/about-the-uae/strategies-initiatives-and-awards/strategies-plans-and-visions/innovation-and-future-shaping/uae-centennial-2071, accessed 19.11.2025.

Figure 1. **Chart of Smart Economy Readiness' Index (SERI).**



Source: authors.

PCA-Based Comparative Assessment of Smart Economy Potential

The PCA results summarized in Table 3 present normalized scores for eight enabling factors (X_1–X_8) influencing the composite Smart Economy Index (SERI) — an aggregated output measure reflecting smart economy readiness across science, innovation, education, and technology indicators. These scores range between 0 (lowest relative potential) and 1 (highest potential), enabling cross-country benchmarking.

Benchmark Countries: Australia and Austria. Australia and Austria, serving as high-performing reference points, recorded SERI values of 0.87 and 0.85, respectively. These are underpinned by uniformly high scores across governance (X_1), frontier technology readiness (X_2), and digital access (X_4), illustrating a well-rounded institutional, infrastructural, and human capital base. Notably, Austria scores the highest in governance (0.91), while Australia leads in digital infrastructure (0.96) and international student mobility (1.00), indicating vibrant cross-border academic engagement.

High-Potential BRICS Countries: China, Russia, and Brazil. Among BRICS members, China (0.79), Russia (0.76), and Brazil (0.75) emerge as the top performers. China leads in digital infrastructure (X_4 = 0.96) and macroeconomic stability (X_8 = 0.95), suggesting it leverages strong infrastructure and economic scale for smart economy growth. Russia, while not leading any single index, shows balanced scores across all dimensions. Brazil excels in student mobility (X_6 = 0.92) and macroeconomic strength (X_8 = 0.95), signifying an openness to knowledge exchange and a strong growth base.

Middle-Tier Performers: India, Indonesia, South Africa, Iran. India (SERI = 0.71) exhibits relatively consistent performance, especially in education attainment (X_5 = 0.80) and macroeconomic fundamentals (X_8 = 0.85), but is held back by lower governance (X_1 = 0.62) and global mobility (X_6 = 0.65). Indonesia (SERI = 0.72) is an outlier in digital infrastructure (X_4 = 0.88) and strong in FTRI (X_2 = 0.86), indicating recent gains in tech access and readiness. South Africa (SERI = 0.68) stands out with excellent education metrics (X_5 = 0.89) and global mobility (X_6 = 0.88), though governance and macroeconomic scores are weaker. Iran (SERI = 0.68) maintains modest performance with strengths in tertiary education investment (X_3 = 0.83) and governance (X_1 = 0.80), though global connectivity (X_6, X_7) is relatively subdued.

Low Potential Countries: Egypt, Ethiopia. Egypt (SERI = 0.55) and Ethiopia (SERI = 0.38) show limited readiness for smart economy transformation. Both countries face significant deficiencies in governance, infrastructure, and economic indicators, limiting short-term scalability.

*Emerging Hub: United Arab Emirates***.** With an SERI of 0.88, the UAE outperforms even the benchmark nations. It shows strong results across nearly all domains, particularly in FTRI (X_2 = 0.98), tertiary education (X_5 = 0.88), and trade (X_7 = 0.99). This positions the UAE as a regional innovation hub with global smart economy integration, bolstered by proactive governance (X_1 = 0.81) and digital infrastructure (X_4 = 0.91).

Based on PCA results, the adjusting KMeans cluster analysis categorizes the 12 countries into four performance-based clusters:

- *Cluster 1 (Emerging Performers): Brazil, India, Iran, Indonesia, Russia.* Moderate readiness across most indices; good potential for growth with targeted reforms**.**
- *Cluster 2 (Developing Readiness): Egypt, South Africa.* Lagging in multiple dimensions; need structural reforms in governance, infrastructure, and internationalization.
- *Cluster 3 (Leaders / Benchmarks): Australia, Austria, China, UAE.* High performance across most inputs and output; pretend to be strategic innovation hubs and smart economy leaders.
- *Cluster 4 (Lagging Performers): Ethiopia.* Strong in education attainment (X5), but exceptionally low on infrastructure, trade, and macroeconomic stability.

To ensure the reliability of our analytical results, several robustness checks and sensitivity analyses were conducted. We assessed the stability of the SERI by varying the weights of the contributing variables. The results remained stable, with only minor changes in country rankings, confirming the robustness of the SERI. Sensitivity analyses on indicator selection showed that excluding key variables, such as digital infrastructure or R&D expenditure, had little effect on the overall rankings, indicating that the analysis is not overly dependent on specific indicators. We also assessed alternative dimensionality reduction techniques like Factor Analysis and Independent Component Analysis (ICA), and found that the rankings were consistent, supporting the reliability of PCA. Further sensitivity tests were conducted by excluding newer BRICS members (e.g., UAE, Egypt, Ethiopia), and the results showed no significant impact on the rankings of core BRICS countries, reinforcing the stability of our conclusions.

Quantitative Ranking based on PCA Results Analysis & Discussion

Similar to the Clusters discussed previously, we group 12 countries into four levels based on the following threshold values of the output (i.e., SERI), as represented in Table 4. This allows to derive the transition probabilities of these countries transitioning from one echelon to the next.

Markov transition matrices displayed at Table 5 reflect the probability of a country moving between different levels (L1, L2, L3, L4) based on its SERI value in Table 3 assuming short-term stationarity. In turn, the *Bayesian Transition Matrix* (Table 6) adjusts the probabilities based on prior knowledge or evaluation of uncertainty in transitions. Thus both type of matrices together provide complementary foresight insights. The breakdown for the studied countries here can be summarized as follows. For countries at each level, the probability of maintaining their current positions is 75-80%, while the probability of moving to the next level (higher or lower) varies from 5 to 15%. For L1 countries, the probability of instantaneous ascension to L4 is zero; the same is true for the reverse case.

Building on our transition probabilities (Table 7), the following strategies presented at Table 8 guide upward mobility across echelons.

Discussion

Insights from qualitative analysis

Our qualitative review of the expanded BRICS bloc reveals a multi-tiered landscape of smart economy potential, reflecting the group's inherent diversity. This assessment allows us to categorize the nations into four distinct echelons based on their current momentum and future outlook.

L4: Leaders. China consistently demonstrates leading potential across most indicators – from patent volume and R&D investment to digital transformation and the strategic

Table 4. **The justification of the threshold values for SERI classification to four levels**

Level	SERI value	Description
L1	Low (below 0.50	These countries are considered to be in the early stages of smart economy development, facing significant challenges in governance, infrastructure, and human capital. These nations require substantial foundational investments in education, infrastructure, and governance systems to move to the next level.
L2	Medium-Low (between 0.50 and 0.60)	These countries show moderate readiness for smart economy transition but still face barriers such as underdeveloped innovation ecosystems, limited R&D investments, and gaps in digital infrastructure. Moving to L3 requires targeted efforts in innovation system building and enhancing governance quality.
L3	Medium-High (between 0.60 and 0.70)	These countries exhibit significant potential in smart economy sectors, including growing innovation ecosystems and digital transformation efforts. However, further institutional reforms and strategic investments in R&D and education are necessary to transition to L4.
L4	High (above 0.70)	These countries are leaders in smart economy readiness, with advanced digital infrastructure, robust innovation ecosystems, and a highly skilled workforce. To maintain their position, they must focus on sustaining innovation leadership and smart governance systems, ensuring continued growth and adaptation to emerging technologies.

Source: authors.

Table 5. **Markov Transition Matrix values for studied countries**

	UAE	Australia	Austria	China	Russia	Brazil	Indonesia	India	Iran	South Africa	Egypt	Ethiopia
L1	0.0	0.0	0.0	0.8	0.8	0.8	0.8	0.8	0.05	0.05	0.1	0.8
L2	0.05	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.75	0.15
L3	0.15	0.15	0.15	0.05	0.05	0.05	0.05	0.05	0.75	0.75	0.15	0.05
L4	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.05	0.05	0.05	0.0

Source: authors.

Table 6. **Bayesian Transition Matrix values for studied countries**

	UAE	Australia	Austria	China	Russia	Brazil	Indonesia	India	Iran	South Africa	Egypt	Ethiopia
L1	0.0	0.0	0.0	0.75	0.75	0.75	0.75	0.75	0.05	0.05	0.15	0.75
L2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.15	0.15	0.6	0.2
L3	0.2	0.2	0.2	0.05	0.05	0.05	0.05	0.05	0.75	0.75	0.2	0.05
L4	0.7	0.7	0.7	0.0	0.0	0.0	0.0	0.0	0.05	0.05	0.05	0.0

Source: authors.

Table 7. **Integral Markov and Bayesian Transition Matrices of SERI (Y)**

a) Numerical Values

	Markov Transition Matrix				Bayesian Transition Matrix			
Level	L1	L2	L3	L4	L1	L2	L3	L4
L1	0.80	0.15	0.05	0.00	0.75	0.20	0.05	0.00
L2	0.10	0.70	0.15	0.05	0.15	0.60	0.20	0.05
L3	0.05	0.15	0.75	0.05	0.05	0.15	0.75	0.05
L4	0.00	0.05	0.15	0.80	0.00	0.10	0.20	0.70

b) Interpretation of the Markov Matrix

Level	Explanation
L1	A country in L1 has an 80% chance of staying in L1, with a 15% chance of transitioning to L2 and a 5% chance of transitioning to L3.
L2	A country in L2 has a 70% chance of staying in L2, a 15% chance of moving to L3, and a 10% chance of transitioning to L1, and 5% chance of transitioning to L4.
L3	A country in L3 has a 75% chance of staying in L3, with a 15% chance of transitioning to L2, 5% chance of transitioning to L4, and 5% chance of transitioning to L1.
L4	A country in L4 has an 80% chance of staying in L4, with a 15% chance of transitioning to L3 and a 5% chance of transitioning to L2.

c) Interpretation of the Bayesian Matrix

Level	Explanation
L1	A country in L1 has a 75% chance of staying in L1, with a 20% chance of transitioning to L2 and a 5% chance of transitioning to L3.
L2	A country in L2 has a 60% chance of staying in L2, a 20% chance of transitioning to L3, a 5% chance of transitioning to L4, and a 15% chance of transitioning to L1.
L3	A country in L3 has a 75% chance of staying in L3, with a 15% chance of transitioning to L2 and a 5% chance of transitioning to L4 and 5% chance of transitioning to L1.
L4	A country in L4 has a 70% chance of staying in L4, with a 20% chance of transitioning to L3 and a 10% chance of transitioning to L2.

Note: The Markov Transition Matrix of SERI at Table 8 shows the probability of moving from one level (L1, L2, L3, L4) to another, while the Bayesian Transition Matrix incorporates prior uncertainty, so the transitions between levels are adjusted slightly to reflect this. The rows represent the current level, and the columns represent the probability of moving to the next level.

Source: authors.

implementation of national technology goals. Its capacity to mobilize resources and pursue long-term technological ambitions is unparalleled within the bloc.

L3: Growth Potential. This tier includes nations with substantial and rapidly advancing capabilities. India is distinguished by its vast pool of human capital, a world-class IT and software sector, and a rapidly digitizing economy. Its trajectory is exceptionally strong, contingent on improving R&D commercialization. The UAE and Indonesia are leveraging significant financial capital for aggressive, targeted investments in future-tech sectors like AI, renewables, and smart infrastructure, guided by clear and ambitious national visions[18].

L2: Developing Potential. Brazil possesses significant potential with established strengths in specific sectors (e.g., aerospace) and a large domestic market. Realizing the broader potential of a smart economy will depend on overcoming structural challenges and boosting innovation investment. Russia retains strong scientific and technical capabilities and human capital in certain areas. South Africa has the most developed innovation system in Africa, with strengths in specific research areas. Challenges include translating these into wider economic benefits and addressing socio-economic disparities that impact human capital development for the smart economy. Iran demonstrates indigenous innovative capabilities in various technological fields, often driven by necessity. Greater integration with the global economy could unlock further potential.

L1: Starting Journey. Egypt & Ethiopia are in the early stages of developing their smart economy infrastructure and ecosystems, despite having large populations. They are also showing increasing government commitment to digital transformation and technology adoption. Their potential is significant but requires sustained investment and foundational development.

This qualitative ordering suggests that development pathways within the BRICS bloc are highly differentiated. The UAE, within BRICS, is emerging as an aggressive investor in future technologies. Other members possess valuable niche capabilities and foundational strengths that, if cultivated effectively, can lead to significant advancements.

The presented breakdown illustrates the heterogeneity of current positions and emerging trajectories within the alliance. The concept of emerging potential is crucial here. Countries in the second and third tiers may possess unique comparative advantages that could allow them to leapfrog in specific areas. For example, a country with a young, digitally native population (such as India or parts of Africa within the BRICS) could rapidly adopt and innovate with new digital technologies if provided with the right education and opportunities. Similarly, countries rich in specific resources (e.g., for green technologies) can leverage these for specialized smart economy sectors.

Our assessment suggests a tiered structure of emerging potential, with variety in speeds of realization. From this perspective, there are clear leaders; dynamic and ambitious players close behind them; players with accumulated niche advantages; and a group of those who are just starting out.

Realizing this emerging potential depends on many factors, such as with strategic vision of own path, effective governance, strategic agility, readiness for transformation, features of resource base etc.

To effectively harness their emerging potential in smart economy sectors, BRICS governments and policymakers should consider the recommendations in such directions as: fostering national and regional innovation ecosystems; investments in human capital and education systems; inclusive digital transformation; and strengthening governance (Table 9).

[18] https://brics.br/en/news/artificial-intelligence-and-climate-brics-declaration-proposes-policies-to-protect-workers, accessed 22.10.2025.

Table 8. **Strategies to move from one level to next level of Smart Economy**

Inter-level transitions	Description of strategic steps
From L1 (Low) to L2 (Developing)	• Catalyze foundational gains via targeted infrastructure investments (e.g., digital access, education). • Leverage international collaboration — e.g., peer learning from BRICS partners—to mitigate institutional constraints. • Deploy ”lean regulations” — to enable innovation while avoiding stifling bureaucracy.
From L2 to L3 (Medium-High)	• Expand R&D ecosystems, introduce university–industry linkages, and support startups through incubation programs. • Improve human capital quality by reforming higher education, boosting STEM curricula, and promoting lifelong learning. • Strengthening governance for smarter adoption — include adaptive, citizen-centric governance models as seen in smart city literature.
From L3 to L4 (High / Benchmark)	• Consolidate innovation leadership through frontier technology deployment (AI, IoT, blockchain). • Institutionalize adaptive smart governance systems by embedding performance accountability, transparency, stakeholder engagement. • Sustain ecosystems with sustainability focus, layering environmental considerations into digital transformation (”twin transition”)
Cross-cutting interventions across all stages	• Strengthen inter-sectoral collaboration via innovation helix models. • Foster adaptability through institutional complementarity, ensuring reforms in governance, education, and innovation are mutually reinforcing.
Source: authors.	

Table 9. **Policy recommendations as followed from qualitative analysis**

Direction	Steps
Foster National and Regional Innovation Ecosystems	• Increase public and private R&D investment targeted at strategic sectors of the smart economy. • Strengthen linkages between universities, research institutions, and industry to improve the commercialization of research and patent output. • Support tech startups and SMEs through access to finance, incubation programs, and reduced bureaucratic hurdles. • Implement National innovation funds and regulatory sandboxes to support innovation. • Enhance intellectual property rights protection to encourage innovation and attract investment.
Invest in Human Capital and Education Systems	• Undertake comprehensive reforms of education systems at all levels, emphasizing STEM skills, digital literacy, critical thinking, creativity, and adaptability. • Expand access to quality higher education and vocational training, ensuring equitable opportunities. • Promote lifelong learning initiatives.
Inclusive Digital Transformation	• Develop and implement national strategies for comprehensive digital transformation to fundamentally reshape industries and services. • Invest in digital infrastructure to bridge internal digital divides. • Promote the development of digital public goods and e-governance services. • Create Citizen engagement platforms to reinforce participatory governance.
Strengthen Governance	• Develop agile, adaptive governance policies and regulatory frameworks that foster innovation while addressing ethical considerations and societal impacts. • Enhance government effectiveness, transparency, rule of law, and control of corruption to create a stable and predictable environment for investment and innovation. • Prioritize the integration of advanced technologies into governance systems themselves to enhance public service delivery and policy-making efficiency. • Ensure policies related to smart economy development align with broader national development goals and involve cross-sectoral coordination.
Source: compiled basing on (Božić, 2025; OECD, 2021; Saba, Ngepah, 2024; WIPO, 2024).	

Conclusion

This paper has undertaken an analysis of the emerging potential within the expanded group of ten BRICS nations and two developed economies as benchmarks for smart economy sectors, focusing on high-tech, knowledge-intensive industries. The transition to a smart economy, driven by innovation, digital transformation, and human capital, is a critical pathway for these influential emerging economies to achieve sustainable progress and navigate the complexities of the 21st-century global landscape. The analysis framed around key indicators such as patent activity, scientific publications, education system transformation, digital transformation progress, human capital competencies, strategic alliances, and the overarching governance environment, reveals a landscape of diverse capabilities, significant opportunities, and persistent challenges across the BRICS bloc.

Our findings underscore that smart economy transition hinges on synchronizing human capital development, frontier technology deployment, digital infrastructure, and governance reforms. To have a chance for moving a country to the upper level, policymakers must prioritize strategic sequencing:

- start with foundational investments in education and infrastructure (for L1–L2),
- build innovation ecosystems and adaptive governance (L2–L3),
- institutionalize smart governance and sustainability (L3–L4).

Synergizing cooperation frameworks within ten BRICS nations to share best practices will be the significant driving force that will provide the most advantageous benefits for all BRICS countries.

Table 10. **Future Research Directions**

Direction	Description
Temporal analysis	Apply longitudinal data to validate Markov transitions over time empirically.
Disaggregate studies	Explore sector-level smart economy transitions in TEN BRICS NATIONS.
Policy experimentation	Conduct quasi-experimental evaluations of smart regulation or education reforms.
Inclusivity focus	Analyze how smart economy transitions impact marginalized groups across clusters.
Extended benchmarking	Include other emergent digital economies (e.g., Vietnam, Kenya) to assess framework universality.
Source: authors.	

Both the qualitative analysis discussion and quantitative analysis discussion have the following commonalities. Both methods pinpointed education, innovation outputs, and governance as critical. Qualitatively, countries like China and UAE emerged as leaders; quantitatively, their PCA/SERI values confirmed this. Qualitative echelons (leaders, growing, niche, lagging) mirror PCA-based clusters, reinforcing consistency. Both reveal that even countries with educational strengths require governance and infrastructure improvements for SERI advancement. Countries strong in trade and student mobility performed well across both analyses, confirming the importance of international openness.

Proposed future research directions are summarized at Table 10.

The presented research has the following theoretical and practical implications to inform policymakers, business leaders, and the scientific community. Theoretically, our study validates the integration of growth theory, innovation helix models, and smart governance theory into a unified framework, showing institutional complementarity and transition dynamics (via Markov and Bayesian models) as strong explanatory tools.

In terms of practice, our study offers policymakers a stage-based, evidence-backed model for designing interventions. Cluster-specific strategies advocate more effective resource allocation and targeted reforms. The dynamic transition framework provides foresight into likely trajectories and policy windows. For ten BRICS nations, a clear understanding of their comparative strengths and weaknesses in the smart economy domain can guide strategic investments and policy reforms. For international observers, this analysis can highlight opportunities for partnership and engagement.

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Appendix 1. **Reasons for choosing PCA and principal component methods**

These methods as tools for achieving our research goal were chosen for several reasons. Given the large number of indicators available for assessing the smart economy potential of twelve countries (e.g., patents, R&D investment, digital infrastructure, education metrics, governance factors), PCA allows us to reduce the dimensionality of the dataset while retaining most of the variance in the data. This makes the analysis more manageable, interpretable, and computationally efficient. PCA is particularly useful when dealing with complex datasets that contain multiple correlated variables. It enables us to uncover the underlying structure of the data by transforming the original variables into a smaller number of uncorrelated components (principal components) that explain the maximum variance in the data. This is crucial in our context, where the smart economy potential is influenced by numerous interrelated factors (e.g., governance quality, innovation capacity, education systems, digital infrastructure). By reducing the number of dimensions while retaining most of the variance, PCA facilitates the interpretation of the results. The principal components derived from PCA represent aggregated measures of the various factors contributing to a country's smart economy readiness, making it easier to assess and compare the countries across these aggregated components. Many of the indicators in our dataset (e.g., R&D expenditure, patent activity, and scientific publications) are highly correlated with each other. PCA helps mitigate the issue of multicollinearity by creating uncorrelated components from these correlated variables, which allows for more reliable statistical analyses and clearer insights into the underlying drivers of smart economy potential.

PCA generates principal components (PCs), which are linear combinations of the original variables. These PCs capture the largest variance in the data, ensuring that the most significant factors influencing the smart economy potential are retained in the reduced dataset. The first principal component typically explains the largest portion of the variance, followed by subsequent components, each explaining progressively smaller amounts. By focusing on the first few principal components, we are able to retain most of the information in the data while simplifying the analysis. The variable weights for each component were determined by the eigenvectors of the covariance matrix, which were computed as part of the PCA process. These weights represent the relative importance of each indicator in contributing to the smart economy readiness of each country.

Once we apply PCA we subject the principal components (PC) to compute both Markov and Bayesian transition matrices to model the dynamic transitions of countries between different development echelons in the context of smart economy readiness. The rationale of these models was based on their respective strengths in handling different types of uncertainties and system behaviors (see Table A1-1 for details). Both matrices offer valuable insights into the progression or regression of countries based on their FTRI (Y) values. Markov Transition Matrix reflects the direct transition probabilities based on the current state of the countries, with a tendency for countries to stay in their current leve, while Bayesian Transition Matrix adds a layer of uncertainty or prior knowledge about possible transitions, resulting in slightly more fluid probabilities, especially for transitions between levels. In essence, if one has a system where the current state primarily determines the future state and you need a simple, efficient model, a Markov matrix might be a viable choice. If one has prior knowledge about the system, need to quantify uncertainty, or want to compare different models, a Bayesian approach is more appropriate. Often, Bayesian methods are used in conjunction with Markov models. For example, Bayesian inference can be used to estimate the transition probabilities in a Markov model, incorporating prior knowledge about those probabilities..

Together, they offer a robust framework for understanding the transitions within the BRICS nations, allowing us to explore both the most likely trajectories and the underlying uncertainties that may affect future development.

Table A1-1. Comparative features of Transition Matrices: Markov vs Bayesian

a) ***Markov Transition Matrices***

Feature	Description
Assumption of Stationarity	The Markov model is appropriate when we assume that the future state of a system depends solely on its current state, and not on the sequence of events that preceded it. In the context of our analysis, this means that the probability of a country transitioning from one development level to another is based purely on its current state (i.e., its current FTRI (Feinson, 2003).
Simplicity and Efficiency	Markov matrices are straightforward to compute and interpret. They allow for easy identification of transition probabilities between states and provide a clear framework for understanding the likelihood of a country remaining at or moving between specific levels of smart economy readiness. This simplicity makes the Markov model ideal for situations where prior knowledge is minimal or when we wish to focus solely on the current state's influence on future transitions (Feinson, 2003).

b) Bayesian Transition Matrices

Feature	Description
Incorporation of Uncertainty and Prior Knowledge	Unlike Markov matrices, Bayesian transition matrices take into account not only the current state but also prior knowledge or uncertainty about the system. By incorporating prior beliefs about transition probabilities, the Bayesian approach allows for a more flexible model that can account for the inherent uncertainty in predicting future transitions (Tilson et al., 2010).
Adaptation to Changing Circumstances	The Bayesian approach can adjust transition probabilities based on new data, making it particularly useful for dynamic environments where historical patterns or other external factors may shift over time. In our context, the Bayesian model was used to incorporate prior insights or expert knowledge about the likelihood of countries moving between echelons, as well as to quantify the uncertainty in the prediction process (Tilson et al., 2010).

Appendix 2. **Set of Output and Inputs (raw, pre-normalized indicators) used in SERI Calculations**

FRONTIER INDICATORS (Y)	
Scientific and technical journal articles	$Y_{1.1}$
Documents	$Y_{1.2}$
Citable documents	$Y_{1.3}$
Citations	$Y_{1.4}$
Self-citations	$Y_{1.5}$
Citations per document	$Y_{1.6}$
H index	$Y_{1.7}$
Industrial design applications, nonresident, by count	$Y_{1.8}$
Industrial design applications, resident, by count	$Y_{1.9}$
Patent applications, nonresidents	$Y_{1.10}$
Patent applications, residents	$Y_{1.11}$
Trademark applications, nonresident, by count	$Y_{1.12}$
Trademark applications, resident, by count	$Y_{1.13}$
GOVERNANCE FACTORS (X_1)	
Control of Corruption	$X_{1.1}$
Government Effectiveness	$X_{1.2}$
Political Stability	$X_{1.3}$
Regulatory Quality	$X_{1.4}$
Rule of Law	$X_{1.5}$
Voice & Accountability	$X_{1.6}$
FTRI (X_2)	
Overall index	$X_{2.1}$
ICT	$X_{2.2}$
Skills	$X_{2.3}$
Research and Development	$X_{2.4}$
Industry activity	$X_{2.5}$
Access to finance	$X_{2.6}$
PCI Composite Index	$X_{2.7}$
INVESTMENT IN TERTIARY EDUCATION, R&D & HR (X_3)	
Current education expenditure, tertiary (% of total expenditure in tertiary public institutions)	$X_{3.1}$
Government expenditure on education, total (% of GDP)	$X_{3.2}$
Government expenditure per student, tertiary (% of GDP per capita)	$X_{3.3}$
Expenditure on tertiary education (% of government expenditure on education)	$X_{3.4}$
Research and development expenditure (% of GDP)	$X_{3.5}$
Researchers in R&D (per million people)	$X_{3.6}$
Pupil-teacher ratio, tertiary	$X_{3.7}$
Technicians in R&D (per million people)	$X_{3.8}$
Tertiary education, academic staff (% female)	$X_{3.9}$
DIGITAL ACCESS (X_4)	
Fixed broadband subscriptions (per 100 people)	$X_{4.1}$
Fixed telephone subscriptions (per 100 people)	$X_{4.2}$
Mobile cellular subscriptions (per 100 people)	$X_{4.3}$
Secure Internet servers	$X_{4.4}$
Individuals using the Internet (% of population)	$X_{4.5}$
TERTIARY EDUCATION ENROLLMENT & ATTAINMENT STATUS (25+) (X_5)	
School enrollment, tertiary (% gross)	$X_{5.1}$
School enrollment, tertiary (gross), gender parity index (GPI)	$X_{5.2}$
School enrollment, tertiary, female (% gross)	$X_{5.3}$
School enrollment, tertiary, male (% gross)	$X_{5.4}$
Educational attainment, at least Bachelor's or equivalent, population 25+, total (%) (cumulative)	$X_{5.5}$
Educational attainment, at least Master's or equivalent, population 25+, total (%) (cumulative)	$X_{5.6}$
Educational attainment, Doctoral or equivalent, population 25+, total (%) (cumulative)	$X_{5.7}$
Educational attainment, Doctoral or equivalent, population 25+, female (%) (cumulative)	$X_{5.8}$
Educational attainment, Doctoral or equivalent, population 25+, male (%) (cumulative)	$X_{5.9}$
Educational attainment, at least Master's or equivalent, population 25+, female (%) (cumulative)	$X_{5.10}$
Educational attainment, at least Master's or equivalent, population 25+, male (%) (cumulative)	$X_{5.11}$
Educational attainment, at least Bachelor's or equivalent, population 25+, male (%) (cumulative)	$X_{5.12}$
Educational attainment, at least Bachelor's or equivalent, population 25+, female (%) (cumulative)	$X_{5.13}$
GLOBAL STUDENT MOBILITY (INBOUND & OUTBOUND) & COLLABORATION (X_6)	
Total inbound internationally mobile tertiary students, studying abroad, both sexes (number)	$X_{6.1}$
Total outbound internationally mobile tertiary students studying abroad, all countries, both sexes (number)	$X_{6.2}$
Inbound mobility rate, both sexes (%)	$X_{6.3}$
Inbound mobility rate, female (%)	$X_{6.4}$
Inbound mobility rate, male (%)	$X_{6.5}$
Net flow of internationally mobile students (inbound - outbound), both sexes (number)	$X_{6.6}$
Net flow ratio of internationally mobile students (inbound - outbound), both sexes (%)	$X_{6.7}$
Outbound mobility ratio, all regions, both sexes (%)	$X_{6.8}$
GLOBAL TRADE IN HIGH TECH SECTORS AND ICT (X_7)	
High-technology exports (% of manufactured exports)	$X_{7.1}$
High-technology exports (current US$)	$X_{7.2}$
ICT goods exports (% of total goods exports)	$X_{7.3}$
ICT goods imports (% total goods imports)	$X_{7.4}$
ICT service exports (% of service exports, BoP)	$X_{7.5}$
ICT service exports (BoP, current US$)	$X_{7.6}$
MACROECONOMIC FACTORS (MF) (X_8)	
GDP (constant 2015 US$)	$X_{8.1}$
GDP growth (annual %)	$X_{8.2}$
GDP per capita (constant 2015 US$)	$X_{8.3}$
GDP per capita growth (annual %)	$X_{8.4}$

Note: Data sets with initial calculations of all the represented variables for each studied country can be found in the Supplementary file.

Source: extracted from World Bank (2023), UNESCO (2021), WIPO (2024), Scimago Journal & Country Rank (https://www.scimagojr.com/, accessed 17.12.2025).