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Powering progress: The interplay of energy security and institutional quality in driving economic growth

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HIGHLIGHTS

- Energy security impacts economic growth, both directly and indirectly, with institutional quality playing a key role.
- Initial energy development boosts growth, but energy availability, supply, demand, and efficiency hinder growth in the region.
- Institutional quality mitigates the negative impacts of energy security elements, transforming them into positive influences on growth.
- The aggregate energy security index and institutional quality index positively influence growth, as do urbanization and FDI.

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ABSTRACT

Energy security is a crucial determinant of sustainable economic growth, especially in the South Asian region, where persistent energy challenges and institutional shortcomings have stifled developmental potential. This study aims to elucidate the complex interplay between energy security and economic growth, with a focus on how institutional quality moderates and transforms these dynamics to promote more resilient growth in the region. Drawing on data from eight South Asian countries from 2000 to 2022, the study employs a panel-corrected standard error (PCSE) model, reinforced by robust feasible generalized least squares (FGLS) method. The results reveal that energy availability, energy supply capacity, energy demand, and energy efficiency exert negative impacts on economic growth, whereas energy development capacity contributes positively to economic growth. Additionally, the novel aggregate energy security index and institutional quality index demonstrate positive effects on growth, alongside urbanization and foreign direct investment. Conversely, trade openness is found to have a negative influence on economic growth. Crucially, the institutional quality index absorbs the adverse effects of energy availability, energy supply capacity, energy demand, and energy efficiency on growth, while amplifying the positive impacts of both individual elements of energy security and its aggregate index. These results highlight the necessity for urgent policy interventions to simultaneously address existing energy security and institutional quality concerns to achieve sustainable economic growth.

1. Introduction

The profound interconnection between economic growth and energy security extends across all economies [1]. Energy security is increasingly recognized as a fundamental driver of economic expansion and sectoral development across the globe [2]. For countries striving to achieve sustainable economic development, ensuring a reliable and adequate energy supply is essential [3]. This not only fuels industrial output but also supports broader economic growth [4]; Rosa et al., [5]). The risks associated with energy supply disruptions can significantly undermine economic stability and growth prospects. As nations grapple with the challenges of rapid globalization and aim to enhance living standards while combating poverty and inequality, a focused approach to energy security becomes paramount. This involves implementing macroeconomic policies that foster resilient energy infrastructure, diversify energy sources, and integrate innovative technologies to meet the escalating energy demands affordably and sustainably [6].

Specifically, South Asia presents a distinctive landscape of challenges and opportunities in the pursuit realm of energy security and economic growth [7]. With rapidly growing populations, accelerating

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urbanization, and immense economic potential, the region stands at a critical juncture in its development trajectory [8]. However, South Asia's progress is hindered by weak institutional frameworks, inadequate energy infrastructure and a heavy reliance on imported fuels, which together contribute to environmental degradation and energy insecurity ([9]; [10–13]). The region's energy sector is marked by inefficiencies and supply constraints, further deepening economic disparities and slowing development [14]. Despite these considerable challenges, South Asia also holds vast potential for sustainable growth through the diversification of energy sources, increased investments in renewable energy, and enhanced regional cooperation. Addressing energy security in a holistic manner is not only essential for unlocking the region's full economic potential but also for ensuring sustained, long-term growth and stability [15].

Ensuring resilience and sustainable energy security in South Asia depends critically on the region's institutional capacity, which remains a major obstacle in its development pathway. Effective and robust institutions are key to implementing policies and regulatory frameworks that support energy security, innovation, and long-term economic growth [16]. By promoting regulatory stability, reducing market uncertainty, and facilitating investment in energy infrastructure, strong institutions can mitigate some of the region's most pressing energy challenges [17,18]. However, South Asia continues to struggle with fragile institutional setups plagued by significant administrative corruption, weak regulatory enforcement, political instability, and ineffective governance [11,19,20]. These institutional inefficiencies not only impair the region's ability to develop resilient energy systems but also exacerbate the challenges of achieving sustainable growth. Despite recognizing institutional quality as a pivotal driver of sustainable energy sources [21,22], which leads to sustainable economic development [23,24], existing studies often short fall in considering how institutional quality can influence the relationship between energy security and sustainable economic growth. While extensive research has been conducted on the effects of energy consumption, renewable energy, and institutional quality on economic growth [25–29], the role of institutional quality as a moderating factor in this nexus remains significantly underexplored. Specifically, the interaction between energy security and institutional metrics has not been addressed in the context of South Asia. This gap is critical, as it leaves policymakers with an incomplete understanding of how to address the region's compounded energy and economic growth challenges simultaneously.

To fill this gap, the present study is driven by two primary objectives: First, it seeks to analyze how key element of energy security, individually and collectively, impact economic growth in South Asia, considering the influence of major environmental and macroeconomic predictors. Second, the study aims to elucidate how existing institutional quality directly impacts economic growth and how it moderates the relationship between economic growth and energy security. This dual focus on energy security and institutional quality highlights the intricacies of these two interrelated domains in shaping South Asia's economic future. The important aspect of this study lies in its nuanced exploration of the key elements of energy security to drive sustainable economic growth in South Asia. Energy security, perhaps, includes five crucial elements: energy availability, energy supply capacity, energy demand, energy development capacity, and energy efficiency (Tayyab Ayaz et al., [30]). Collectively, these elements define a nation's energy security dynamics, enabling countries to establish a resilient and robust energy system that supports sustainable growth. Individually, energy availability ensures that the necessary energy is consistently accessible to support both household and industrial consumption, a key factor in sustaining economic prospects and daily life [31]. On the other hand, energy supply capacity is the ability of a nation to generate or import the required energy to meet its needs, reflecting the nation's potential to withstand global energy shocks and mitigate energy dependencies [32]. Energy demand represents the quantity and type of energy required for household and industrial consumption, informing essential decisions about energy production and distribution [33]. Furthermore, energy development capacity pertains to the generation of environmentally sustainable energy, particularly renewable energy, and represents a nation's ability to foster long-term economic sustainability through the creation of low-emission industries [34,35]. Finally, energy efficiency focuses on optimizing the use of energy to produce desired economic output while minimizing waste, reducing costs, and enhancing efficiency [36].

Building on the exploration of energy security and its interplay with institutional quality, this study makes several key contributions to the existing knowledge. First, while numerous studies have highlighted the energy implications of economic growth, the nuanced dynamics of energy security remain largely underexplored. This oversight is likely due to the relatively recent focus on energy security and the absence of a standardized method for measuring energy security. To address this gap, the study establishes a novel framework for understanding energy security, breaking it down into five core elements, constructed through a diverse set of variables and complex modeling. This innovative approach not only advances a more precise understanding of how various facets of energy security influence growth but also enriches the contemporary discourse on energy security. Second, although a few studies, such as those by Le and Nguyen [37] and D'Errico [38], have examined the role of energy security in driving economic growth across diverse economies, South Asia remains notably underexplored despite its vast population, high levels of emissions, and significant growth potential. By focusing on South Asian region, the study offers an in-depth analysis of how energy security, in all its dimensions, influences economic growth. This enables the study to highlight specific areas of policy that warrant urgent attention, particularly in a region grappling with institutional challenges, environmental degradation, and energy efficiency. Third, the study emphasizes the pivotal role of institutional quality both as a direct determinant and a moderating predictor in the relationship between energy security and growth. By employing an innovatively constructed institutional quality index, derived from key measures of the Worldwide Governance Indicators (WGI), this research uniquely quantifies the influence of institutional factors on energy security. This novel approach distinguishes the study from prior literature, as it not only assesses the direct effects of institutional quality but also its moderating spillovers in the relationship between energy security and growth. This dual focus enables policymakers to prioritize resources effectively and implement simultaneous efforts aimed at improving institutional performance, thereby supporting energy security and fostering economic growth in the region.

The remainder of this study is structured as follows: Section 2 provides an extensive reviews of the relevant literature, highlighting key theories, empirical findings, and research gaps. Section 3 outlines the data sources, defines the variables used, and details the estimation techniques. In Section 4, the statistical results are presented and interpreted, offering insights into the relationships explored. Section 5 offers a thorough discussion of the findings, linking them to the existing body of knowledge and contextualizing their implications. Finally, Section 6 concludes the study by summarizing key insights, presenting specific policy recommendations, addressing the study's limitations, and proposing avenues for future research.

2. Literature review

2.1. Conceptual insights

Energy security, though lacking a universally agreed-upon definition, is generally known as the uninterrupted and reliable access to necessary energy sources for both households and industrial consumption at an affordable price [39,40]. This concept highlights energy's crucial role in sustaining economic stability and growth. Within economic theories, energy is often regarded as a fundamental input in production processes, alongside labor, capital, and technology, emphasizing its indispensable role in driving economic activity [41,42]. Moreover, emerging literature points to the growing importance of intellectual property and intellectual capital in explaining the development of renewable sources, highlighting innovation and communication technologies as drivers of the sustainable energy transition [24,43–45]. The intricate relationship between energy and economic growth has been fundamentally conceptualized through various hypotheses that attempt to capture these interdependencies [46–48]. The first of these is the "growth-led hypothesis," which posits that energy is a fundamental catalyst for economic growth. According to this perspective, energy ensures the availability, accessibility, and affordability of essential sources that support industrial activities, transportation, and household consumption. The steady and affordable supply of energy enables production, drives innovation, and creates jobs, thus establishing a positive correlation between energy and economic output [49]. The second perspective, the "reciprocal hypothesis" suggests that the relationship between energy and growth is mutually reinforcing. According to this view, economic growth stimulates energy demand, as expanding industries, services, and households require more energy. In return, energy availability further accelerates growth by supporting increased industrial output and technological innovation [50]. Proactive energy policies, such as investments in renewable energy and infrastructural development, can enhance both energy security and economic performance, whereas restrictive energy policies may hamper economic growth [37,51]. The third hypothesis, known as the "directional hypothesis," suggests a unidirectional influence where only economic output drives energy consumption, not the other way round. In this scenario, as an economy grows, it demands more energy to support industrialization, urbanization, and transportation, but energy availability does not directly promote growth [52,53]. Finally, the "neutral hypothesis" posits that energy consumption and growth are not interdependent [46,54]. Under this framework, the level of energy consumption does not influence economic output, nor does economic growth alter energy demand. This views aligns with certain environmental and sustainability theories, suggesting that economies can decouple growth energy consumption, especially through the adoption of cleaner, more efficient technologies [55]. In such cases, energy policies could prioritize sustainability and environmental goals without concerns for harming economic performance [56].

2.2. Empirical insights

The available literature documents a wide range of studies delving into the investigation of each hypothesis across diverse economies, employing different methodological approaches. For instance, studies by Tang et al. [57], Yusuf [58], Tao et al. [59], Zhou [60], Hu et al. [61], Odhiambo [62], Wang et al. [63], Rahman et al. [64], and Tiwari [65] have examined the impact of primary energy consumption on economic growth within various regions, validating the growth-led hypothesis in the presence of major socioeconomic and environmental predictors. Consequently, given the globally growing environmental and health pressures associated with primary energy consumption as an industrial input, another body of literature emerged, focusing on the importance and impact of renewable energy consumption on economic growth. This body of work underscores the transition to renewable energy as a viable and environmentally sustainable pathway for contemporary economic development, necessitating substantial investments and commitments to achieving carbon-free growth. For instance, studies conducted by Aziz et al. [66], Akram et al. [67], Djellouli et al. [68], Wang et al. [69–71], Dasanayaka et al. [72], Ojekemi and Ağa [73], Chen et al. [74], Xie et al. [75], Schembri et al. [76], You et al. [77], and As'ad [78], collectively demonstrate the positive influence of renewable energy on economic growth. However, these studies often overlook the implication of sufficiency and accessibility of innovative sources of energy, leaving ample room for the next wave of empirical studies to explore the crucial nexus between energy security and economic growth.

Although the shift from qualitative to purely quantitative analysis of the impact of energy security on economic growth is a burgeoning area of research, there remains a paucity of studies that thoroughly examine this critical relationship. For example, Gasparatos and Gadda [79] employed a set of data spanning from 1979 to 2003 and examined the impact of energy security on economic output and environmental degradation in Japan. Their results indicate a 66.9 % increase in energy consumption and a 93.7 % rise in environmental pressures. Growing reliance on imported energy threatens Japan's long-term economic sustainability and resources security. More specifically, Le and Nguyen [37] investigated the influence of energy security on economic growth in a panel 74 developing countries from 2002 to 2013. Utilizing a panel-corrected standard error model, their findings reveal a positive relationship between energy security and economic growth. Conversely, they observed that energy insecurity has detrimental effects on economic growth across all the included nations, underscoring the critical importance of stable energy supply for sustainable development. Additionally, Fang et al. [6] investigated the dynamics of energy security and its relationship with economic growth in China using dataset spanning from 2005 to 2015. They found that energy security shows a fluctuating trend, forming an inverted U-shaped curve with growth, indicating significant risk to sustainable energy security. China's energy security scored well in acceptability and development capacity, but the continuous decline in availability highlighted the need for a stronger regulation. Additionally, Mahmood and Ayaz [80] examined the impact of energy security represented by energy demand and supply gaps on economic growth in Pakistan from 1980 to 2012. The authors employed the error-correction approach and found there exists unidirectional causality between economic growth and energy demand and supply gaps in both the short- and long-run. Their findings documented a negative nexus between growth and energy security, underscoring that insufficient energy security severely impedes Pakistan's economic growth. Likewise, Balitskiy et al. [81] analyzed the effects of energy security on economic in a panel of 26 European Union countries from 1997 to 2011 using a panel cointegration model grounded in the neoclassical growth approach. Their results revealed a long-term cointegration between natural gas consumption and economic growth. In the short-term, both the directional and growth-led hypotheses were validated, indicating mutual reinforcement and growth potential through energy security.

Nepal and Paija [82] explored the nexus between energy security, measured via electricity availability, and economic growth in Nepal. Their analysis incorporated the influence of capital formation and population. Employing the ARDL bounds test model and the Toda-Yamamoto Granger causality approach, the study analyzed data from 1975 to 2014. Their findings revealed no long-run cointegration between economic growth and electricity consumption, setting Nepal apart within South Asian context. Additionally, Nepal and Musibau [83] examined the impact of energy security, renewable energy, and non-renewable energy on economic growth in ASEAN countries from 1980 to 2018 using a dynamic common correlation effect model. The study revealed a long-run nexus between energy security, renewable energy, non-renewable energy, and growth, and identified a feedback loop between economic growth and renewable energy. Kartal [84] analyzed the causal relationship between economic growth and energy security across a panel of 74 countries, classified into high-, upper-middle-, and lower-middle-income economies. Using a panel Granger causality model grounded in Konya's approach, the study found diverse causality patterns: unidirectional causality from energy security to economic growth in 14 countries, a feedback response in 20 countries, bidirectional causality in another 22 countries, and no causality in the remaining 18 countries. Among others, Banna et al. [2] examined the impact of energy security risk on economic stability using a panel data from 68 countries over the period from 1980 to 2021. Their results indicate that enegy security risk negatively affects GDP growth across their recipient panel, moderated by institutional quality, worsend by high inflation and geopolitical risks. Lastly, an exceptional study by Adedeji et al. [85] offers valuabe insights into the nexus between energy security and economic growth in the presence of governance quality in Sub-Saharan Africa from 2000 to 2020. Using the Poisson Pseudo-Maximum Likelihood Estimator (PPMLE) method, their findings indicate that while energy security enhances growth, the interaction with governance quality improves the efficiency of energy availability, further boosting economic performance.

2.3. Literature insights

From the available literature on the energy-growth nexus, though still evolving, several significant gaps are identified across the various hypotheses. While numerous theoretical and descriptive studies exist ([86,87]; Tufail et al., [88]; [89–91]), there remains a notable scarcity of empirically sophisticated examinations exploring the relationship between energy security and economic growth. This gap is particularly pronounced in studies focusing on South Asian economies. Additionally, the critical role of institutional quality in shaping the energy-growth landscape is often overlooked. This oversight limits our understanding of how robust institutional frameworks can enhance the effectiveness of energy policies and their subsequent influence on economic growth in South Asia. Collectively, these critical gaps lead to an incomplete understanding and missed opportunities to formulate strategies that effectively combine institutional improvements within energy security initiatives. To address these gaps and extend the existing literature, the present study develops new hypotheses as follows: H_1: Energy security enhances economic growth, considering growth potential and the influence of major macroeconomic predictors in South Asia. H_2: Institutional quality exerts a significantly positive impact on economic growth as a critical growth predictor. H_3: Institutional quality mitigates the adverse consequences caused by inefficient energy security and enhances the energy-growth nexus.

3. Methodology

To maintain clarity, coherence, and a well-organized analysis, we adopted a rigorous systematic approach. While detailed descriptions are provided in the relevant sub-sections, this methodology, adhering to a series of scientific steps, is visually illustrated in Fig. 1. It serves as a guiding framework for the analysis, ensuring a thorough and logical exploration of the research objectives.

3.1. Data

In this study, we utilize a set of panel data for South Asian countries, including Afghanistan, Bangladesh, Bhutan, India, Nepal, Maldives, Sri Lanka, and Pakistan. The dataset used spans from 2000 to 2022, prioritizing data availability from diverse reputable sources and representing the latest available data with annual observations. To maintain analytical integrity, periods with insufficient data were excluded from analysis, ensuring a balanced panel dataset for all augmented variables. Notably, consistent data for institutional quality indicators is only available from the year 2000 onward, necessitating this specific timeframe for a comprehensive and robust analysis. We selected South Asia for several compelling reasons: Despite its critical role as a regional hub of emissions and growth, South Asia has been relatively underexplored by scholars examining the role of energy security in economic growth. The region's diverse economic landscape, high population density, and significant environmental challenges provide a unique opportunity to understand the complex balance between economic growth, energy security, and environmental preservation [12]. South Asian countries, with their substantial resource extraction and consumption patterns, offer insights into the impact of domestic energy security practices. Additionally, the policy relevance of our study is heightened in this region, where policymakers are increasingly focused on achieving SDGs. South Asia also presents a platform for potential regional cooperation initiatives to address common and spatial economic and environmental challenges. The region's emerging interest in advancing economic growth to combat existing poverty underscores the need to explore the

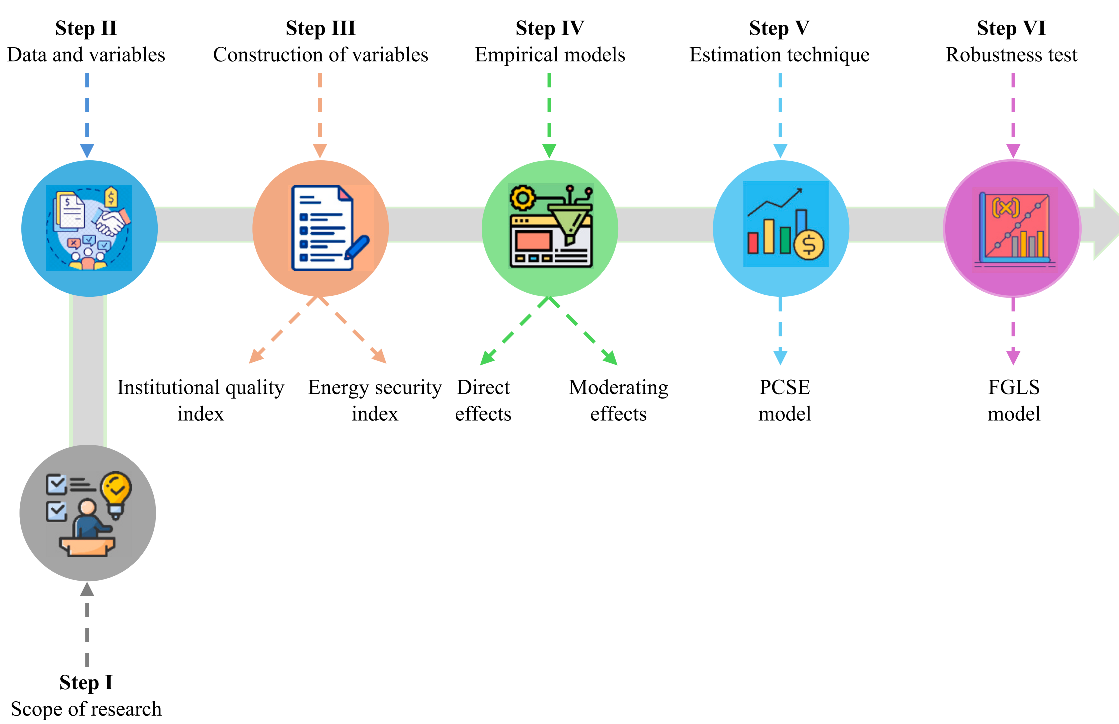

Fig. 1. Methodological framework.
(Source: Authors' depiction.)

Table 1
Variables' derivation and compilation.

Input variables (initial symbols, measurement)	Calculation	Empirical variables (measurement)	Final symbols	Sources
Primary energy consumption (PEC, kilowatt-hrs, m)	PEC/PEG	Energy availability (ratio)	EnS_1	OWD
Primary energy generation (PEG, kilowatt-hrs, m)				
Total population (POP, persons)	PEC/POP	Energy supply capacity per capita (ratio)	EnS_2	WDI
Primary energy demand (PED, kilowatt-hrs)	PED/POP	Energy demand per capita (ratio)	EnS_3	OWD
Renewable energy consumption (REN, kilowatt-hrs, m)	REN/FPEC	Energy development capacity (ratio)	EnS_4	WDI
Final primary energy consumption (FPEC, kilowatt-hrs, m)				
Total labor force (L, persons)	SSBM-DEA model	Energy efficiency (numbers)	EnS_5	WDI
Gross fixed capital formation (K, constant US dollars)				WDI
CO_2 emission (CO_2, metric tons per capita)				OWD
Primary energy consumption (E, kilowatt-hrs/capita)				OWD
EnS_1, EnS_2, EnS_3, EnS_4, and EnS_5 (ratio)	Sarma [102]	Energy security index (numbers)	AgEnS	
CoC, RoL, VoC, GoE, PoS, and ReQ (percentile)	Sarma [102]	Institutional quality index (numbers)	InQ	WGI
Per capita GDP (EcG, constant 2015 US dollars)		Economic growth (hundreds of US$)	EcG	WDI
Foreign direct investment, net inflows (GDP %)		Foreign direct investment (%)	FDI	WDI
Trade openness (GDP %)		Trade openness (%)	TrO	WDI
Urbanization (POP %)		Urbanization (%)	UrB	WDI

Notes: WDI: World Development Indicators, OWD: Our World in Data, WGI: Worldwide Governance Indicators..
Source: Authors' compilation.

potential of these initiatives in achieving a sustainable economic future.

3.2. Selection of variables

3.2.1. Dependent variable

Economic growth (EcG) is employed as the dependent variable. It is quantified by per capita gross domestic product, which is measured in hundreds of constant 2015 US dollars. The choice of EcG stems from its pivotal role in accurately reflecting the net response of South Asia's contemporary growth trajectory to variations in both critical measures of energy security and institutional quality. EcG has been a widely used metric in prior literature, including studies by Islam [92], Nathaniel and Adeleye [93], Nguyen et al. [94], Amin et al. [95], and Awan and Azam [96].

3.2.2. Explanatory variables

In this study, energy security (EnS) and its five core elements (EnS_1 to EnS_5), along with institutional quality index (InQ) serve as the primary explanatory variables. The following sub-section details the construction of these new variables. Additionally, in line with established literature, including studies by Singh et al. [97], Fankem and Oumarou [98], Rakshit [99], and Liu et al. [100,101], our study addresses potential specification biases stemming from omitted variables. We incorporate essential control variables, such as foreign direct investment (FDI), trade openness (TrO), and urbanization (UrB). These variables are instrumental for elucidating their effects in conjunction with our key explanatory variables on EcG. Table 1 details information about the variables, their measurement, calculation, symbols, and sources of compilation.

3.2.3. Construction of new variables

EnS is a central focus of this study, and we devised five novel metrics (EnS_1–EnS_5) to comprehensively assess its impacts on EcG. **EnS_1** measures energy availability as the ratio of PEC to PEG (Ayaz et al., 2024), with a higher value indicating wider gaps in meeting energy demand. **EnS_2** assesses supply capacity, computed as the ratio of PEC to POP, where a higher ratio signifies improvements in the energy supply chain. **EnS_3** evaluates per capita energy demand, using the ratio of PED to POP; a higher ratio represents advancements in energy setups. **EnS_4** focuses on renewable energy adoption, estimated as the ratio of REN to FPEC, with an elevated value reflecting progress in renewable energy alternatives and reducing reliance on non-renewable sources [103]. Furthermore, **EnS_5** is a crucial indicator of energy efficiency, significantly contributing to economic growth [104]. Unlike previous methodologies that use the ratio of energy consumption to GDP (Tayyab Ayaz et al., [30]; [37]), which reflects energy intensity, or conventional Slack-Based Measure Data Envelopment Analysis (SBM-DEA) focusing solely on desirable output ([105]; Shah et al., [106]), we employ the Super-efficient SBM-DEA (SSBM-DEA) model of Tone [107]. This model introduces a paradigm shift by incorporating undesirable output [100,101,108], providing a more nuanced and comprehensive assessment of energy efficiency. In our analysis, we consider eight Decision Making Units (DMUs), representing eight South Asian countries, where each DMU is characterized by m inputs and two types of outputs: $\vartheta 1$ for positive output and $\vartheta 2$ for negative outputs. Our SSBM-DEA model is formulated as follows:

$$\rho = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{\overline{x}}{x_{ik}}\right)}{\frac{1}{(\vartheta_1+\vartheta_2)}\left(\sum_{r=1}^{\vartheta_1}\frac{\overline{y^u}}{y^u_{rk}}+\sum_{r=1}^{\vartheta_2}\frac{\overline{y^v}}{y^v_{rk}}\right)}$$

$$s.t.\begin{cases}\overline{x} \geq \sum_{j=1,4k}^{n} x_{ij}\theta_j \\ \overline{y^u} \leq \sum_{j=1,\neq k}^{n} y^u_{rj}\theta_j \\ \overline{y^{u\tau}} \geq \sum_{j=1,\neq k}^{n} y^v_{tj}\theta_j\end{cases} \quad (1)$$

where $i = 1,\dots,m$, $j = 1,\dots,\vartheta_1$, $t = 1,\dots,\vartheta_2$, and $\overline{x}$, $\overline{y^v}$, and $\overline{y^u}$ represent the input, undesirable output, and desirable output slack variables, respectively. θ denotes the vector weight, while ρ signifies the optimal value. A value of $\rho \geq 1$ indicates that the DMU is efficient. Additionally, $X = [x_1\dots x_n] \in R^{m\times n}$, $Y^{nu} = [y^u_1\dots y^u_n] \in R^{\vartheta 1\times n}$, and $Y^v = [y^A_1\dots y^{vt}_n] \in R^{\vartheta 2\times n}$ represent the input-output matrix. Here, EnS_5 values ≥ 1 indicates efficient DMUs, while EnS_5 values < 1 indicates otherwise [3,109]. To estimate SSBM-DEA EnS_5, this study incorporates a well-rounded selection of input and output variables. The total labor force (L) serves as a crucial input variable, reflecting the contribution of human capital to productivity and economic efficiency [110]. Gross fixed capital formation (K), another input, captures investments in infrastructure and capital goods, which are fundamental to driving economic growth and energy efficiency. Primary energy consumption (E) is also included as a vital input, as it directly influences energy efficiency and economic performance [111]. CO_2 emissions (CO_2e), considered an undesirable output, reflect environmental inefficiencies linked to energy use, thereby emphasizing the sustainability dimension of the model [112]. Furthermore, GDP in constant 2015 dollars serves as the output variable, effectively measuring the economic growth generated from the inputs employed [113]. This comprehensive selection of variables ensures a robust assessment of energy efficiency by capturing both productive and environmental dimensions. While the number of DMUs and sample size may seem modest, the SSBM-DEA approach remains highly effective for several reasons. It enhances the discriminatory power of the analysis, allowing for greater precision in evaluating the performance of individual DMUs. Additionally, the relatively homogenous nature of the South Asian countries in terms of socioeconomic and energy profile makes the dataset sufficiently robust for drawing meaningful conclusions.

Additionally, we enhance our analysis by exploring the aggregate impact of EnS on EcG through the construction of an aggregate index (AgEnS) derived from EnS_1–EnS_5. **AgEnS** is constructed using the method proposed by Sarma [102]. This method offers distinct advantages over traditional approaches like Principal Component Analysis (PCA) and factor analysis. It generates composite index values ranging from 0 to 1, avoiding negative integers and ensuring easy interpretation [114]. It also accommodates lower and upper limits to address overlying benchmarks [115]. This approach upholds precision by using a distance point function that traverses from a worst-case scenario to an ideal point, avoiding simplistic equal weighting. To construct AgEnS, we first normalize the values of EnS_1 to EnS_5 as follows:

$$d_i = w_i \frac{EnS_i - lowl_i}{upl_i - lowl_i} \tag{2}$$

where d_i represents the normalized values for EnS_1–EnS_5, derived individually, w_i denotes the allocated weights estimated by σ_{EnS}/μ_{EnS}, $lowl_i$ indicates the lower limit value set at zero, and upl_i stands for the upper limit value set at 0.90. The selection of 0.90 as the upper limit aims to capture any overlying benchmarks across the variables [116]. Next, the study computes the normalized Euclidean (X_1) and the inversed normalized (X_2) values using the distance points between $d_1, \ldots, d_5$ and $w_1, \ldots, w_5$ as follows:

$$X_1 = \frac{\sqrt{d_1^2 + \ldots + d_5^2}}{\sqrt{w_1^2 + \ldots + w_5^2}}, \quad X_2 = 1 - \frac{\sqrt{(d_1 - w_1)^2 + \ldots + (d_5 - w_5)^2}}{\sqrt{w_1^2 + \ldots + w_5^2}} \tag{3}$$

Finally, we construct the AgEnS as follows:

$$AgEnS_i = \frac{1}{2}(X_1 + X_2) \tag{4}$$

Here, AgEnS is represented in numbers ranging from 0 (low) to 1 (high). Higher values of AgEnS indicates enhanced energy security in South Asia and vice-versa. The complete dataset and estimation do-file for STATA package are available in the supplementary information file (SI) provided. Moreover, while energy security is crucial for growth, institutional quality plays an even more critical role in resource management, especially in regions like South Asia with governance challenges [19,38]. To examine the direct and moderating impact of institutional quality index (**InQ**) on EcG, the study employs WGI's metrics, including CoC, ReQ, RoL, GoE, PoS, and VoC, all expressed as percentile ranks from 0 to 100. The InQ is constructed using procedures outlined in eqs. 2 and 3. Higher InQ values indicate greater institutional efficiency, based on established procedures (see Appendix C for STATA do-file). Fig. 2 presents the boxplots of the constructed AgEns and InQ for South Asia, with their probability distribution plots shown in Fig. B1 of Appendix B.

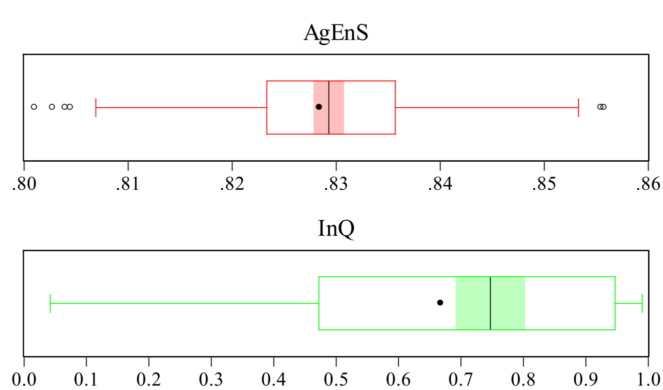

Fig. 2. Constructed AgEns and InQ.
(Source: Authors' depiction.)

3.3. Baseline model

The Cob-Douglass (1928) production function is a widely used model that describes the relationship between input—typically labor and capital—and the total output of an economy [41]. It is a core concept in growth theory and production analysis. Although it is not a "growth model" itself, it can serve as a key component in the Solow-Swan model [117,118], integrating multiple endogenous and exogenous inputs that contribute to economic output in a panel setting as follows:

$$EcG_{it} = f(EnS_{it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it}) \tag{5}$$

where all variables are defined earlier. EnS refers to both the aggregate energy security index and its core components, EnS_1 through EnS_5. Using this framework, we commence our analysis by investigating the direct effects of individual EnS on EcG in the presence of InQ and the control variables. This is accomplished through the following long-run linear model:

$$\begin{aligned} EcG_{it} = {} & \phi + \theta_1 EnS_{1,it} + \theta_2 EnS_{2,it} + \theta_3 EnS_{3,it} + \theta_4 EnS_{4,it} + \theta_5 EnS_{5,it} \\ & + \gamma InQ_{it} + \delta_1 FDI_{it} + \delta_2 UrB_{it} + \delta_3 TrO_{it} + \eta_i + u_{it} \end{aligned} \tag{6}$$

Here, ϕ indicates the intercept, η_i represents country-specific unobserved effects, θ_1 to θ_5 represent the long-run coefficients of EnS_1 to EnS_5, γ represents the coefficient of InQ, δ_1 to δ_3 are the coefficients of control variables, and u_{it} indicates the error term. Eqs. (6) examines how each individual elements of energy security impacts economic growth across the region. To underline the aggregate effects of energy security on the subject, we specify the following equation:

$$EcG_{it} = \phi + \theta AgEnS_{it} + \gamma InQ_{it} + \delta_1 FDI_{it} + \delta_2 UrB_{it} + \delta_3 TrO_{it} + \eta_i + u_{it} \tag{7}$$

where $AgEnS_{it}$ indicates the aggregate energy security index constructed from EnS_1 to EnS_5 and all other vectors and variables remain similar as described in eq. (6). Additionally, given the overarching governance performance in South Asia, it is imperative to examine how InQ moderates the impact of EnS on EcG. This will help underline both sector-specific and macroeconomic impact of the energy security influencing growth through conduits of institutional quality. To this end, we delineate the following interaction model:

$$\begin{aligned} EcG_{it} = {} & \phi + \theta_1 EnS_{1,it} + \theta_2 EnS_{2,it} + \theta_3 EnS_{3,it} + \theta_4 EnS_{4,it} + \theta_5 EnS_{5,it} \\ & + \beta(InQ_{it} \times EnS_{it}) + \gamma InQ_{it} + \delta X_{it} + \eta_i + u_{it} \end{aligned} \tag{8}$$

Here, $\beta(InQ_{it} \times EnS_{it})$ represents the moderating impact of institutional quality on the relationship between energy security and economic growth and δ denotes the coefficients of the control variables (X_{it}), with all other vectors and variables retaining their previously defined meanings. Appendix A provides detailed information about the mathematical derivation of the interaction term incorporated into eq. (8).

3.4. Estimation techniques

While panel data analysis offers significant statistical advantages—such as controlling for unobserved heterogeneity, enhancing data richness, increasing variability, and improving analytical efficiency [119]—it also has inherent limitations. A key issue is cross-sectional dependence (CD) among nations, which can stem from rapid globalization and shared energy consumption patterns [120]. Neglecting CD can undermine analytical quality [121,122]. To address this, we begin our estimation by testing the null of cross-sectional independence and slope homogeneity (SH) using methodologies from Pesaran [123] and Pesaran and Yamagata [124], respectively. If these hypotheses are rejected, we then apply second-generation panel unit root tests to examine the stationarity of our variables. Specifically, we utilize Pesaran's [125] cross-sectionally augmented Im, Pesaran, and Shin (CIPS) test as our primary model, supplemented by Maddala and Wu's [126] technique, which also considers CD [127].

With the mixed integrating orders of the variables confirmed, we proceed to assess the long-run relationship between them. We employ the second-generation panel cointegration test of Westerlund and Edgerton [128], which effectively accounts for structural breaks, mean shift, and regime shift across units. Following preliminary tests, we estimate eqs. 6–8 to explore both direct and spillover effects of energy security and the included control variables on economic growth, modulated by institutional quality index. To address CD and correct for potential heteroskedasticity and autocorrelation, we use the panel corrected standard error (PCSE) technique of Greene [129]. The PCSE model offers several advantages over Driscoll and Kraay's [130] method, which is more suited for microeconomic analysis, and the cross-sectionally augmented autoregressive distributed lags (CS-ARDL) model of Chudik and Pesaran [131], which estimates both short- and long-run coefficients in large panel datasets. Notably, the PCSE model maximizes efficiency in panel with more time observations than units, and it aligns well with the gradual effects of energy security and institutional quality, making short-run estimates unnecessary [132]. To further validate the robustness of our results, we also estimate the feasible generalized least squares (FGLS) model, which is adept at estimating long-run coefficients amid heteroskedasticity and cross-sectional correlation [133]. This additional analysis reinforces the reliability of our findings.

4. Empirical results

4.1. Preliminary results

Table 2 presents some important characteristics of the variables under consideration. EcG, as represented by per capita GDP, shows a mean value of $2398.78, with a maximum of $11,035.58 across South Asia. Despite EnS_1's mean value being 9.49 %, its maximum value of 49.72 % highlights a considerable energy gap within the region. This result is consistent with the findings of Kohli [134] and Nepal and Paija [82], who identified that substantial energy gap in South Asia as being primarily driven by rapid population growth and insufficient investments in energy infrastructure across the region. EnS_2, with an average value of 1155.6 kW-hours per capita, ranges from a minimum energy supply capacity of 204.23 to a maximum capacity of 2778.5.35 kW-hours per capita, indicating substantial volatility within the region, albeit with minor improvements in energy supply chain. Building on the findings of Singh [9], Shah et al. [15], and Rahman et al. [7], South Asia continues to experience persistent energy supply imbalances, driven by inefficient energy policies, aging power grids, geopolitical tensions, and the region's reliance on non-renewable sources. Additionally, EnS_3, which measures energy demand, has a mean value of 735.72 kW-hours per capita, a maximum of 4874.68 kW-hours per capita, and a standard deviation of 836.222 kW-hours per capita. These statistics underscore the significant disparity in energy demand in the region. The relatively high standard deviation, compared to the mean, suggests that while some countries experience relatively low demand, others face much higher demand, likely driven by population, market scale, and industrialization. In terms of energy efficiency, EnS_5 has an average score of 0.716 and a maximum of 0.999, suggesting that the region continues to operate with considerable inefficiency in its energy use. These findings align with studies by Hou et al. [135], Azhgaliyeva et al. [136], and Jain and Goswami [14], which highlight similar trends. Literally, the region's rising energy intensity, driven by rapid industrialization and a heavy

Table 2
Descriptive statistics.

Variables	Observations	Mean	Standard deviation	Minimum	Maximum
EcG	184	2398.982	2638.785	300.449	11,035.582
EnS_1	184	9.491	7.858	1.675	49.72
EnS_2	184	1155.609	912.619	204.231	2778.357
EnS_3	184	735.727	836.222	29.166	4874.686
EnS_4	184	5.635	3.809	0.052	13.598
EnS_5	184	0.716	0.183	0.231	0.999
AgEnS	184	0.828	0.010	0.801	0.856
InQ	184	0.668	0.291	0.042	0.990
FDI	184	1.889	2.891	0.006	16.783
UrB	184	28.653	7.927	13.397	43.686
TrO	184	45.498	24.522	12.785	116.55

Source: Authors' estimations.

reliance on fossil fuels, exacerbates inefficiencies in energy utilization, underscoring the urgent need to transition towards cleaner energy sources and implement more sustainable energy policies.

Moreover, the results from Table 3 and Fig. 3, showing the estimated EnS_5 for South Asia across the years 2000, 2005, 2010, 2015, and 2022, highlight key insights into the region's energy efficiency trends, as measured by the SSBM-DEA model. The Maldives ranks first, reflecting its relatively better energy management due to factors like a smaller population and growing investments in renewable energy, though it still has room to improve. Bhutan follows closely, benefiting from its hydropower exports, while Sri Lanka and India rank mid-tier, with India's heavy reliance on coal and grid inefficiencies hindering its progress despite recent renewable energy investments. Recent empirical studies by Alola et al. [36], Yunus et al. [137], Usman et al. [138], and Majewski et al. [139] have yielded similar findings, corroborating the ongoing challenges in energy efficiency and sustainability. Furthermore, Pakistan and Bangladesh face challenges from aging infrastructure and reliance on imported fuels, contributing to lower rankings [140,141], while Afghanistan's armed conflict-driven energy deficits and Nepal's underutilized hydropower potential leave them at the bottom. These results closely align with the findings of Fahimi et al. [142], Hang and Singh [143], Ahmadzai and McKinna [144], and Adhikari [145], further reinforcing the prevailing trends in energy efficiency observed in Afghanistan and Nepal.

Moreover, when examining the results presented in Table 4, it becomes evident that the patterns of total factor productivity change (TFPCH), technical change (TECCH), and efficiency change (EFCCH) within EnS_5 reflect a landscape of inconsistent and volatile progress. Unlike regions such as East Asia [146], which have demonstrated more stable and sustained improvements in energy efficiency and productivity, South Asia's fluctuations—from minor gains in 2000–2001 and 2001–2002 to significantly declines in periods like 2002–2003, 2019–2020, and 2020–2021—highlight the ongoing challenges in TFPCH and TECCH elements that the region faces. While these results are in line with the findings of Saha [147], and Park [148], they emphasize the complexities and challenges inherent in achieving sustained improvements in in this domain. In contrast, East Asia, particularly China and South Korea, has benefited from strategic investments in technology and infrastructure, leading to a more stable and consistent upward trajectory in energy efficiency metrics [149,150], despite facing their own challenges. These nations have effectively harnessed technological advancements and policy reforms to achieve a more seamless integration of energy efficiency improvements. Additionally, Fig. 4 illustrates the cross-country TFPCH in energy efficiency, revealing distinct trends among the nations analyzed. The Maldives shows slight yet stable improvements in TFPCH, indicating modest progress in energy efficiency. In contrast, Afghanistan, Sri Lanka, and India experience a decline in TFPCH, reflecting setbacks in their energy efficiency efforts. Other countries in the region display highly volatile patterns, marked by significant fluctuations in their energy efficiency improvements. This

Table 3
SSBM EnS_5 in South Asia.

Year	Afghanistan	Bangladesh	Bhutan	India	Sri Lanka	Maldives	Nepal	Pakistan
2000	0.304	0.418	0.716	0.528	0.820	0.823	0.218	0.454
2005	0.338	0.457	0.818	0.545	0.820	0.827	0.258	0.603
2010	0.400	0.512	0.793	0.597	0.812	0.837	0.266	0.679
2015	0.491	0.628	0.817	0.779	0.852	0.856	0.303	0.803
2022	0.525	0.773	0.943	0.988	0.813	0.871	0.376	0.808
Avg. EnS_5	0.411	0.562	0.827	0.704	0.823	0.846	0.292	0.674
Rank	7	6	2	4	3	1	8	5

Notes: Replicate using STATA code as shown in (https://sourceforge.net/p/deas/code/HEAD/tree/) with K, L, CO_2e, and E as input and Y as output variables.
Source: Authors' estimations.

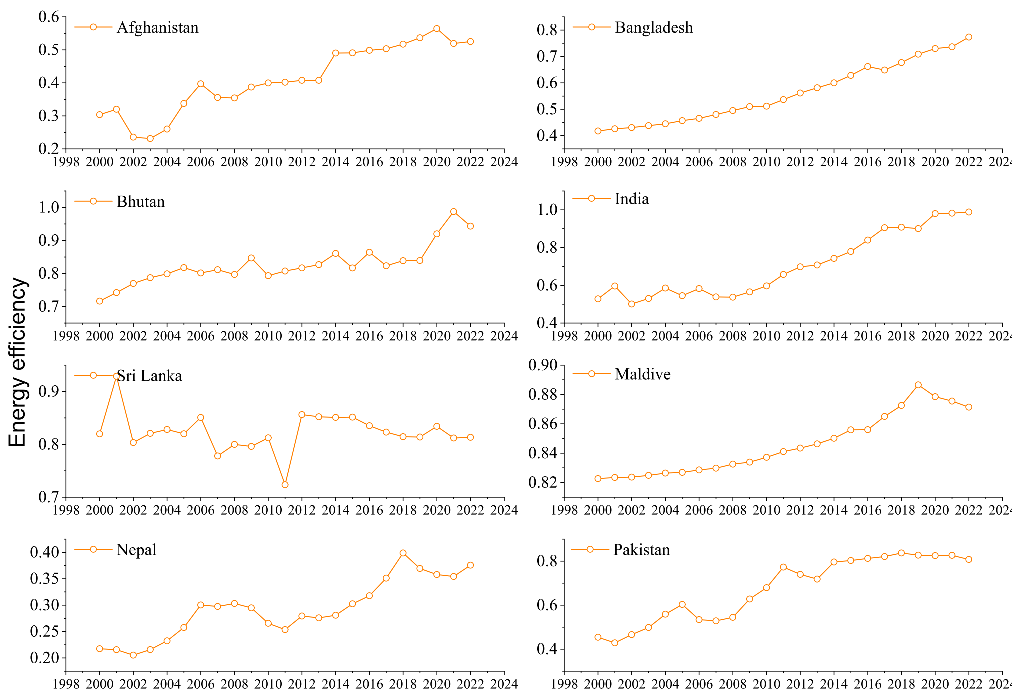

Fig. 3. SSBM-DEA EnS_5 in South Asia.
Notes: Replicate using STATA code as shown underneath Table 3, and plot by panel.
Source: Author's depiction.

variability underscores the inconsistent progress across South Asia, pinpointing the need for more targeted strategies to enhance energy performance and stability in the region.

4.2. Correlation, CD, SH, unit root, and cointegration

Subsequently, prior to advancing to the key estimations on examining the direct and conditional effects of energy security on economic growth in South Asia, additional preliminary tests are conducted to support appropriate specification. Table 5 delineates the correlations analysis among the panel variables, which reveals either moderate or weak relationships, thereby confirming the absence of perfect or extreme multicollinearity. The presence of multicollinearity among variables can often result in significant ambiguities in the outcomes [151]. Additionally, the right-hand column of Table 5 outlines the results of the cross-sectional dependence test of Pesaran [123], indicating that all variables, with the exception of EnS_1, exhibit significant cross-sectional dependence at 1 % and 5 % significance levels. The rejection of the null hypothesis of cross-sectional independence underscores the necessity for a deeper examination of the variables' slope properties.

Accordingly, Table 6 reports the slope heterogeneity analysis, wherein the delta and adjusted delta statistics significantly reject the null hypothesis of slope homogeneity across models 1–6 at 1 % and 5 % significance levels. The rejection of slope homogeneity suggests that the relationship between economic growth, energy security, institutional quality, and the control variables varies across the different countries within South Asia. As a result, using static panel models could lead to misleading conclusions [152]. In these analyses and subsequent regressions, model 1 includes EnS_1 as the primary explanatory variable alongside InQ and other control variables. Model 2 incorporates EnS_2, with subsequent models adhering to this schema, culminating in model 6, which includes AgEnS alongside InQ and other control variables.

Employing the CIPS panel unit root test of Pesaran [125], renowned for its proficiency in discerning the true stationarity properties of panel variables amidst cross-sectional dependence, and subsequently applying Maddala and Wu's [126] model, the study delineates the findings in Table 7. The results reveal that TrO maintains level stationarity at the 1 % significance level under both approaches. Conversely, all other variables attain significant stationarity only after first differencing. The overall results indicate that the variables exhibit mixed orders of integrating orders of I(0) and I(1), with no statistical evidence of higher-order integration. This implies a compelling case for investigating long-run cointegration relationships among the panel variables under consideration.

Furthermore, the study employs the panel cointegration approach proposed by Westerlund and Edgerton [128], utilizing tests that that

Table 4
Total factor productivity change in energy across South Asia.

Period-wise	TFPCH	TECCH	EFCCH
2000–2001	1.024	1.034	0.991
2001–2002	1.049	1.035	1.015
2002–2003	1.035	0.997	1.038
2003–2004	1.023	0.988	1.036
2004–2005	1.017	0.995	1.022
2005–2006	1.046	0.990	1.056
2006–2007	1.040	1.012	1.028
2007–2008	1.041	1.021	1.020
2008–2009	1.022	1.023	1.000
2009–2010	1.034	1.019	1.015
2010–2011	1.028	1.000	1.028
2011–2012	1.034	1.015	1.019
2012–2013	1.021	0.999	1.022
2013–2014	1.026	0.994	1.032
2014–2015	1.011	1.006	1.004
2015–2016	1.022	0.984	1.039
2016–2017	1.023	0.988	1.035
2017–2018	1.030	0.993	1.038
2018–2019	1.013	1.001	1.012
2019–2020	0.975	1.032	0.944
2020–2021	0.992	0.939	1.057
2021–2022	1.015	1.009	1.006

Notes: Replicate using STATA code as: (malmq2 K L CO_2e E = GDP, global), (malmq2 K L CO_2e E = GDP, seq ort(o) fgnz), and by sort: mean function. TFPCH: Total factor productivity change, TECCH: Technical change, EFCCH: efficiency change.
Source: Authors' estimations.

account for potential without structural breaks, mean shifts, and regime shifts. The results, as illustrated in Table 8, reveal a compelling insight: EcG establishes a long-run relationship with EnS across both its individual elements (models 1–5) and aggregate index (model 6). This suggests that EnS, in conjunction with InQ and other control variables, exert significant influence on EcG, manifesting in varied effects across the South Asian context. These results underscore the complexity of the interactions among our variables, indicating that energy security does not exert a uniform impact; rather, its influence on growth varies on specific contextual factors. Given these intriguing findings, it is essential to explore not only the nature of these relationships but also the direction and magnitude of their effects on economic growth.

4.3. Baseline results

4.3.1. Direct effects

The key findings are comprehensively presented in Table 9, delineating the results across 6 distinct columns (models 1–6). The results indicate a nuanced relationship between EnS and EcG. Specifically, a 1 % increase in EnS_1 correlates with a \$2.097 reduction in EcG, underscoring the adverse impact of energy availability shortage on regional economic growth. While sufficient energy supply fuels expansion and boosts industrial output, constraints in energy availability impose serious limitations on a nation's overall economic cycle. Recent studies by Best and Burke [153], Fedajev et al. [154], Liu and Lu [155], Gershon et al. [156], Sarsar and Echaoui [157], and Skare et al. [158] corroborate these observations with robust statistics evidence. Furthermore, the results indicate that a 1 % increase in EnS_2 reduces EcG by \$1.0167, showing that the existing capacity in energy supply is insufficient to bolster economic growth in South Asia. This insufficiency could be attributed to several factors, including inadequate infrastructure, ineffective energy distribution, weak institutional frameworks, and the inability to meet the region's growing energy demand. Recent studies by Deka et al. [159], Makieła et al. [160], and Samawi et al. [161] similarly conclude on the pivotal role of energy supply in fostering economic growth and shaping sustainable trajectories across diverse economies. A 1 % increase in EnS_3 decreases EcG by \$2.002. Theoretically, when energy demand surpasses energy supply, economic output is hindered. In such scenarios, the necessity for tightened and conservative energy consumption becomes paramount, leading to suppressed economic performance. This constraint can stifle industrial productivity, limit expansion opportunities, and reduce overall economic efficiency, pinpointing the critical need for balanced energy demand and supply dynamics. These results are comprehensively supportive to those of the initial energy market equilibrium findings of Huntington and Liddle [29] and consistent with those of Guerra et al. [162], Rakpho and

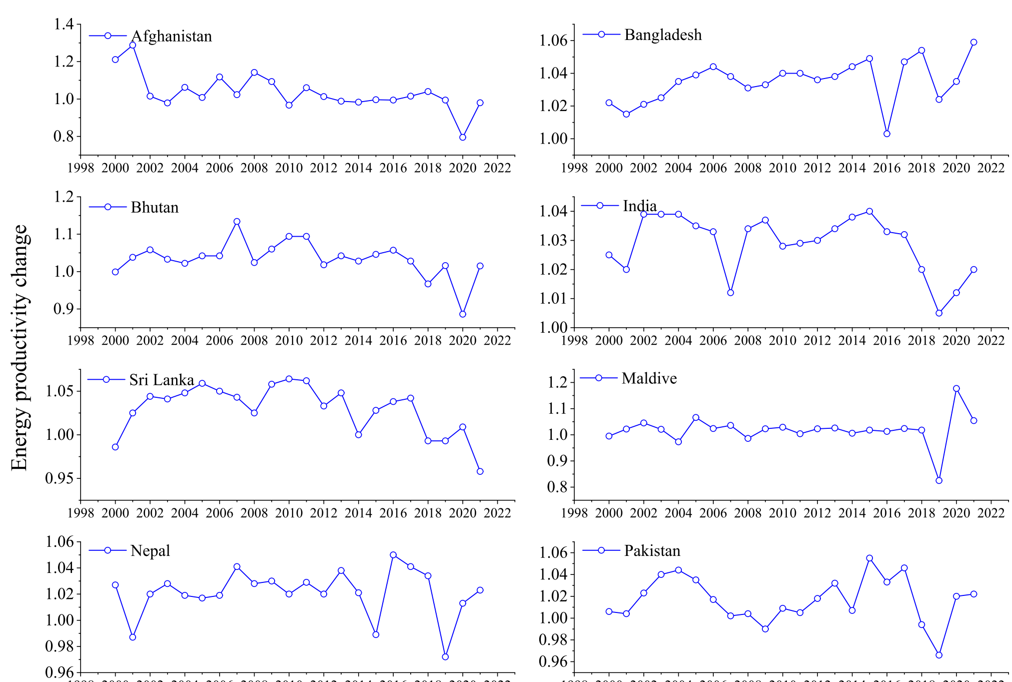

Fig. 4. Cross-country energy productivity change.
Notes: Replicate through TFPCH (total factor productivity change) from malmq2 K L CO_2e E = GDP, seq ort(o) fgnz function in STATA.
Source: Authors' depiction.

Table 5
Correlation matrix.

Variables	Correlation matrix											CD-statistics
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	
(1) EcG	1											24.38***
(2) EnS_1	−0.181	1										1.03
(3) EnS_2	0.074	−0.212	1									19.87***
(4) EnS_3	0.028	−0.336	0.405	1								23.56***
(5) EnS_4	−0.015	−0.331	0.280	0.286	1							3.40***
(6) EnS_5	0.006	−0.303	0.442	0.416	0.501	1						15.73***
(7) AgEnS	0.172	−0.106	−0.496	−0.180	−0.155	−0.195	1					8.66***
(8) InQ	0.116	−0.438	0.599	0.556	0.403	0.662	−0.415	1				5.40***
(9) FDI	0.108	0.128	0.444	0.175	0.249	0.205	−0.547	0.284	1			2.16**
(10) UrB	0.075	−0.095	0.635	0.584	0.276	0.101	−0.329	0.209	0.417	1		22.47***
(11) TrO	0.141	−0.508	0.612	0.626	0.111	0.520	−0.222	0.679	−0.011	0.052	1	6.08***

Notes: *** and ** reject the null hypothesis at 1 % and 5 % significant levels, respectively.
Source: Authors' estimations.

Table 6
Slope heterogeneity results.

Dependent variable: EcG	Model 1 (EnS_1)	Model 2 (EnS_2)	Model 3 (EnS_3)	Model 4 (EnS_4)	Model 5 (EnS_5)	Model 6 (AgEnS)
Delta	9.487***	10.740***	10.948***	9.438***	8.761***	10.517***
p-value	0.000	0.000	0.000	0.000	0.000	0.000
Adjusted delta	11.375***	12.877***	13.127***	11.316***	10.504***	12.609***
p-value	0.0000	0.000	0.000	0.000	0.000	0.000

Notes: *** rejects the null hypothesis at a 1 % significance level.
Source: Authors' estimations.

Table 7
Unit root test results.

Variables	CIPS test		Maddala and Wu test	
	Level	First difference	Level	First difference
EcG	−2.616	−3.613***	−2.936**	−4.012***
EnS_1	−1.743	−3.749***	−2.444	−5.275***
EnS_2	−2.295	−2.931**	−2.473	−4.220***
EnS_3	−1.766	−2.522**	−1.698	−3.325***
EnS_4	−1.711	−3.364***	−2.166	−5.007***
EnS_5	−2.552	−3.622***	−2.562	−4.927***
AgEnS	−2.111	−3.403***	−2.395	−3.772***
InQ	−2.515	−2.915**	−2.657	−4.871***
FDI	−2.661	−3.153***	−2.504	−4.386***
UrB	−0.808	−3.063**	0.144	−3.864***
TrO	−3.259***	−3.473***	−2.885**	−4.453***

Notes: *** and ** indicate rejection of the null hypothesis of non-stationarity at 1 % and 5 % significance levels, respectively.
Source: Authors' estimations.

Yamaka [163], Huang et al. [164], Bastos et al. [165], Zhou et al. [166], and Wang et al. [44,45] regarding the dynamics of energy supply and demand influences across various economies.

Conversely, the results show that a 1 % increase in EnS_4 increases EcG by $3.173, indicating that enhanced energy development capacity positively impacts growth. The favorable influence of EnS_4 implies that further investments in energy infrastructure and development can boost economic progress in South Asia. Consistently, studies conducted by Surya et al. [167], Jaiswal et al. [168], Kuang et al. [169], and Jin et al. [170] have reached similar conclusions about the favorable impact of enhancing energy development capacity on growth. On the other hand, the results indicate that a 1 % increase in EnS_5 leads to a reduction in EcG, underscoring the negative implications of existing energy inefficiency within the region. This adverse impact of EnS_5 suggests the urgent need for policy-related initiatives aimed at advancing energy efficiency to bolster sustainable economic growth. Likewise, a rich body of literature, including those by Rajbhandari and Zhang [171], Adom et al. [172], Ilesanmi and Tewari [173], Lin and Zhou [174], Yuan et al. [175], Sueyoshi and Goto [176], Wu et al. [177], Kadir et al. [178], and Chen et al. [179] offer a strong statistical support on the impact of energy efficiency on economic growth resilience. Literally, energy efficiency not only enhances economic output but also fortifies economies against energy supply disruptions, thereby supporting sustainable growth.

Table 8
Westerlund and Edgerton's [128] panel cointegration results.

Models estimated	(1) Without break	(2) Mean shift	(3) Regime shift
Model 1: $EcG_{it} = f(EnS_{1,it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−8.244***	−7.321***	−7.867***
Z_{tau} (N)	−9.016***	−8.210***	−8.337***
Model 2: $EcG_{it} = f(EnS_{2,it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−12.139***	−10.044***	−10.423***
Z_{tau} (N)	−12.288***	−11.290***	−11.072***
Model 3: $EcG_{it} = f(EnS_{3,it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−9.081***	−10.218***	−10.009***
Z_{tau} (N)	−11.370***	−10.219***	−9.256***
Model 4: $EcG_{it} = f(EnS_{4,it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−7.904***	−8.416***	−7.503***
Z_{tau} (N)	−7.633***	−9.202***	−9.554***
Model 5: $EcG_{it} = f(EnS_{5,it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−11.093***	−10.891***	−10.901***
Z_{tau} (N)	−10.847***	−10.788***	−10.631***
Model 6: $EcG_{it} = f(AgEnS_{it}, InQ_{it}, FDI_{it}, UrB_{it}, TrO_{it})$			
Z_{phi} (N)	−12.802***	−11.734***	−12.066***
Z_{tau} (N)	−10.922***	−10.612***	−10.702***

Notes: *** indicates rejection of the null hypothesis of no cointegration at a 1 % significance level.
Source: Authors' estimations.

Table 9
PCSE model results.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	EnS_1	EnS_2	EnS_3	EnS_4	EnS_5	AgEnS
InQ	3.271*** (4.90)	4.480*** (7.53)	4.439*** (5.41)	2.747*** (3.35)	4.241*** (4.57)	4.624*** (6.07)
TrO	−0.076*** (−7.17)	−0.008 (−1.01)	−0.040*** (−4.54)	−0.059*** (−6.15)	−0.066*** (−6.53)	−0.064*** (−6.84)
UrB	0.289** (2.06)	0.204*** (16.50)	0.131*** (7.79)	0.026** (1.99)	0.039*** (3.12)	0.050*** (3.87)
FDI	0.312*** (6.03)	0.177*** (3.48)	0.418*** (5.22)	0.384*** (6.17)	0.376*** (5.18)	0.245*** (4.15)
EnS1	−2.097*** (−5.64)					
EnS2		−1.0176*** (−8.48)				
EnS3			−2.002*** (−4.48)			
EnS4				3.173*** (7.27)		
EnS5					−3.790 (−0.95)	
AgEnS						83.248*** (5.33)
Constant	26.384*** (49.54)	18.553*** (38.69)	21.351*** (36.03)	24.242*** (76.87)	24.678*** (43.19)	−45.746*** (−3.45)
Observations	184	184	184	184	184	184
R-squared	0.440	0.649	0.455	0.427	0.362	0.454
Number of groups	8	8	8	8	8	8

Notes: *** indicates significance at 1 % level. z-statistics in parentheses.
Source: Authors' estimations.

Moreover, the findings reveal that a 1 % increase in AgEnS elevates EcG by $83.248. Compared to each element of EnS (EnS_1–EnS_5), AgEnS exerts a substantially larger positive influence on EcG. This implies that a comprehensive focus on all aspects of EnS simultaneously yields a more significant and tangible effect on growth, highlighting the importance of an integrated energy security strategy for the region's sustainable economic growth. Studies by Balitskiy et al. [81], Alekhina [180], Ul-Haq et al. [181], Banna et al. [2], Lee et al. [182], Gökgöz and Yalçın [183], and D'Errico [38] have consistently found statistical support for the positive impact of energy security on the resilience of economic growth across diverse economies. Our results reveal a noteworthy positive correlation between InQ and EcG, indicating that each percentage increase in InQ is associated with an average increase of $4.5 in EcG across all models. This finding highlights the pivotal role of institutional quality in fostering economic growth, suggesting that enhancement in governance, regulatory frameworks, and institutional efficiency can significantly drive economic progress. The consistent relationship observed across all models reinforces the importance of robust institutions in creating an enabling environment for sustainable economic development. Thus, as South Asia strives to improve its institutional frameworks, it may not only bolster economic growth but also enhance the overall resilience and competitiveness of its economies in the global landscape. These results are consistent with the findings of Abdelbary and Benhin [184], Ahmad et al. [185], Khan et al. [186], Law et al. [187], Osman et al. [188], Radulović [189], and Raza et al. [190], who collectively found the positive impact of institutional frameworks on economic growth across diverse nations. On the other hand, TrO has been found to negatively affect EcG, with a 1 % increase in TrO resulting in a $0.076 reduction in EcG. This could be attributed to the region's inefficacy to competitively integrate into the international markets, trade imbalances, and lack of effective regional collaboration. However, while a numerous number of studies have concluded the positive impact of trade openness on growth, our results strongly corroborate those of Ali and Abdullah [191], Elijah and Musa [192], SenGupta [193], Fatima et al. [194], Nguyen et al. [195], and Kinfack and Bonga-Bonga [196].

Moreover, the findings reveal that a 1 % increase in UrB corresponds to a $0.289 increase in EcG, highlighting the positive economic contribution of urban expansion in the region. These results are consistent with the findings of a large part of the existing literature and specifically with those of Clemente et al. [197], Gross and Ouyang [198], Lubonja and Shehu [199], and Liu et al. [100,101]. Similarly, FDI appears to have a positive impact on EcG, with each 1 % increase leading to a $0.312 increase in EcG. Although the magnitude of the effect is positive, its size is relatively lower than initially expected. This may be exacerbated by weak institutional quality and low market security in South Asia, mainly limiting the spillover effects to the local economy and undermining the higher positive effects of FDI on growth. Prior literature, particularly studies by Chaudhury et al. [200], Husnain et al. [201], Rao et al. [202], and Islam [203], has consistently found a positive influence of FDI on economic growth across South Asia.

Furthermore, the study employs the feasible generalized least squares (FGLS) model to ensure the robustness and reliability of the estimates obtained from the PCSE model. The results reported in Table 10, confirm the consistency of the findings across both estimation techniques. Specifically, all coefficients retain the same sign as those estimated by the PCSE model, indicating the directional relationships between variables are stable and reliable. While minor differences in the magnitude of the coefficients are observed, these variations are within acceptable ranges, further reinforcing the robustness of the findings.

4.3.2. Moderating effects

To delve deeper into the role of InQ in the relationship between EnS and EcG, we extend our analysis by estimating Models 1–6 with interaction terms between InQ and each element of EnS (EnS_1–EnS_5) and its aggregate index (AgEnS). This assessment is performed using the PCSE approach, and the robustness of the estimations are validated through the FGLS model. The results are detailed in Tables 11 and 12 for the PCSE and FGLS approaches, respectively. With all other variables held constant and consistent with the findings presented in Tables 9 and 10 regarding direct effects, the moderating results underscore the significant role of InQ in enhancing the relationship between EnS_1 and EcG. The results reveal that when InQ interacts with EnS_1, the negative coefficient of EnS_1 converts into positive effects, leading to an increase in EcG by $2.208. Similarly, Adedeji et al. [85] found that effective governance interactions enhance energy availability, thereby leading to economic expansion in Sub-Saharan African countries. Likewise, InQ effectively mitigates the negative impact of EnS_2 on EcG, resulting in an increase of $4.013 in EcG. This favorable transformation arises from improved efficiencies in institutional frameworks across the region. Such improvements align with fundamental governance-growth and energy transfer theories [204,205]. Moreover, the results reveal that InQ effectively moderates the relationship between EnS_3 and EcG, turning the negative correlation into a positive one and resulting in an increase of $3.044 in EcG. Recent studies by Simionescu et al. [206] and Wang et al. [69] echo these findings, highlighting the critical role of robust institutional frameworks in optimizing energy demand and ensuring efficient energy use, both of which collectively contribute to enhanced economic performance. The findings demonstrate that while the interaction of InQ with EnS_4 maintains the initial positive impact on EcG, it notably amplifies the effect size, resulting in an increase of $5.055 in EcG. This suggests that enhanced institutional quality significantly boosts the advantages the energy development capacity, further

Table 10
FGLS model estimates.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	EnS_1	EnS_2	EnS_3	EnS_4	EnS_5	AgEnS
InQ	3.882*** (5.08)	4.230*** (8.97)	4.435*** (7.10)	2.742*** (3.99)	4.241*** (5.66)	4.622*** (7.32)
TrO	−0.077*** (−9.32)	−0.008 (−1.10)	−0.042*** (−4.65)	−0.057*** (−8.04)	−0.065*** (−8.53)	−0.066*** (−9.04)
UrB	0.2806 (1.60)	0.202*** (10.73)	0.133*** (5.62)	0.029 (1.49)	0.038** (2.14)	0.051*** (2.96)
FDI	0.311*** (6.07)	0.178*** (4.14)	0.417*** (8.43)	0.385*** (7.64)	0.375*** (7.05)	0.246*** (4.48)
EnS_1	−2.098*** (−5.10)					
EnS_2		−1.0178*** (−12.31)				
EnS_3			−2.002*** (−5.66)			
EnS_4				3.174*** (4.62)		
EnS_5					−3.789 (−0.81)	
AgEnS						83.248*** (5.62)
Constant	26.384*** (39.61)	18.553*** (29.55)	21.351*** (28.90)	24.242*** (45.30)	24.678*** (34.37)	−45.746*** (−3.66)
Observations	184	184	184	184	184	184
Number of groups	8	8	8	8	8	8

Notes: *** indicates significance at 1 % level. z-statistics in parentheses.
Source: Authors' estimations.

Table 11
PCSE model estimates; moderating effects.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	InQ on EcG-EnS_1 nexus	InQ on EcG-EnS_2 nexus	InQ on EcG-EnS_3 nexus	InQ on EcG-EnS_4 nexus	InQ on EcG-EnS_5 nexus	InQ on EcG-AgEnS nexus
InQ	4.455*** (6.73)	5.379*** (9.75)	5.843*** (8.55)	2.610*** (2.85)	10.136*** (6.07)	24.831*** (7.22)
TrO	−0.084*** (−6.96)	−0.013* (−1.94)	−0.026*** (−4.39)	−0.057*** (−6.13)	−0.056*** (−6.64)	−0.062*** (−7.14)
UrB	0.269 (1.63)	0.180*** (15.87)	0.165*** (10.24)	0.041*** (3.08)	0.045*** (3.25)	0.041*** (3.14)
FDI	0.172*** (4.12)	0.115** (2.61)	0.242*** (4.78)	0.295*** (5.79)	0.182*** (3.66)	0.105** (2.32)
EnS_1	−3.093*** (−4.98)					
EnS_2		−1.00008*** (−6.46)				
EnS_3			−2.016*** (−3.97)			
EnS_4				3.170*** (4.37)		
EnS_5					−3.766 (−0.92)	
AgEnS						96.071*** (5.35)
Constant	−16.193 (−0.98)	−36.715*** (−3.50)	−77.060*** (−6.48)	−33.131*** (−3.69)	−52.700*** (−4.15)	113.757*** (5.80)
Moderating effects						
InQ × EnS_1	2.208* (1.99)					
InQ × EnS_2		4.013** (2.44)				
InQ × EnS_3			3.044** (2.12)			
InQ × EnS_4				8.225** (2.15)		
InQ × EnS_5					0.775* (1.93)	
InQ × AgEnS						103.167*** (7.30)
Observations	184	184	184	184	184	184
R-squared	0.492	0.711	0.640	0.488	0.520	0.610
Number of ID	8	8	8	8	8	8

Notes: ***, **, and * indicate significance at 1 %, 5 %, and 10 % levels, respectively. z-statistics in parentheses.
Source: Authors' estimations.

accelerating economic growth. These findings align with prior empirical studies, such as those by Sheng et al. [207], Dam et al. [208], and Rafiq et al. [209], which provide robust statistical evidence supporting the positive effects of institutional quality on energy capacity, leading to enhanced economic output.

Although our initial results, as presented in Tables 9 and 10, indicate a negative influence of EnS_5 on EcG, the interaction results reveal that when InQ moderates the relationship, the effects of EnS_5 on EcG shifts to positive, resulting in a $0.775 increase in EcG. This indicates that strong institutional frameworks can effectively mitigate the inefficiencies in energy utilization, transforming energy inefficiency into a growth-enhancing factor by promoting better energy management, innovation, and sustainable practices. These findings align with prior empirical research conducted by Sun et al. [210], Wenlong et al. [211], and Rahman and Sultana [212]. Finally, our results demonstrate that InQ significantly amplifies the effect size of the AgEnS on EcG, leading to an increase of $7.096. These findings suggest that a collective focus on improving governance quality across the various elements of energy security results in greater positive impacts on economic growth in South Asia. Enhanced institutional quality ensures better coordination and integration of energy security measures, thereby fostering a more stable and conducive environment for sustainable economic expansion.

Additionally, the robustness tests for the moderating effects of InQ on the relationship between EnS and EcG were conducted using the FGLS model, with results presented in Table 12. The coefficients for all variables exhibit remarkable consistency in both size and sign when compared to those estimated by the PCSE model, as illustrated in Table 11. This alignment between the PCSE and FGLS models not only reinforces the robustness and reliability of our results but also validates the integrity of our estimation techniques. Consequently, these consistent findings provide a solid foundation for drawing definitive conclusions about the complex interplay between EnS, InQ, and EcG across the region.

5. Discussion

Economic growth is shaped by a complex interplay of numerous endogenous, social, environmental, and geopolitical factors. Yet, at the heart of this intricate system lies energy—a fundamental catalyst for progress. The rapid pace of industrialization, alongside escalating consumption trends, has exerted unprecedented strain on finite natural resources (Tugcu and Menegaki, [213]). As economies strive to sustain

Table 12
FGLS model estimates; moderating effects.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Variables	InQ on EcG-EnS_1 nexus	InQ on EcG-EnS_2 nexus	InQ on EcG-EnS_3 nexus	InQ on EcG-EnS_4 nexus	InQ on EcG-EnS_5 nexus	InQ on EcG-AgEnS nexus
InQ	4.455*** (8.25)	5.379*** (11.623)	5.843*** (11.072)	2.610*** (3.104)	10.136*** (8.143)	−80.831*** (−8.412)
TrO	−0.084*** (−9.65)	−0.013** (−1.983)	−0.026*** (−3.800)	−0.057*** (−8.103)	−0.056*** (−8.309)	−0.062*** (−10.305)
UrB	0.266 (1.48)	0.180*** (11.240)	0.165*** (9.080)	0.041** (2.475)	0.045*** (2.787)	0.041*** (2.856)
FDI	0.172*** (3.07)	0.115*** (2.807)	0.242*** (5.453)	0.295*** (5.378)	0.182*** (3.461)	0.105** (2.151)
EnS_1	−3.093*** (−5.12)					
EnS_2		−1.00008*** (−5.33)				
EnS_3			−2.012*** (−4.37)			
EnS_4				3.170*** (4.89)		
EnS_5					−3.766 (−0.91)	
AgEnS						98.220*** (4.46)
Constant	−16.193 (−1.12)	−36.715*** (−4.03)	−77.060*** (−7.24)	−33.131*** (−2.62)	−52.700*** (−4.47)	113.757*** (5.32)
Moderating effects						
InQ × EnS_1	2.208** (2.13)					
InQ × EnS_2		4.012*** (12.81)				
InQ × EnS_3			3.002*** (9.73)			
InQ × EnS_4				8.225* (1.88)		
InQ × EnS_5					0.775*** (5.03)	
InQ × AgEnS						103.167*** (8.57)
Observations	184	184	184	184	184	184
Number of ID	8	8	8	8	8	8

Notes: ***, **, and * indicate significance at 1 %, 5 %, and 10 % levels, respectively. z-statistics in parentheses.
Source: Authors' estimations.

their growth trajectories, energy security emerges as a critical pillar, not only to support immediate development needs but also to ensure long-term stability. In this context, securing reliable energy sources becomes indispensable for maintaining and driving economic expansion [214]. In our examination of the interplay between energy security and economic growth in South Asian nations, the results revealed compelling insights under two distinct scenarios. The first scenario evaluates the direct impact of energy security on economic growth within the context of a broader institutional framework, highlighting the role of governance and policy structures (Tables 9 and 10). The second scenario delves deeper, analyzing how institutional quality modulates the influence of diverse energy security elements on economic growth (Tables 11 and 12). This nuanced approach unravels the dynamic interplay between energy security and institutional quality in shaping contemporary economic outcomes across the region. The initial findings (Table 2, Figs. 3 and 4) underscore the pronounced volatility in key energy security indicators, such as energy availability, supply capacity, demand, and the development of alternative sources. Moreover, the region's energy efficiency remains below critical benchmarks, signaling significant room for improvement. Compounding these challenges is the region's consistently low institutional quality, which further exacerbates its ability to effectively manage energy resources and foster sustained economic growth.

Under the first scenario, our findings underscore that energy availability (EnS_1) poses significant constraints on economic growth, reflecting the region's persistent challenges with energy shortages. This aligns with well-established economic theories that emphasize the pivotal role of energy as a fundamental production input, operating alongside labor and capital [215]. While conventional economic models, such as the "cost-sharing theorem" [216], predominantly emphasize the contributions of labor and capital, emerging energy-growth theories highlight the crucial role of energy availability as a vital catalyst that ensures the efficient functioning and productivity of these inputs. Prior research, including the works of Ullah et al. [217], Öncel et al. [218], Adi et al. [219], Avazkhodjaev et al. [220], Khan et al. [221], Rehman et al. [222], Oyeleke and Akinlo [223], and Singh and Inglesi-Lotz [224], collectively offer robust statistical evidence supporting the critical role of energy in driving economic growth across a variety of global economies. Furthermore, both energy supply capacity (EnS_2) and energy demand (EnS_3) have been identified as formidable barriers to economic growth in the region. These challenges stem from a significant shortfall in the current energy infrastructure, which fails to adequately address the escalating demands of industrialization and economic expansion in South Asia. Such limitations not only lead to chronic energy shortages but also stifle productivity and curtail vital investment opportunities. These results are corroborated by recent studies from Olujobi et al. [225], Zhao et al. [226], Eldowma et al. [227], Makieła et al. [160], Sulub et al. [228], Gielen et al. [229], Coester et al. [230], and Samawi et al. [161], all of which highlight the importance of comprehensive enhancement in energy capacity to facilitate sustainable development and growth trajectories. Energy capacity development (EnS_4) from renewable sources, conversely, exerts a substantial positive impact on economic growth, emphasizing that targeted investments in energy infrastructure and cutting-edge technologies can markedly enhance eco-friendly production capabilities. This synergy between energy capacity and growth is well-supported by prior empirical studies conducted by Abbasi et al. [231] Bhuiyan et al. [56], Minh and Van [232], Chen et al. [233], Chen et al. [74], Doytch and Narayan [234], Gyimah et al. [235], Oliveira and Moutinho [236], Shahbaz et al. [237], Umeji et al. [238], Wang et al. [69–71], and Xie et al. [75].

Contrary to a large portion of the literature [36,171,172,174,239–246], our findings reveal that energy efficiency (EnS_5) negatively impacts economic growth in South Asia. This outcome likely stems from several regional-specific factors. Despite efforts to improve energy efficiency, the region's heavy reliance on aging infrastructure diminishes the expected benefits. Moreover, the significant upfront costs associated with transitioning to energy-efficient systems may divert scares resources away from growth-enhancing investments, especially in developing economies like South Asia [247]. The aggregate energy security index (AgEnS) positively impacts economic growth in the region, aligning with theories in energy economics and sustainable development. The energy-growth nexus highlights that energy security drives stable productivity that stimulates economic performance [248]. Our results are consistent with recent empirical studies by Gasparatos and Gadda [79], Balitskiy et al. [81], Fang et al. [6], Mahmood and Ayaz (2018), Le and Nguyen [37], Nepal and Paija [82], Nepal and Musibau [83], Kartal [84], Banna et al. [2], Lee et al. [182], and Ul-Haq et al. [181], which collectively povide statistical evidence on the positive impact of energy security on economic growth across diverse economies. While the results of the control variables closely mirror existing literature, thereby reinforcing their significance in our analysis, our findings concerning the direct positive impact of institutional quality on economic growth resonate with the works of Mahran [249], Azimi [250], Ashraf et al. [251], Okunade [252], Zhuo et al. [253], Ahmed et al. [254], and Osman et al. [188]. Similar to results, these studies collectively emphasize the pivotal role of robust institutions as catalysts for economic advancements. Specifically, mechanisms such as effective anti-corruption initiatives, unwavering adherence to the rule of law, effective governance, and political stability serve as foundational pillars that underpin economic progress.

In the context of the second scenario, our findings unveil several critical insights. First, the interaction between institutional quality and EnS_1 transforms its previously detrimental effects into a positive one. This positive transition is primarily attributable to the heightened institutional quality, which enhances the reliability and efficiency of energy availability, thus fostering a more conducive environment for further growth. Second, institutional quality proves effective in absorbing the negative impact of EnS_2 on economic growth. This shift is based on the premise that enhanced institutional setups increase both management and distribution of energy supply capacity, thereby promoting inclusive growth across the region. Third, institutional quality is found to effectively moderate the nexus between EnS_3 and economic growth, absorbing its negative correlation and leading to an upsurge in the effect of EnS_3 on growth. Literally, strong institutional quality optimizes energy demand, ensures efficient energy use, and minimizes energy wastage. Fourth, while the interaction of institutional quality with EnS_4 retains the initial positive impact on economic growth, it significantly enhances the effect size. This implies that higher institutional quality amplifies the benefits of energy development capacity, further improving economic growth. Fifth, initial results showed that energy inefficiency could suppress growth within the region. However, when institutional quality moderates the relationship between EnS_5 and economic growth, the sign shifts to positive, leading to improved economic growth. This necessitates the urgent need for policymakers to enhance existing institutional quality, as such improvements can significantly boost energy efficiency and thus foster economic growth. Finally, our results indicate that institutional quality is effective in increasing the effect size of the AgEnS on economic growth. This demonstrates that a simultaneous focus on sectoral institutional quality yields higher positive effects of EnS on economic growth across South Asia. Notably, this approach aligns with emerging methodologies in the literature; as demonstrated by Tayyab Ayaz et al. [30], the moderating effects of institutional quality on the EnS-growth nexus can yield significant insights, despite the current lack of technical measurement metrics.

6. Conclusions

This study utilizes a set of panel data for South Asian countries, including Afghanistan, Bangladesh, Bhutan, India, Nepal, Maldives, Sri Lanka, and Pakistan. The study period spans from 2000 to 2022, selected based on data availability from various reliable sources. The key objective of the study is to examine the impact of energy security on regional economic growth, both individually and in conjunction with the modulation of institutional quality. For a precise evaluation, the study innovatively constructed both individual elements of energy security form diverse predictors and an aggregate energy security index. Additionally, using a distance-based method, the study further developed a comprehensive institutional quality index to gauge its direct and moderating role on the nexus between energy security and economic growth. Variables are selected meticulously, and based on their initial statistical properties, the study employed the panel-corrected standard error (PCSE) model as a key estimation technique, validated through the feasible generalized least squares (FGLS) approach. The preliminary statistical results revealed significant volatility in energy security indicators and consistently low institutional quality scores across the region, prompting an urgent need for macroeconomic policy interventions. Through the application of the SSBM-DEA approach, the analysis uncovers that while South Asia generally shows a superficial performance in energy efficiency, there are notable disparities among the included countries, with the Maldives ranking the highest performer and Nepal the lowest in energy efficiency. Additionally, the results obtained from the PCSE model indicate that energy availability, energy supply capacity, energy demand, and energy efficiency exert negative impacts on economic growth, whereas energy development capacity positively influences growth within South Asia. Moreover, the findings revealed that the aggregate energy security index and institutional quality index positively influence growth, alongside urbanization and foreign direct investment. Conversely, trade openness adversely impacts on the region's economic growth. Given the initial results, the study innovatively estimated the moderating effects of institutional quality on both individual elements of energy security and its aggregate index to highlight more specific policy areas where effective interventions are sought. The findings indicated that institutional quality is an effective policy tool in enhancing economic growth both directly and indirectly. Not only does institutional quality efficiently transform the negative impact of energy security elements into positive ones, but it also significantly moderates to increase the effect size of the energy security on the subject. This underscores the crucial role of institutional quality in shaping the contemporary economic landscape of the region.

6.1. Policy implications

The extensive analysis identifies several specific policy implications: First, there is an urgent need for sustainable investment in energy infrastructure to address challenges related to energy availability, supply capacity, and efficiency. Strengthening energy development capacity can have a positive influence on economic growth. Policymakers need to prioritize modernizing energy infrastructure, adopting innovative technologies, and ensuring reliable energy supply to meet industrial expansion and overall economic growth. Second, the promotion of energy efficiency is crucial. Considering the desirable output (economic output, GDP) and the undesirable output (environmental degradation, CO_2e), the findings show that South Asia superficially performs in energy efficiency. Thus, implementing policies aimed at enhancing energy efficiency is critical for the region's economic progress. This can be achieved by adopting innovative technologies, following global best practices, and energy-saving measures to enhance existing schema. Third, the enhancement of institutional quality is essential for the region's economic progress. South Asia consistently scores low in this domain, and the findings show that economic growth is closely tied to improvements in institutional quality. Governments need to focus on enhancing existing good governance practices, judicial efficiency, rule of law, government effectiveness, and regulatory quality. Effective institutions are crucial to absorb negative impacts of energy security elements on economic growth, fostering a more conducive environment for enhanced investments and economic performance. Finally, regional cooperation on energy security is crucial for addressing common energy challenges and improving energy availability across South Asia. Countries in the region need to collaborate on energy projects, develop innovative regional energy grids to sustain energy supplies, and share best practices. Improving regional energy cooperation is critical to ensure more efficient utilization of resources, reduce the cost of energy, and support collective economic growth.

6.2. Limitations

The study mainly focuses on the contemporaneous links between energy security and economic growth both independently and modulated by institutional quality within South Asia, potentially overlooking external factors that could affect these dynamics. This could include global economic conditions, geopolitical tensions, international energy security market fluctuations, and climate change that are critical in influencing the existing energy security and economic growth in South Asia. This limitations suggest that the findings might not fully encapsulate the broader context within which South Asia performs. Future studies may account for these limitations and offer a broader picture on the nexus between energy security and economic growth.

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CRediT authorship contribution statement

Mohammad Naim Azimi: Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Mohammad Mafizur Rahman:** Writing – review & editing, Validation, Supervision, Conceptualization. **Tek Maraseni:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All datasets used are publicly available on the World Bank Group Databases.

Appendix A. Partial derivative of InQ with respect to EnS

Given that InQ (institutional quality index) moderates the relationship between EnS (energy security, both the elements like EnS_1–EnS_5 and the AgEnS) and EcG (economic growth), we express this relationship as follows:

Step I: Identification of the function

$$EcG_{it} = f(EnS_{it}, InQ_{it}) + \beta(InQ_{it} \times EnS_{it}) \tag{A1}$$

Step II: Differentiation with respect to EnS.

We now focus on the term that includes the moderating effect:

$$\frac{\partial}{\partial EnS_{it}}(\beta(InQ_{it} \times EnS_{it})) \tag{A2}$$

Using the product rule:

$$\frac{\partial}{\partial EnS_{it}}(InQ_{it} \times EnS_{it}) = InQ_{it} + EnS_{it}.\frac{\partial InQ_{it}}{\partial EnS_{it}} \tag{A3}$$

Assuming that InQ is independent of EnS:

$$\frac{\partial}{\partial EnS_{it}}(InQ_{it} \times EnS_{it}) = InQ_{it} \tag{A4}$$

Step III: Now, substituting back into the expression for EcG:

$$\frac{\partial EcG_{it}}{\partial EnS_{it}} = \frac{\partial f}{EnS_{it}} + \beta.InQ_{it} \tag{A5}$$

Eq. (A5) indicates the partial derivative of EcG with respect to EnS. This shows how economic growth response to changes in energy security, considering the moderating impact of InQ.

Appendix B. Further graphical analysis

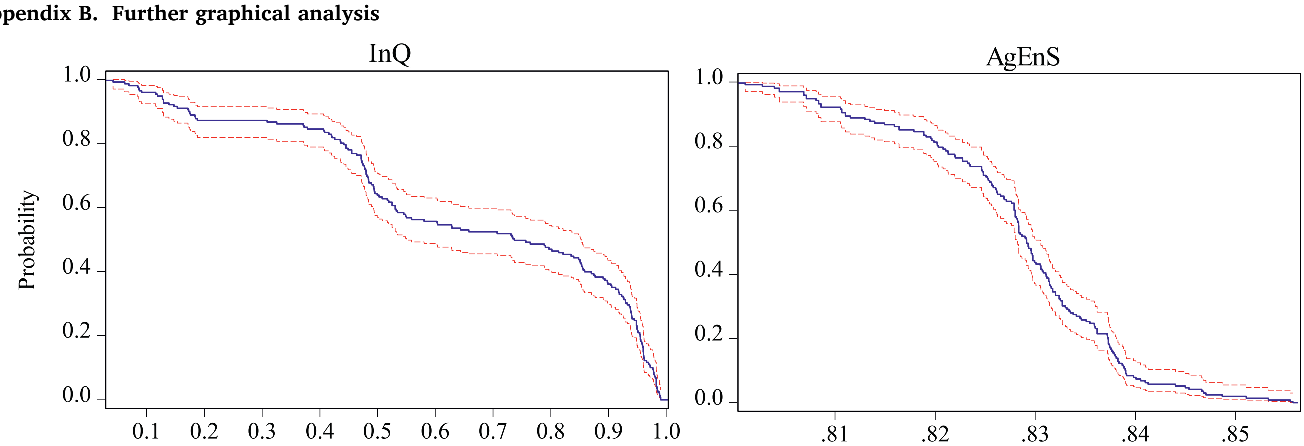

Fig. B1. Probability plots of the constructed AgEns and InQ.

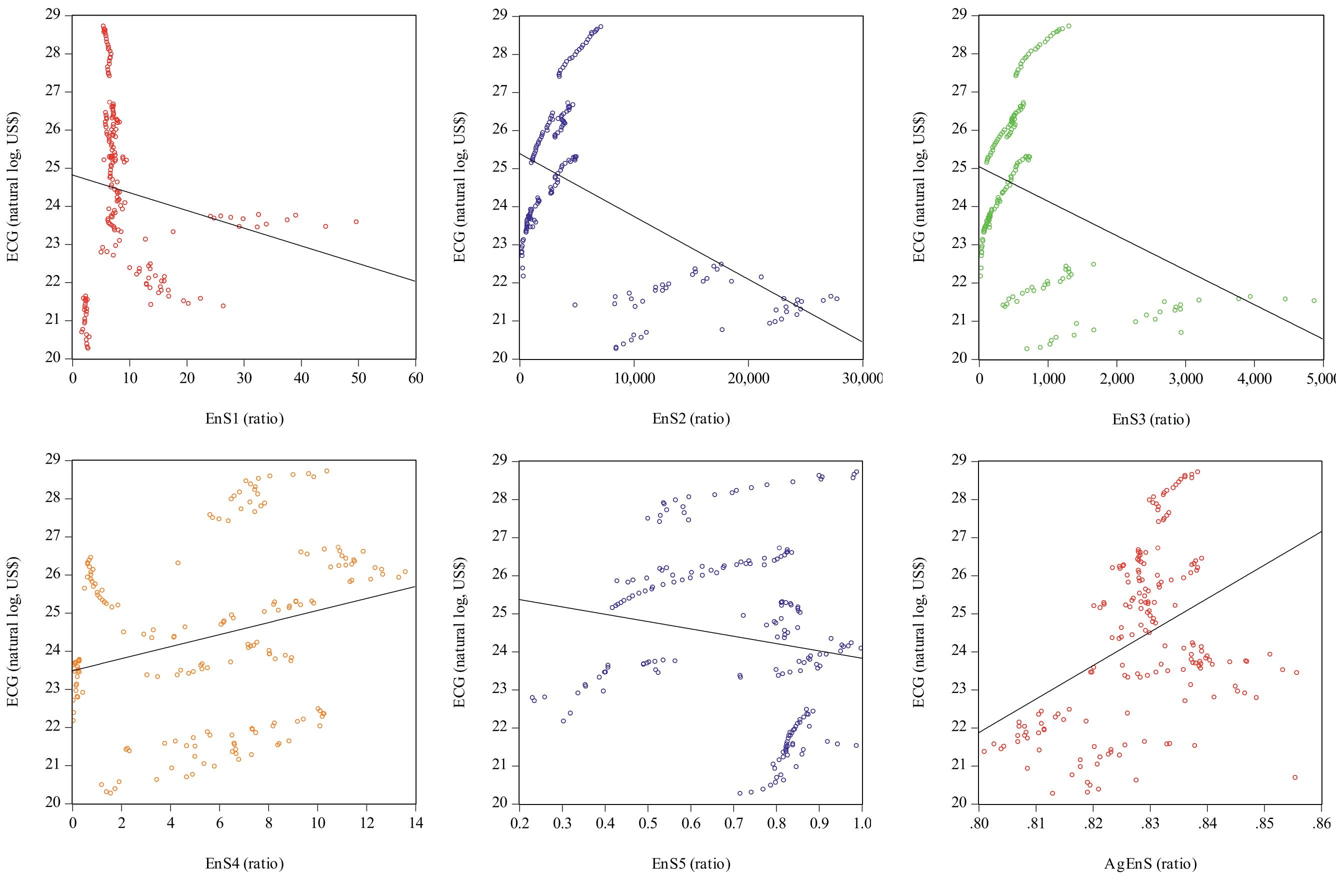

Fig. B2. Scatter plots of EnS and EcG.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124835.

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