

Assessing Energy Security in South Asia: A Composite Index Approach Incorporating Governance, Sustainability, and Socioeconomic Dimensions

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Abstract

Background and Objectives: Energy security extends beyond resource availability and affordability to encompass governance, environmental sustainability, and socioeconomic dimensions that are critical for sustainable development. In South Asia, rising energy demand, rapid population growth, and urbanization are intensifying pressure on limited energy resources. A comprehensive assessment of energy security helps identify structural weaknesses, including import dependence, inefficient energy use, and unequal access to modern energy services across countries such as Pakistan, India, Bangladesh, Nepal, Bhutan, and Sri Lanka. It also provides insights into institutional effectiveness, environmental performance, and the long-term resilience of energy systems. Accordingly, this study develops a multifaceted energy security index for South Asian countries over the period 2001–2022.

Methodology: Data suitability is assessed using the Kaiser–Meyer–Olkin (KMO) measure and Bartlett’s test of sphericity. A KMO value above 0.05 indicates adequate sampling, while a significant Bartlett’s test ($p < 0.05$) confirms sufficient correlations for factor analysis. Internal consistency among indicators is evaluated using Cronbach’s alpha (acceptable range: 0.7–0.9). Principal Component Analysis (PCA) is then applied to reduce dimensionality and extract latent components. Component weights are derived from eigenvalues, reflecting their contribution to total variance. The Min–Max normalization method is used to standardize variables, which are subsequently aggregated into a composite index based on weighted components.

Key Findings: The results indicate strong internal consistency (Cronbach’s alpha = 0.733) and high sampling adequacy (KMO = 0.863), with Bartlett’s test confirming significant inter-item correlations. The PCA yields a Multifaceted Energy Security Index (MFESI) comprising eight dimensions: energy sustainability, governance and efficiency, socio-environmental sustainability, affordability, energy access, human

resilience, energy transition, and labor market dynamics. The index rankings show that India leads in overall energy security, followed by Pakistan, Bangladesh, Bhutan, Sri Lanka, and Nepal. Classification into four categories, Poor (1–2.5), Fair (2.5–5.0), Good (5.0–7.5), and Excellent (7.5–10) reveals that most countries fall within the “Fair” range. Dimension-wise analysis highlights India’s strength in sustainability and renewable energy, Bhutan’s strong governance performance but weak sustainability, and Pakistan’s strengths in socio-environmental sustainability alongside affordability challenges. Nepal consistently ranks lowest in governance and resilience, indicating structural constraints.

Policy Implications: The findings highlight significant regional disparities in energy security and underscore the need for coordinated policy responses. Strengthening regional cooperation through cross-border electricity trade and renewable energy collaboration is essential. Policy priorities include improving affordability through targeted subsidies and tariff reforms, enhancing climate-resilient energy infrastructure, and promoting institutional reforms. Country-specific strategies suggest improving governance and affordability in Pakistan, enhancing human resilience and sustainability in India, expanding energy access in Bangladesh, diversifying energy sources in Bhutan and Nepal, and strengthening governance and renewable energy development in Sri Lanka. These measures are critical for achieving Sustainable Development Goals (SDGs) 7, 13, and 16.

Keywords: Energy Security; Composite Index; Principal Component Analysis; South Asia; Sustainable Development

JEL Classification Codes: Q43; Q48; O13; C38

1. Introduction

Energy security is of critical importance for policymakers, businesses, and society at large, as sustainable development depends on a reliable and adequate supply of energy (Ayaz et al., 2024; Banna et al., 2023; Mahmood & Ayaz, 2018; Shahbaz et al., 2018). It is commonly defined as the continuous availability of energy at affordable prices (Aydin & Azhgaliyeva, 2019; Winzer, 2012). The International Energy Agency (2007) further defines energy security as the uninterrupted availability of energy sources at an affordable price. Achieving energy security remains particularly challenging for resource-constrained economies that struggle to meet basic energy needs, as emphasized in Sustainable Development Goal 7 (SDG 7), which focuses on access to affordable and sustainable energy (Opoku, 2016; Taghizadeh-Hesary et al., 2021).

Energy security is a pressing concern for developing regions such as South Asia, where diverse energy profiles often result in supply shortages and unstable distribution networks, thereby disrupting industrial production and agricultural productivity (Ul-Haq et al., 2020). Energy shortages can reduce GDP growth by up to 2% annually in the region, underscoring the significant economic risks associated with energy

insecurity (Alam et al., 2024; Jain & Goswami, 2021; Katekar et al., 2021). Total primary energy consumption (TPEC) in South Asia has increased substantially, rising from 761 Mtoe in 2012 to 1,310 Mtoe in 2023, and is projected to exceed 1,670 Mtoe by 2030 (SAARC Energy Centre, 2018). India accounts for approximately 84% of total regional energy demand, followed by Pakistan at 8.3%, while the remaining countries jointly contribute around 7.5%. Overall energy demand is expected to grow by nearly 50% between 2018 and 2050, largely driven by rapid economic expansion (Turiel, 2022).

The region remains heavily dependent on non-renewable energy sources. For example, India imports approximately 85% of its crude oil and more than 50% of its natural gas (Jain, 2022; Nandi et al., 2022; Sinha et al., 2022). Despite progress in electrification, around 250 million people in South Asia still lack access to electricity, constraining both economic and social development (International Energy Agency [IEA], International Renewable Energy Agency [IRENA], United Nations Statistics Division [UNSD], World Bank, & World Health Organization [WHO], 2019). Environmental challenges further exacerbate the situation, as economies such as India, Pakistan, and Bangladesh are among the most polluted globally due to extensive reliance on fossil fuels (Adedoyin et al., 2021). Transitioning toward renewable energy is therefore essential to mitigate environmental degradation and support sustainable development (Chu et al., 2023).

Existing studies on energy security in South Asia have primarily focused on individual countries or limited dimensions. For instance, Malik et al. (2020) and Bin Amin et al. (2022) assess energy security in Pakistan and Bangladesh using the 4A framework: availability, accessibility, affordability, and acceptability. Other studies, such as Le et al. (2019), Azzuni and Breyer (2020), Gasser (2020), Abdullah et al. (2022a), and Bhattarai et al. (2024), incorporate governance, technological, and environmental considerations in evaluating energy security. However, only a limited number of studies (e.g., Ayaz et al., 2024; Bazilian et al., 2014; Bhattarai et al., 2024; Bin Amin et al., 2022; Dagar et al., 2024; Florini & Sovacool, 2009; Nazir et al., 2026) integrate governance and environmental factors using a relatively narrow set of indicators.

The motivation for this study stems from the recognition that South Asian countries share common energy challenges, including rapidly increasing demand, dependence on fossil fuels, and gaps in energy access, while simultaneously exhibiting significant heterogeneity in resource endowments, institutional quality, and social infrastructure. In this context, a region-specific and comparative assessment of energy security is particularly valuable. This study provides a standardized framework for cross-country comparison and supports evidence-based policymaking. It also highlights opportunities for regional cooperation and policy learning. Furthermore, the proposed framework can be applied to other developing regions facing similar energy challenges, thereby enhancing its broader policy relevance.

Despite the growing body of literature, most existing studies rely on aggregate energy security indices and lack detailed dimension-wise analysis. In addition, many studies are based on predefined dimensions such as availability, accessibility, affordability, environmental sustainability, and governance while overlooking other important aspects, including energy transition, labor market conditions, education, health, and broader socioeconomic factors. These omissions limit the ability to capture the multidimensional nature of energy security, particularly in region-specific analyses.

To address these gaps, this study develops a multifaceted energy security index (MFESI) for South Asia, covering Pakistan, India, Bangladesh, Bhutan, Nepal, and Sri Lanka, using a comprehensive set of fifty-six indicators drawn from the literature. The study employs Principal Component Analysis (PCA) to construct eight latent dimensions: energy sustainability, governance and efficiency, socio-environmental sustainability, affordability, human resilience, energy access, energy transition, and labor market dynamics. In addition, a dimension-wise comparative analysis is conducted to provide deeper insights into country-level performance.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the conceptual framework. Section 4 describes the data and methodology. Section 5 reports the empirical results and discussion. Finally, Section 6 presents the conclusions, and Section 7 provides the policy implications.

2. Literature Review

Energy security has become a critical concern for countries worldwide due to its strong interlinkages with energy access, environmental sustainability, and socioeconomic stability. The development of energy security indices has emerged as an important analytical tool for policymakers to capture its multidimensional nature and to support effective energy policy design for economic development. Early and influential contributions by Vivoda (2010) and Sovacool and Mukherjee (2011) laid the foundation for constructing energy security indices by proposing comprehensive theoretical frameworks that integrate multiple dimensions and indicators.

A substantial body of literature has focused on measuring energy security across different country contexts. China, as one of the world's largest energy consumers, has received considerable attention. Studies such as Lee and Wang (2022), Bazilian et al. (2014), Ayaz et al. (2024), Dagar et al. (2024), Nazir et al. (2026), Bin Amin et al. (2022), Bhattarai et al. (2024), Florini and Sovacool (2009), and Zhao et al. (2023) construct energy security indices based on the 4A framework availability, accessibility, affordability, and acceptability. This framework is particularly relevant in the Chinese context, where ensuring a stable energy supply must be balanced with environmental sustainability and socioeconomic development challenges.

Beyond China, other studies have adopted alternative methodological approaches and regional perspectives. For example, Kharazishvili et al. (2021) employ principal component analysis (PCA) to assess energy security in Ukraine by integrating

dimensions such as availability, reliability, environmental sustainability, and governance. Similarly, Martišauskas et al. (2022) evaluate energy security in the Baltic States, Lithuania, Latvia, and Estonia using an expert-based assessment framework. These studies highlight the diversity of methodological approaches in measuring energy security and the importance of adapting frameworks to country-specific contexts.

In the South Asian context, existing research has primarily focused on country-level analyses. Malik et al. (2019) develop an energy security index for Pakistan based on the 4A framework, incorporating availability, affordability, applicability, and acceptability. Their findings emphasize that energy security extends beyond technical and economic considerations to include political and social dimensions. Nandy (2024) examines energy security in Pakistan and Bangladesh, highlighting the alignment between national energy policies and sustainable development objectives. Furthermore, Shah et al. (2019) construct a composite index combining energy security and environmental sustainability for South Asian countries. In Pakistan, Abdullah (2020) and Abdullah et al. (2022b) extend the traditional framework by incorporating governance, regulatory quality, and environmental sustainability into energy security assessment.

Despite these contributions, a significant gap remains in the literature. Most existing studies rely on limited sets of indicators and predefined dimensions, often focusing primarily on availability, accessibility, affordability, and environmental factors. As a result, broader dimensions such as socioeconomic conditions, labor market dynamics, energy transition, education, and health are frequently overlooked. This limitation restricts the ability of existing indices to fully capture the complex and multidimensional nature of energy security, particularly in developing regions. To address these limitations, this study develops a comprehensive multifaceted energy security index that incorporates a broader set of socioeconomic, institutional, and structural dimensions using a data-driven PCA approach.

3. Conceptual Framework

Traditionally, energy security has been defined in terms of supply stability and affordability (IEA, 2007). However, evolving global energy challenges have broadened this concept to include environmental sustainability, governance, social equity, and system resilience (SAARC Energy Centre, 2018). Recent studies argue that conventional definitions are insufficient, as they fail to capture the complex interactions among technical, institutional, environmental, and social systems that shape energy outcomes.

Sovacool and Mukherjee (2011) and Vivoda (2010) emphasize that energy security should extend beyond physical supply to incorporate affordability, environmental acceptability, governance quality, and diversification. Building on these frameworks, the present study develops a comprehensive conceptual framework for assessing energy security in South Asia. This framework integrates multiple

dimensions and indicators to construct a Multifaceted Energy Security Index (MFESI). The conceptual framework is illustrated in Figure 1.

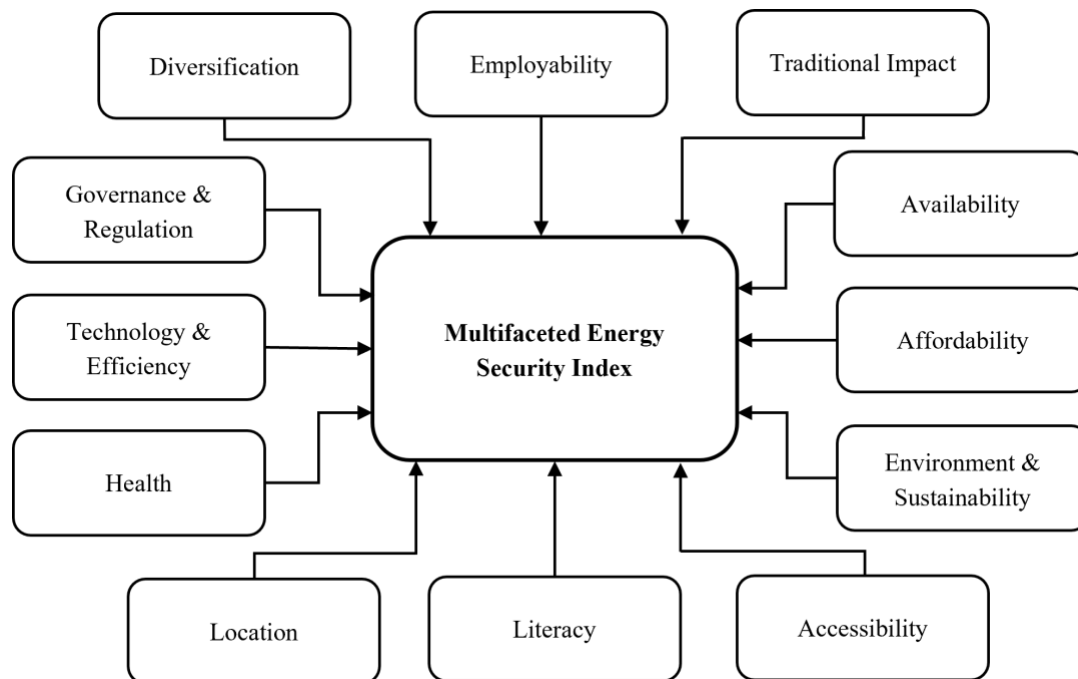


Figure 1. Conceptual Framework of Multifaceted Energy Security Index Dimensions
Source: Adapted from Vivoda (2010) and Sovacool and Mukherjee (2011).

Note: The figure illustrates the multidimensional structure of energy security, integrating traditional and extended dimensions used to construct the MFESI.

Figure 1 highlights that energy security is inherently multidimensional. The literature identifies several key dimensions, including availability, affordability, accessibility, environmental sustainability, diversification, governance, technology and efficiency, employability, literacy, health, and location. Availability ensures that sufficient energy resources and infrastructure exist to meet demand, while affordability determines whether energy services are accessible without imposing economic burdens. Accessibility reflects the physical availability of energy services across populations and regions. Environmental sustainability focuses on long-term viability by mitigating ecological degradation and climate-related risks. Diversification reduces dependence on single energy sources or suppliers, thereby enhancing resilience to external shocks. Governance captures regulatory quality, institutional effectiveness, and policy implementation, while technology and efficiency contribute to system reliability, innovation, and modernization. Collectively, these core dimensions influence supply reliability, price stability, and the capacity for energy transition.

In addition to these core dimensions, broader socioeconomic factors such as literacy, health, employability, location, and traditional practices also play an important role in shaping energy security. Although these factors do not directly determine energy supply, they influence the long-term resilience and sustainability of energy systems. The literature increasingly recognizes the importance of health and education as integral

components of energy security, as they enhance human capital, innovation capacity, and social adaptability (Sovacool & Mukherjee, 2011; Vivoda, 2010). For example, Azzuni and Breyer (2020), in their Global Energy Security Index, include education expenditure as a proxy for the literacy dimension, highlighting its role in promoting awareness and adoption of sustainable energy practices. Similarly, health indicators such as mortality rates and disease prevalence reflect the externalities of energy systems, particularly pollution-related impacts, and influence labor productivity and overall social welfare.

4. Data, Variables, and Methodology

4.1 Data and Variables

This study aims to develop a comprehensive framework for assessing energy security in South Asia. To construct the Multifaceted Energy Security Index (MFESI), a broad set of indicators is selected from the literature based on the dimensions identified in the conceptual framework. The indicators, along with their units, data availability, and sources, are presented in Table 1.

Table 1. Proposed Indicators for Multifaceted Energy Security Index (MFESI)

No.	Indicators	Data Availability	Unit	Data Source
1	Final Energy Consumption (FEC)	Yes	billion kWh	US EIA
2	Energy Intensity/POP (EI/POP)	Yes	MMBtu/person	US EIA
3	Energy Intensity/GDP (EI/GDP)	Yes	1000Btu/2015\$GDP	US EIA
4	Nuclear Energy Generation (NLREG)	Yes	billion kWh	US EIA
5	Fossil Fuel Energy Generation (FFEG)	Yes	billion kWh	US EIA
6	Hydro Energy Generation (HYDEG)	Yes	billion kWh	US EIA
7	Solar Energy Generation (SEG)	Yes	billion kWh	US EIA
8	Wind Energy Generation (WEG)	Yes	billion kWh	US EIA
9	Biomass Energy Generation (BEG)	Yes	billion kWh	US EIA
10	Electricity Import (ELEM)	Yes	billion kWh	US EIA
11	Distribution losses (DL)	Yes	billion kWh	US EIA
12	Nuclear Capacity (NLREC)	Yes	million kW	US EIA
13	Fossil Fuel Capacity (FFC)	Yes	million kW	US EIA
14	Hydro Capacity (HYDEC)	Yes	million kW	US EIA
15	Solar Capacity (SEC)	Yes	million kW	US EIA
16	Wind Capacity (WEC)	Yes	million kW	US EIA
17	Biomass Capacity (BEC)	Yes	million kW	US EIA
18	Total Primary Energy Supply (TPES)	Yes	Kgoe	SAARC Indicators
19	Total Primary Energy Supply /Capita (TPES/C)	Yes	Kgoe	SAARC Indicators
20	Population (POP)	Yes	Thousands	WDI

No.	Indicators	Data Availability	Unit	Data Source
21	Coal Reserves (CRES)	Yes	ratio	SAARC Indicators
22	Oil Reserves (ORES)	Yes	ratio	SAARC Indicators
23	Gas Reserves (GRES)	Yes	ratio	SAARC indicators
24	Energy Self-Sufficiency (ESS)	Yes	Kgoe/Capita	SAARC Indicators
25	Access to Electricity (ATE)	Yes	percentage	WDI
26	Oil prices (OP)	Yes	\$/liter	SAARC indicators
27	Gasoline Prices (GP)	Yes	\$/liter	SAARC indicators
28	Electricity Prices (EP)	No	\$/MWh	SAARC indicators
29	Access to clean Fuel (ATCF)	Yes	percentage	WDI
30	CO ₂ Emissions/TPES (CO ₂ E/TPES)	Yes	Kg/kgoe	WDI
31	CO ₂ Emissions/GDP (CO ₂ E/GDP)	Yes	%	WDI
32	GHG Emissions (GHGE)	Yes	MtCO ₂ eq	WDI
33	Forest Area (% of land Area) (FAL)	Yes	percentage	WDI
34	CO ₂ Emissions Per Capita (CO ₂ E/C)	Yes	tons/capita	WDI
35	Oil Rent% of GDP (ORE)	Yes	%	WDI
36	Gas Rent % of GDP (GRE)	Yes	%	WDI
37	Coal Rent % of GDP (CRE)	Yes	rank	WDI
38	Voice and Accountability (VA)	Yes	rank	WDI
39	Fragile State Index (FSI)	Yes	rank	WDI
40	Government Effectiveness Index (GEI)	Yes	rank	WDI
41	Rule of Law (ROL)	Yes	rank	WDI
42	Corruption Perception Index (CPI)	Yes	rank	WDI
43	Political Stability (PS)	Yes	rank	WDI
44	Employment in the Power Sector (EPS)	No	%	WDI
45	Unemployment (UMP)	Yes	%	WDI
46	Labor Force (LF)	Yes	number	WDI
47	Poverty Head Count Ratio (PHCR)	Yes	percentage	WDI
48	Gini Index (GI)	Yes	rank	WDI
49	Food Supply (FS)	Yes	rank	WDI
50	Human Development Index (HDI)	Yes	rank	WDI
51	Area (AR)	Yes	M ²	WDI
52	Terrestrial and Marine Protected Areas (TMPA)	No	percentage	WDI
53	Industrial Value Added (IVA)	Yes	\$	WDI
54	Educational Expenditure (percentage)	Yes	%	WDI

No.	Indicators	Data Availability	Unit	Data Source
	of GDP) (EDUE)			
55	Expenditures on Research and Development (% of GDP) (ERD)	No	%	WDI
56	Health expenditure	Yes	%of GDP	WDI
57	Mortality Rate of Infants (MRI)	Yes	number	WDI
58	Number of Deaths Caused by Cancer in the Population (NDCC)	Yes	number	WDI
59	Coal Production (CPRO)	Yes	%	US EIA
60	Gas Production (GPRO)	Yes	%	US EIA
61	Petroleum Production (PPRO)	Yes	%	US EIA

Source: Compiled by the authors based on data from the U.S. Energy Information Administration (EIA, 2024), SAARC Energy Indicators, and World Development Indicators (WDI).

Note: Indicators are selected based on the conceptual framework and existing literature. Variables with insufficient data availability—namely electricity prices, employment in the power sector, expenditures on research and development, and terrestrial and marine protected areas—are excluded from the empirical analysis.

5.1 Methodology

The construction of the MFESI is based on a series of statistical procedures, including reliability testing, sampling adequacy assessment, principal component analysis (PCA), data normalization, weight assignment, and index aggregation.

First, all selected indicators are compiled and assessed for reliability. Internal consistency is evaluated using Cronbach's alpha, where values between 0.7 and 0.9 are considered acceptable. To ensure data consistency, variables with substantial missing observations—such as labor force—are excluded from the analysis.

Next, the suitability of the dataset for PCA is examined using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. A KMO value greater than 0.5 indicates that the data are appropriate for factor analysis, while a statistically significant Bartlett's test ($p < 0.05$) confirms that sufficient correlations exist among variables. PCA is then applied to transform correlated variables into a smaller set of uncorrelated components that capture the maximum variance in the dataset.

Following component extraction, the data are normalized to ensure comparability across different measurement units and scales. The Min–Max normalization approach is applied to transform all variables onto a common scale ranging from 1 to 10, using the following formula:

$$Xi' = 1 + \frac{[Xi - \text{Min}(Ai)]}{[\text{Max}(Ai) - \text{Min}(Ai)]} * (10 - 1)$$

where X_i' represents the normalized value of indicator i , X_i is the original value, and $\min(A_i)$ and $\max(A_i)$ denote the minimum and maximum values of the indicator range, respectively.

After normalization, weights are assigned to each component based on their corresponding eigenvalues obtained from PCA. The weight for each component is calculated as:

$$W_i = V_i / \sum V_k$$

where W_i represents the weight of component i , and V_i is its eigenvalue.

Finally, the weighted components are aggregated to construct the MFESI, which reflects the overall level of energy security. The composite index is calculated as:

$$MFESI = \sum_{k=1}^n C_k W_k$$

where C_k represents the normalized score of component k , and W_k denotes its corresponding weight.

5. Results and Discussion

5.1 Descriptive Statistics Analysis

This section presents the descriptive statistics of the selected indicators (see Appendix), including the range, mean, standard deviation, and minimum and maximum values. The results indicate substantial variation across variables.

Greenhouse Gas Emissions (GHGE) exhibit the largest range (3,435,495.44), indicating considerable variability across observations. In contrast, oil reserves (OR) show a relatively small range (5.85), suggesting limited variation and values clustered near zero. Total Primary Energy Supply (TPES) has a mean value of 120.27, while population (POP) records a substantially higher mean (233,116.01), reflecting differences in measurement scales across indicators.

In terms of dispersion, GHGE has the highest standard deviation (936,685.07), indicating significant variability in emissions across countries and over time. Conversely, Energy Self-Sufficiency (ESS) exhibits a relatively low standard deviation (0.33), suggesting that observations are more closely concentrated around the mean value (0.67).

Overall, these descriptive statistics provide an overview of the distributional characteristics of the variables and highlight the heterogeneity across indicators, thereby justifying the need for normalization and dimensionality reduction techniques.

5.2 Reliability and Sampling Adequacy Test

The reliability and suitability of the dataset for factor analysis are assessed using Cronbach's alpha, the Kaiser–Meyer–Olkin (KMO) measure, and Bartlett's Test of Sphericity.

The Cronbach's alpha value of 0.733 indicates a satisfactory level of internal consistency among the indicators, suggesting that the selected variables are appropriate

for constructing a composite index. The final dataset includes 56 indicators after excluding variables with insufficient data availability.

The KMO statistic is 0.863, which exceeds the commonly accepted threshold of 0.5, indicating strong sampling adequacy for principal component analysis (PCA). In addition, Bartlett's Test of Sphericity yields a statistically significant result ($p = 0.000 < 0.05$), confirming the presence of sufficient correlations among variables and supporting the application of PCA.

Table 2. Reliability and Sampling Adequacy Results

Statistic	Value
Cronbach's Alpha	0.733
Number of Items	56
KMO Measure of Sampling Adequacy	0.863
Bartlett's Test (Chi-square)	26,108.193
Degrees of Freedom	1,540
Significance (p-value)	0.000

Source: Authors' calculations.

Note: Cronbach's alpha values between 0.7 and 0.9 indicate acceptable internal consistency. A KMO value greater than 0.5 suggests adequate sampling, while a statistically significant Bartlett's test ($p < 0.05$) confirms the suitability of the data for PCA.

5.3 Principal Component Analysis (PCA) Results

The PCA results indicate that the first principal component explains 44.71% of the total variance, which is expected as it captures the dominant structure in the data. The first three components jointly explain 67.41% of the variance, while the first eight components account for 94.03% of the total variance before rotation.

Following Varimax rotation, the total explained variance remains unchanged, although the distribution of variance across components becomes more balanced, thereby improving interpretability. Based on the eigenvalue-greater-than-one criterion, eight components are retained for further analysis.

Table 3. Principal Component Analysis: Total Variance Explained

Comp.	Total Variance Explained								
	Initial EigenValues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %
1.	25.79	46.06	46.06	25.79	46.06	46.06	25.04	44.71	44.71
2.	9.24	16.49	62.55	9.24	16.49	62.55	6.61	11.79	56.51
3.	5.18	9.26	71.81	5.18	9.26	71.81	6.10	10.90	67.41
4.	3.99	7.12	78.93	3.99	7.12	78.93	4.47	7.98	75.39
5.	3.07	5.48	84.41	3.07	5.48	84.41	3.08	5.50	80.89
6.	2.24	3.99	88.41	2.24	3.99	88.41	2.99	5.34	86.23

Comp.	Total Variance Explained								
	Initial EigenValues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %
7.	1.88	3.36	91.77	1.88	3.36	91.77	2.37	4.24	90.46
8.	1.26	2.26	94.03	1.26	2.26	94.03	1.99	3.56	94.03*

Source: Authors' calculations.

Note: Components with eigenvalues greater than one are retained. The cumulative variance explained by the first eight components reaches 94.03%, indicating strong explanatory power of the extracted components.

5.4 Scree Plot and Components Interpretations

The PCA results are further illustrated using a scree plot (see Appendix), which confirms the selection of eight components based on the point of inflection. The rotated component matrix (Table 4) groups energy, environmental, institutional, and socioeconomic variables into distinct components, reflecting the multidimensional structure of energy security.

Component 1 (C1) primarily captures energy consumption and environmental pressure, as variables such as final energy consumption (FEC), population (POP), greenhouse gas emissions (GHGE), and energy production indicators exhibit high loadings.

Component 2 (C2) represents energy efficiency and institutional quality, incorporating indicators such as energy intensity, governance measures (e.g., CPI, rule of law), and education-related variables.

Component 3 (C3) reflects resource management, inequality, and environmental sustainability, with strong loadings from indicators such as resource rents, inequality measures, and health-related variables.

Component 4 (C4) captures affordability and welfare conditions, including energy prices, poverty, and food security indicators.

Component 5 (C5) represents energy access, particularly through access to clean fuels and related indicators.

Components 6, 7, and 8 correspond to human resilience, energy transition, and labor market dynamics, respectively, capturing broader socioeconomic and structural aspects of energy security.

Table 4. Rotated Component Matrix

No.	C1	C2	C3	C4	C5	C6	C7	C8
1	FEC (0.99)	EI/POP (0.70)	FA L (-0.78)	ATE (0.63)	ATCF (0.87)	ESS (0.88)	SEG (0.66)	UMP (0.87)
2	EI/GDP (0.60)	TPES/C (0.87)	ORE (0.87)	GP (0.89)	GRE (0.91)	HDI (0.90)	SEC (0.61)	
3	NLREG (0.96)	CO ₂ E/C (0.58)	GI (-0.85)	OP (0.88)				

No.	C1	C2	C3	C4	C5	C6	C7	C8
4	FFEG (0.99)	CPI (0.83)	HEX (0.65)	FS (0.76)				
5	HYDEG (0.97)	CRE (0.75)	NDCC (0.718)	PHCR (-0.73)				
6	WEG (0.88)	ROL (0.64)	GPRO (0.73)					
7	BEG (0.93)	PS (0.83)	MRI (0.57)					
8	ELEM (0.72)	IVA (0.80)						
9	TPES (0.99)	EDUEX (0.53)						
10	CRES (0.99)	FSI (-0.49)						
11	ORES (0.95)	GEI (0.80)						
12	GRES (0.84)							
13	POP (0.98)							
14	GHGE (0.99)							
15	CO ₂ E/TPES (0.62)							
16	CO ₂ /GDP (0.60)							
17	VA (0.66)							
18	AR (0.96)							
19	CPRO (0.99)							
20	PPRO (0.96)							
21	NLREC (0.97)							
22	FFEC (0.97)							
23	DL (0.99)							
24	HYDEC (0.99)							
25	WEC (0.90)							

No.	C1	C2	C3	C4	C5	C6	C7	C8
26	BEC (0.88)							

Source: Authors' calculations.

Note: Only variables with significant loadings are reported. Component labels are assigned based on the dominant variables within each component.

5.5 Data Normalization and Weight Assignment

Following the extraction of principal components, the dataset is normalized to ensure comparability across indicators with different units and scales. The Min–Max normalization approach is applied to transform all values onto a common scale ranging from 1 to 10.

The PCA results yield eight components. After normalization, weights are assigned to each component based on its corresponding eigenvalues. The weight of each component reflects its relative contribution to the total explained variance.

For example, the weight of the first component (W_1) is calculated as the ratio of its explained variance to the cumulative variance of the retained components, i.e., $44.71 / 94.03 = 0.475$. Similarly, the weights of the remaining components are computed and presented in Table 5.

Table 5. Weights Assigned to Principal Components

Weights	W1	W2	W3	W4	W5	W6	W7	W8
Value	0.475	0.125	0.115	0.084	0.058	0.056	0.045	0.037
Components	1.	2.	3.	4.	5.	6.	7.	8.

Source: Authors' calculations.

Note: Weights are derived from the proportion of variance explained by each component relative to the total variance of the retained components.

5.6 Construction of Multifaceted Energy Security Index Dimensions

After assigning weights, the extracted components are interpreted and grouped into eight dimensions based on their dominant factor loadings. The classification of indicators into each dimension is determined by the rotated component matrix, ensuring that the grouping reflects the underlying data structure.

While Figure 1 and Table 1 present the theoretical and literature-based dimensions of energy security, Table 6 reports the empirically derived dimensions obtained from PCA. This approach allows the study to reconcile theoretical constructs with data-driven evidence.

The first dimension, Energy Sustainability (ES), consists of 26 indicators and primarily captures energy availability alongside environmental pressures.

The second dimension, Governance and Efficiency (G&E), includes 11 indicators and reflects institutional quality, regulatory effectiveness, and energy efficiency, combining governance, literacy, and technology-related variables.

The third dimension, Socio-Environmental Sustainability (SES), comprises 7 indicators and integrates environmental, health, and inequality-related factors.

The fourth dimension, Affordability (AFF), focuses on energy prices and welfare-related indicators, reflecting the economic accessibility of energy.

The fifth dimension, Energy Access (EA), includes 2 indicators and captures access to modern and clean energy services.

The sixth dimension, Human Resilience (HR), is based on 2 indicators and reflects the capacity of societies to sustain energy systems through human development and self-sufficiency.

The seventh dimension, Energy Transition (ET), captures renewable energy development, particularly solar energy generation and capacity, reflecting progress toward diversification and sustainability.

The eighth dimension, Labor Market Dynamics (LMD), includes 1 indicator and reflects employment conditions and economic resilience.

Table 6. Multifaceted Energy Security Index Dimensions, Descriptions, and Indicators

Dimensions	Description	Indicators
1. Energy Sustainability	These indicators of the “energy sustainability” dimension examine the interactions among energy supply, consumption, environmental effect, and innovation, presenting a holistic analysis of energy security and its long-term sustainability.	Final Energy Consumption, Energy Intensity/GDP, Nuclear Electricity Generation, Fossil Fuels Electricity, Hydro Electricity Generation, Wind Electricity Generation, Biomass Electricity Generation, Electricity Import, Distribution Losses, Nuclear Electricity Capacity, Fossil Fuels Electricity Capacity, Hydro Electricity Capacity, Population, Wind Electricity Capacity Biomass Electricity Capacity, Total Primary Energy Supply, Oil Reserves, Gas Reserves, Coal Reserves, Green House Gas Emission, CO ₂ Emissions/TPES, CO ₂ Emissions/GDP, Voice and Accountability, Area, Coal Production, Petroleum production
2. Governance & Efficiency	Governance efficiency supports energy security by allowing effective policy, reducing corruption, and stimulating stability. It confirms sustainable energy use, lowers emissions, and supports economic and social systems crucial for reliable energy access.	Energy Intensity/Population, Total Primary Energy Supply/Capita, CO ₂ emissions/Capita, Fragile State Index, Corruption Rank, Coal Rent, Rule of Law, Political Stability, Industrial Value added, Education Expenditure, Government Effectiveness Index

Dimensions	Description	Indicators
3. Socio–Environmental Sustainability	This dimension supports evaluating how energy policies, environmental management, and economic factors work together to enhance sustainability and lessen the effects of climate change.	Forest Area % Land, Oil Rent, Gini Index, Health Expenditures, Death by Cancer, Infant Mortality rate, Gas Production
4. Affordability	Stable, affordable energy ensures consistent access, supporting economic stability and overall energy security. It reduces poverty and enhances food security as well.	Access to Electricity, Oil prices, Gasoline Prices, Poverty Headcount Ratio, and Food Supply
5. Energy Access	This dimension ensures that populations have reliable, affordable, and sustainable energy for daily needs, they also reflect economic capacity and resource utilization, which support equitable energy access.	Access to Clean Fuel, Gas Rent
6. Human Resilience	In this dimension, energy self-sufficiency reduces supply dependence, while HDI reflects societal capacity to sustain reliable energy systems.	Energy Self-Sufficiency, Human Development Index.
7. Energy Transition	Solar energy and solar capacity support energy security by diversifying energy supply and reducing reliance on imports. It also enhances sustainability through reducing emissions.	Solar Energy, Solar Capacity
8. Labor Market Status	This dimension evaluates the overall employment situation and economic resilience, providing a deeper insight into employee dynamics and their influence on societal well-being.	Unemployment

Source: Authors' classification based on PCA results.

Note: Indicators are grouped into dimensions according to their dominant factor loadings from the rotated component matrix.

5.7 Country Level Energy Security Trends (2001–2022)

The PCA-based results indicate that India demonstrates the most substantial improvement in multifaceted energy security over the study period. This progress is largely driven by a diversified energy portfolio, including significant investments in solar, wind, and nuclear energy, as well as improvements in energy efficiency. India's expansion of renewable energy reflects a strong policy commitment to sustainable

energy transition. However, the country continues to face challenges due to its high dependence on coal and rising overall energy demand, which may constrain long-term sustainability.

Pakistan exhibits moderate but relatively stable growth in energy security between 2001 and 2022. The country has made notable progress in energy supply expansion and diversification. Nevertheless, continued reliance on fossil fuels and persistent distribution losses limit improvements in overall performance. Recent policy efforts aimed at renewable energy integration and efficiency enhancement suggest a gradual transition toward a more sustainable energy system.

Bangladesh shows a steady upward trend in energy security, supported by the gradual diversification of electricity generation and investments in infrastructure. However, the country remains vulnerable due to its dependence on imported fossil fuels, relatively high energy intensity, and limited penetration of renewable energy sources.

Nepal benefits from significant hydropower potential; however, its development has been constrained by infrastructural, financial, and governance challenges. The country continues to experience supply shortages, heavy reliance on traditional biomass in rural areas, and limited diversification of its energy mix.

Bhutan's energy security performance is largely driven by its hydropower-dominated energy sector, which provides low-carbon electricity for both domestic use and export. However, heavy reliance on a single energy source exposes the country to risks associated with climate variability and hydrological uncertainty.

Sri Lanka exhibits uneven progress in energy security. Although the country has initiated renewable energy development, particularly in solar and wind, it remains vulnerable due to its high dependence on imported petroleum products and limited domestic energy resources.

Table 7. Multifaceted Energy Security Index for South Asian Countries (2001–2022)

Years	Pakistan	India	Bangladesh	Bhutan	Nepal	Sri Lanka
2001	3.51	4.48	2.80	2.66	2.13	2.58
2002	3.54	4.55	2.84	2.68	2.18	2.63
2003	3.56	4.64	2.87	2.70	2.19	2.62
2004	3.58	4.72	2.87	2.70	2.18	2.59
2005	3.69	4.88	2.98	2.87	2.23	2.70
2006	3.74	5.02	3.07	2.99	2.25	2.75
2007	3.85	5.24	3.12	3.04	2.32	2.74
2008	3.90	5.33	3.16	2.98	2.34	2.78
2009	3.84	5.47	3.25	3.07	2.39	2.88
2010	3.93	5.70	3.26	3.10	2.60	2.96
2011	4.00	5.86	3.38	3.20	2.64	2.94
2012	4.01	5.95	3.43	3.25	2.73	3.00

Years	Pakistan	India	Bangladesh	Bhutan	Nepal	Sri Lanka
2013	4.09	6.11	3.37	3.28	2.83	3.12
2014	4.08	6.27	3.42	3.30	2.86	3.09
2015	3.96	6.43	3.56	3.36	2.84	3.14
2016	3.94	6.65	3.58	3.43	2.91	3.17
2017	3.88	6.82	3.63	3.53	2.86	3.10
2018	3.99	7.07	3.67	3.53	2.89	3.16
2019	4.00	7.29	3.70	3.56	2.87	3.13
2020	3.97	7.38	3.72	3.73	2.85	3.19
2021	4.08	7.58	3.78	3.95	2.85	3.21
2022	4.09	7.83	3.76	4.00	2.86	3.16

Source: Authors' calculations.

Note: The index is constructed based on PCA-derived weights and normalized indicators.

Higher values indicate better energy security performance.

5.7.1 Trend Analysis

Figure 2 illustrates the evolution of the MFESI across countries. India shows a consistent and significant improvement over time, driven by infrastructure investment, energy diversification, and renewable expansion. Pakistan's trend remains relatively stable, reflecting incremental progress without substantial structural change. Bangladesh demonstrates gradual improvement, supported by electrification efforts and increased use of natural gas.

Bhutan maintains relatively stable performance due to its strong hydropower base but lacks diversification. Nepal records only marginal gains, constrained by infrastructure limitations and reliance on a narrow energy base. Sri Lanka shows modest improvement, although its progress is limited by import dependence and exposure to energy price volatility.

5.7.2 Validation of MFESI

To assess the validity of the proposed MFESI, the results are compared with established global energy security frameworks, including the World Energy Council (2023), Asian Development Bank (2020), and the SAARC Energy Centre (2018).

The comparison indicates that MFESI rankings are broadly consistent with these established indices, particularly in terms of overall performance patterns and sustainability outcomes. Countries that perform well in the Energy Trilemma Index also tend to rank higher in the MFESI, suggesting alignment in capturing key aspects of energy security, such as supply reliability and resource availability.

Observed differences in rankings can be attributed to the broader scope of the MFESI, which incorporates additional dimensions, including governance, affordability, accessibility, and socioeconomic factors such as health, education, and employment. The inclusion of these dimensions enables a more comprehensive and policy relevant assessment of energy security.

Overall, the consistency with existing frameworks supports the robustness of the MFESI, while deviations highlight its added value in capturing the multidimensional nature of energy security in developing regions.

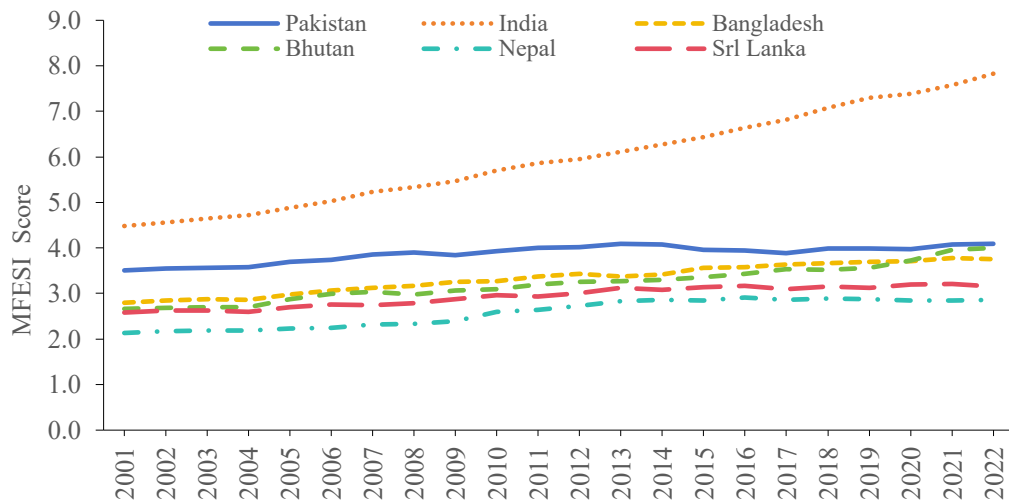


Figure 2. Multifaceted Energy Security Index for South Asian Countries (2001–2022)

Source: Authors' calculations.

Note: The figure presents country-level trends in MFESI over time. Higher values indicate improved energy security performance.

5.8 Comparative Analysis of Multifaceted Energy Security Index

Table 8 presents a comparative assessment of the Multifaceted Energy Security Index (MFESI) across South Asian countries by classifying index scores into four categories: Poor, Fair, Good, and Excellent.

The results indicate that Pakistan (3.9), Bangladesh (3.3), Bhutan (3.2), Nepal (2.6), and Sri Lanka (2.9) fall within the “Fair” category, reflecting moderate progress in energy security. However, these countries continue to face structural challenges, including dependence on fossil fuels, limited adoption of renewable energy, and infrastructural constraints.

In contrast, India (6.0) falls within the “Good” category (5.0–7.5), supported by its diversified energy portfolio, significant renewable energy investments, and improvements in energy efficiency. Notably, no country in the region reaches the “Excellent” category (7.5–10), highlighting persistent regional bottlenecks in achieving sustainable and secure energy systems.

Table 8. Comparative Classification of Multifaceted Energy Security Index

Range	Pakistan	India	Bangladesh	Bhutan	Nepal	Sri Lanka	Energy Security Status
1.0–2.5							Poor
2.5–5.0	3.9		3.3	3.2	2.6	2.9	Fair
5.0–7.5		6.0					Good

Range	Pakistan	India	Bangladesh	Bhutan	Nepal	Sri Lanka	Energy Security Status
7.5–10							Excellent

Source: Authors' calculations.

Note: Index values are categorized as follows: Poor (1.0–2.5), Fair (2.5–5.0), Good (5.0–7.5), and Excellent (7.5–10). Higher scores indicate better energy security performance.

5.9 Dimension-Wise Energy Security Assessment

A dimension-wise analysis provides deeper insights into country-specific strengths and vulnerabilities across different aspects of energy security, including sustainability, governance, affordability, energy access, and transition.

Table 9. Dimension-Wise Comparison of Multifaceted Energy Security Index

Dimensions	Pak	Ind	Ban	Bhu	Nep	Slk	Status
Energy Sustainability (ES)	0.81	3.50	0.62	0.53	0.72	0.58	Ind: High Bhu: Low
Governance & Efficiency (G&E)	0.45	0.58	0.59	1.00	0.21	0.46	Bhu: High Nep: Low
Socio- Environmental Sustainability (SES)	1.06	0.56	0.93	0.34	0.28	0.31	Pak: High Nep: Low
Affordability (AFF)	0.42	0.45	0.51	0.55	0.46	0.49	Nepal: High Pak: Low
Energy Access (EA)	0.26	0.23	0.19	0.16	0.09	0.45	Slk: High Nep: Low
Human Resilience (HR)	0.54	0.32	0.11	0.41	0.38	0.30	Pak: High Ban: Low
Energy Transition (ET)	0.18	0.24	0.21	0.14	0.19	0.19	Ind: High Bhu: Low
Labor Market Dynamics (LMD)	0.20	0.21	0.17	0.18	0.20	0.19	Ind: High Ban: Low

Source: Authors' calculations.

Note: Pak = Pakistan; Ind = India; Ban = Bangladesh; Bhu = Bhutan; Nep = Nepal; Slk = Sri Lanka. "High" and "Low" indicate the relative ranking of countries within each dimension.

Table 9 shows that India has the lead role in the region with a score of 3.50, indicating its diversified energy mix and robust renewable energy policies. Its substantial investments in solar, wind, and nuclear energy are also highlighted by the *International Renewable Energy Agency*. India's renewable energy capacity increased by more than 160 % over the past decade. Due to this advancement, India ranks fourth globally in total installed renewable capacity (IRENA, 2024). Bhutan has a score of 0.53, mostly due to its heavy dependency on hydropower and inadequate energy diversification. These results also align with the fact that Bhutan's reliance on a single energy source exposes it to risks associated with it. These risks are climate variability

and seasonal fluctuations in water availability (Ministry of Energy & Natural Resources, Royal Government of Bhutan, 2025; Bhutan Ecological Society, 2025; World Bank, 2025). In the case of governance, Bhutan shows strong institutional quality, effective policy implementation, and a transparent regulatory structure. These results also align with reports by the World Bank (2025) and Transparency International (2025). On the other hand, Nepal scores 0.31, which represents challenges in governance and regulatory frameworks. Weak governance in Nepal hinders the development and implementation of energy policies.

In Socio-environmental sustainability, Pakistan has a high score (1.06), whereas Nepal has the lowest score (0.28). It reflects that stronger social and environmental resilience in Pakistan. On the other hand, there are structural vulnerabilities in Nepal. In case of affordability, Nepal ranks highest (0.55) and Pakistan lowest (0.42), indicating that electricity and energy costs are relatively more manageable for Nepali households than Pakistani ones. These results are also supported by the report of the IEA, IRENA, UNSD, World Bank, and WHO (2019). Regarding energy access, Sri Lanka tops the region (0.45) while Nepal lags (0.09). It shows disparities in electrification and energy service availability. In the human resilience dimension of energy security, Pakistan again performs best (0.54), and Bangladesh scores lowest (0.11). It indicates Pakistan's stronger capacity to withstand energy-related social and environmental stresses (World Bank, 2025).

In the energy transition, India leads (0.24) and Bhutan scores lowest (0.14). It reflects that India has diversified renewable investments and Bhutan has hydropower dependency, supported by IRENA (2024) and the Ministry of Energy & Natural Resources, Royal Government of Bhutan (2025). Finally, for labor market dynamics, India ranks highest (0.21) and Bangladesh lowest (0.17), indicating stronger employment outcomes in India compared with more constrained labor markets in Bangladesh (World Bank, 2025). The graphical representation of the dimension-wise multifaceted energy security index is given in Figure 3.



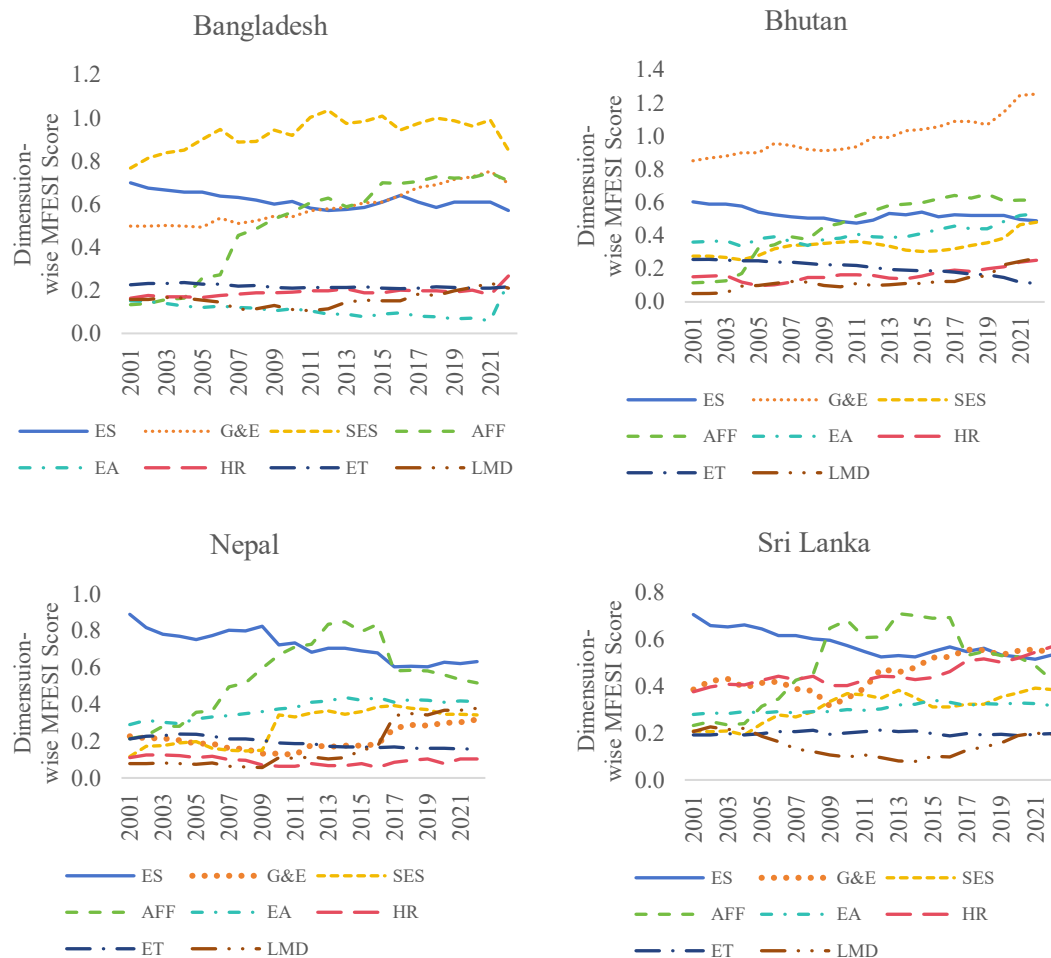


Figure 3. Dimension-Wise Multifaceted Energy Security Index for South Asian Countries

Source: Authors' calculations.

Note: The figure presents comparative performance across energy security dimensions. Higher values indicate stronger performance in the respective dimension.

6. Conclusions

Energy security remains a critical challenge for South Asia, where rapid population growth, limited energy resources, and geopolitical pressures continue to constrain sustainable development. This study develops a Multifaceted Energy Security Index (MFESI) for six South Asian countries (Pakistan, India, Bangladesh, Bhutan, Nepal, and Sri Lanka) over the period 2001–2022. The index is constructed using a comprehensive set of fifty-six indicators and employs Principal Component Analysis (PCA) to capture the multidimensional nature of energy security.

The MFESI is structured around eight dimensions: energy sustainability, governance and efficiency, socio-environmental sustainability, affordability, energy access, human resilience, energy transition, and labor market dynamics. The results indicate that India ranks highest in overall energy security, followed by Pakistan, Bangladesh, Bhutan, Sri Lanka, and Nepal.

The comparative analysis shows that, with the exception of India, all South Asian countries fall within the “Fair” category, reflecting moderate progress but persistent structural challenges, including reliance on fossil fuels, limited infrastructure, and institutional inefficiencies. India is the only country in the “Good” category, supported by its diversified energy mix, strong renewable energy expansion, and improvements in energy efficiency.

The dimension-wise analysis further highlights significant heterogeneity across countries. India leads in energy sustainability and renewable development, while Bhutan performs strongly in governance and affordability but lags in sustainability due to limited diversification. Pakistan shows strong performance in socio-environmental sustainability and human resilience but faces challenges in affordability. Sri Lanka performs relatively well in energy access, whereas Nepal consistently ranks lowest across several dimensions, particularly governance, energy access, and socio-environmental sustainability.

Overall, the findings underscore the multidimensional nature of energy security and reveal substantial disparities across South Asian countries, emphasizing the need for targeted and coordinated policy interventions.

7. Policy Recommendations

The findings highlight the need for a coordinated regional strategy to enhance energy security in South Asia, with a focus on diversification, resilience, and sustainability.

First, governments should accelerate the transition toward renewable energy sources, particularly solar and wind, to reduce dependence on fossil fuels and exposure to global energy price volatility. Strengthening regional cooperation through cross-border electricity trade and shared infrastructure, such as integrated power grids and energy storage systems, can improve supply reliability and system flexibility.

Second, improving energy efficiency across industrial, residential, and transportation sectors should be prioritized within national energy and climate strategies. Efficiency gains can reduce energy demand pressures, lower carbon emissions, and improve affordability, especially for vulnerable populations.

Third, enhancing socio-energy resilience is essential for inclusive and sustainable development. Expanding access to modern energy services, particularly in rural and underserved areas, alongside investments in climate-resilient infrastructure and clean energy awareness, can support long-term energy security. These efforts also contribute to achieving Sustainable Development Goals (SDGs) 7, 8, and 13.

At the country level, policy priorities differ. India should continue accelerating diversification toward non-hydro renewable energy sources, particularly solar, wind, and biomass. Pakistan and Bangladesh should scale up renewable energy adoption while improving affordability through targeted subsidies, demand-side efficiency measures, and expanded rural electrification. Strengthening governance and institutional capacity will further enhance system reliability in these countries.

For Bhutan and Nepal, which are heavily dependent on hydropower, policy efforts should focus on energy diversification and improved resource management. Investments in energy storage systems and grid modernization are essential to mitigate climate-related risks and seasonal variability. These efforts should be supported by strong regulatory frameworks and public-private partnerships.

Sri Lanka should prioritize energy efficiency improvements across households and industries while accelerating the diversification of its energy mix. Enhancing institutional capacity, strengthening socio-energy resilience, and expanding reliable energy access are critical for achieving long-term energy security.

8. Ethics Statement

This study used secondary data from publicly available sources and did not involve human participants, personal identifiable information, or primary data collection. Therefore, ethics committee approval was not required.

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